GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

BIOINSPIRED KINETIC ARCHITECTURE AND ADAPTIVE COMPONENT DESIGN PROPOSAL

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GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

BIOINSPIRED KINETIC ARCHITECTURE AND ADAPTIVE COMPONENT DESIGN PROPOSAL

AISA ATAWULA

MSc. THESIS
DEPARTMENT OF ARCHITECTURE
PROGRAM OF COMPUTER AIDED DESIGN

ADVISER
ASSIST. PROF. DR. TOGAN TONG

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A thesis submitted by AISA ATAWULA in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 22.07.2016 in Department of Architecture, Computer Aided Design Program.

Thesis Adviser

Assist.Prof. Dr. TOGAN TONG

Yıldız Technical University

Approved By the Examining Committee

Assist. Prof. Dr. TOGAN TONG

Yıldız Technical University

Doç. Dr. Çiğdem CANBAY TÜRKYILMAZ

Yıldız Technical University

Prof.Dr.Birgül ÇOLAKOĞLU

İstanbul Technical University

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July, 2016

AISA ATAWULA

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LIST OF ABBREVIATIONS

CO_2	Carbon dioxide
DCV	Demand-Controlled Ventilation
GH	Grasshopper
IEQ	Indoor Environmental Quality
PPM	Particle Per Million
SMA	Shape Memory Alloy
SME	Shape Memory Effect
YTU	Yıldız Technical University

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ABSTRACT

BIOINSPIRED KINETIC ARCHITECTURE AND ADAPTIVE COMPONENT DESIGN PROPOSAL

Aisa ATAWULA

Department of Architecture

MSc. Thesis

Adviser: Assist. Prof. Dr. Togan TONG

Architecture are structures of defined spaces that protect people and their belongings from the exterior environment, among which are the harsh weather conditions, such as wind, rain, and excess sun radiation. Kinetic architecture is the new design method to achieve sustainability by adapting to variable environmental conditions. Previous researches about kinetic architecture mostly considered to use mechanical components and systems for actuation and transformation. Designing kinetic architecture is at the crossroad of either utilizing revolution of shape changing materials with strategies from nature or continue using existing mechanical approaches. In this thesis, adaptation principles from leaves stomata is applied to propose adaptive component that can accommodate to the environmental changes with less energy consumption by utilizing shape changing materials.

In this research alternative design strategies for kinetic adaptable building systems have been investigated based on bioinspired design approach. The internal environment of an organism is kept constant within certain limits by regulating mechanisms called homeostasis. Investigating and analyzing these strategies enables architects and engineers to transfer these strategies to kinetic building design. It is proposed that the implementation of successful adaptation strategies inspired from nature can result in adaptable building systems that "behave" as living organisms that accommodate to the dynamic environmental changes. Plants are recognized as examples of kinetic systems that perform mobility with minimal energy use, due to the fiber elasticity composition, and integrating sensing and actuating capabilities into their system. The stomata of plants leaves are chosen as role model for adaptive component which is capable of adapting to CO_2 level change in space and temperature fluctuation to provide interior environment comfort for users. This adaptive component is most effective in environments where demand control ventilation is needed such as classrooms, theaters, auditoriums, data centers, stadiums and mosques where the occupancy is intermittent and often well below the maximum design occupancy. Working principles of the adaptive component and three application scenario is discussed in detail and its environmental benefits is explained.

Another aim of this research is to explore alternative material systems for actuation of kinetic systems. The development of shape changing materials influenced the design of kinetic architecture. New possibilities of applying shape changing materials in modular systems for architectural skins that respond to various environmental conditions is explored. Shape memory alloy is utilized for adaptive component due to its kinetic behavior in lower temperature and shape memory effect.

It is concluded from the research that through utilizing shape changing materials for kinetic architecture systems bioinspired adaptive sustainable buildings could be achieved by transferring plants adaptation principles into architectural design solutions.

Key words: Kinetic Architecture; Adaptability; Bioinspired Design; Shape Changing Materials; Adaptive Component; Demand Controlled Ventilation; Shape Memory Alloy

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ÖZET

BİYOLOJİDEN ESİNLENMİŞ KİNETİK MİMARİ VE UYARLANABİLİR BİLEŞEN TASARIM ÖNERİSİ

Aisa ATAWULA

Mimarlık Anabilim Dalı

Yüksek Lisans Tezi

Tez Danışmanı:Yrd. Doç. Dr. Togan TONG

Mimari insanları ve onların eşyalarını dış ortamdan, rüzgâr, yağmur ve yoğun güneş ışığı gibi sert iklim koşullarından koruyan strüktürler olarak tanımlanır. Kinetik mimari çeşitli çevresel şartları adapte ederek sürdürülebilirliğe erişmek için kullanılan yeni tasarım yöntemidir. Kinetik mimari ile ilgili önceden yapılan çalışmalar sıklıkla harekete geçirme ve kinetik dönüşüm için mekanik bileşenleri ve sistemleri kullanmayı kapsamaktadır. Kinetik mimariyi tasarlamak ya doğadan biçim değiştiren malzemelerin devriminden; ya da var olan mekanik yaklaşımlardan faydalanır. Bu tezde, yaprak gözeneklerinden adaptasyon prensipleri biçim değiştiren malzemelerden faydalanılarak az enerji tüketimiyle çevresel değişimlere uyum sağlayabilen, uyarlanabilir bileşen sunmak için uygulanır.

Bu araştırmada biyolojiden esinlenmiş tasarım yaklaşımlarına dayanarak kinetik uyarlanabilir bina sistemleri için alternatif tasarım stratejileri araştırılmıştır. Bir organizmanın iç ortamı homeostasis denilen düzenleyici mekanizmalarla çevredeki çeşitliliğe rağmen belirli limitlerde sabit tutulur. Bu stratejilerin araştırılması ve analizi mimar ve mühendislerin bu stratejileri kinetik bina tasarımına transfer etmelerini sağlar. Doğadan esinlenen başarılı uyum stratejilerinin uygulanması, uyum sağlayabilen bina sistemlerinin yaşayan organizmalar ya da dinamik çevresel değişimlere uyum sağlayabilen doğal sistemler gibi davranmasını sağlar. Bitkiler lifli elastiklik kompozisyonlarından dolayı, minimum enerji kullanımıyla mobilete sağlayan kinetik sistemlere örnektir, ve sezme ve harekete geçirme kapasitelerini sistemlerine entegre edebilirler. Bitkilerin gözenekleri, mekândaki kullanıcılara iç ortam konforu sağladığı, CO2 ve sıcaklık değişimlerine adapte olabildikleri için uyarlanabilir bileşen için rol model olarak seçilmiştir. Bu uyarlanabilir bileşen modülü talep kontrollü havalandırmaya ihtiyaç duyulan sınıf, tiyatro, oditoryum, bilgi merkezi, stadyum ve cami gibi kullanımın aralıklı olduğu ve genellikle maksimum tasarım kullanımının olduğu ortamlarda en etkilidir. Uyarlanabilir bileşeninin çalışma prensipleri ve üç uygulana senaryosu detaylı olarak tartışılmış ve çevresel katkıları açıklanmıştır.

Bu araştırmanın bir diğer amacı da kinetik sistemlerin uyarlanması için alternatif malzeme sistemlerini keşfetmektir. Biçim değiştiren malzemelerin gelişimi kinetik mimarinin tasarlanmasını da etkiler. Mimari kabuklar için biçim değiştiren malzemelerin uygulanmasının modüler sitemlerde sağladığı, çeşitli çevresel durumlara yeni olanaklar ortaya çıkarılmıştır. Şekil bellekli alaşım düşük sıcaklıktaki kinetik davranışı ve biçim hafıza etkisi için ADAPTIVE COMPONENT kullanılır.

Bu araştırmadan kinetik mimari sistemler için biçim değiştiren malzemelerden faydanılması, biyolojiden esinlenmiş uyarlanabilir sürdürülebilir binaların bitkilerin uyum prensiplerinin mimari tasarım çözümlerine dönüştürülmesi ile başarılabileceği sonucuna varılabilir.

Anahtar Kelimeler: Kinetik Mimari; Biyolojiden esinlenmiş tasarım; biçim değiştiren malzeme; Uyarlanabilir bileşen; Talep kontrollü havalandırma; Biçim hafıza alaşımı.

CHAPTER 1

INTRODUCTION

1.1 Literature Review

The forms in nature are shaped by responding to environmental impact. For example, the sand dome always changes its forms according to the direction, speed of the wind and other environmental pressures. Natural forms are subject to a continuous adaptation. As in the evolution, forms that are not adabreapt to changes will disappear.

Architecture are envelopes of defined spaces that protect people and their belongings from the exterior environment, among which are the direct harsh weather conditions, such as wind, rain, and excess sun radiation[1]. Traditional buildings, like most of modern architecture are static opposite to changing environmental conditions. However, it is impossible that human need stays the same during decades of building lifecycle. At the moment our world is going through great technical, social, economic change with accelerating pace. Human beings are incredibly flexible thanks to fast and cheap communication and transportation.

Kinetic architecture is the new design method to achieve sustainability by adapting to variable environmental conditions and changing social needs of the space and interact with the user[1] . With the development of recent technology, kinetic building systems have developed to adapt to changing environments and user needs during the decades of building life. The movement in kinetic architecture may provide by simple translation, rotation, folding movement or by complex systems such as mechanic, pneumatic, chemical, magnetic system[2]. However, most of kinetic architecture until today are based on complex, expensive maintaining, energy consuming mechanical systems.

In relation to kinetics, Fox and Kemp predict “the end of mechanics” as a “paradigm shift from the mechanical to the biological in terms of adaptation in architecture”[2]. This will be achieved through novel material development and the close look at biological systems, essentially mimicking natural solutions. To this end, successful strategies could be obtained from nature, which presents an immense source for adaptation strategies. When we turn to nature for solutions, it is noticeable that natural organism have developed special mechanisms to preserve their inner balance from external conditions through 3.8 billion years of evolution[3]. Plants are recognized as examples of kinetic systems that perform mobility with minimal energy use, due to the fiber elasticity composition, and integrating sensing and actuating capabilities into their system[4]. This homeostasis mechanism enables the plant for better photosynthesis. In this research, these homeostasis principles of the plants are going to be analyzed and transfer to kinetic building design solutions. Responsive capability of natural organisms is inspiration source for architects to design kinetic adaptive buildings without relying on complex and expensive mechanical control systems.

Current material advancement allows new materials to be act as plants in terms of kinetic response. Shape changing materials present kinetic behavior when triggered by external stimuli. Current application of shape changing smart martials in other industries, such as Lycra skin system on BMW's GINA concept car and morphing wing technology at NASA, indicates the potential of shape changing materials to be implemented in architectural adaptive systems. Their ability to move without motors or mechanical parts enables creation of climatically adaptive sustainable zero-energy buildings.

1.2 Objective of the Thesis

The understanding of living organisms inspires design thinking. If consider the building as an organism, in which the envelope and inner component together composes a system, we expect our "organism" to be able to keep the interior comfort while the external environment changes, just as the plant world. This research aims at developing kinetic adaptable architecture components to adapt to changing environmental conditions to offer interior air comfort by transferring and integration of functional principles of plants through bioinspired design approach. This will be achieved through evaluating kinetic architectural trends, understanding bioinspired design approaches and analyzing plant adaptation principles.

Another aims of this research is to explore alternative material systems for actuation of kinetic systems. The development of shape changing materials influenced the design of kinetic architecture. Architects need to understand these materials to fully utilize these materials in design process. New possibilities of applying shape changing materials in architectural envelopes that respond to various environmental conditions is explored. The proposed component is able to detect environmental changes and adapt to it by utilizing shape changing material’s inner properties.

1.3 Hypothesis

Like the Lycra skin system that deforms to increase performance at different driving speeds, buildings can perform efficiently, effectively and responsively to changing environmental or programmatic conditions, automatically and smartly. Architectural skins can be sensitive, interactive extensions of our own bodies and not just protection from nature. By combining conceptually abstracted systems found in nature with smart material technologies, the building could adapt in a flexible manner to climatic and functional changes and achieve sustainability. It is proposed that the implementation of successful adaptation strategies inspired from nature can result in adaptable building systems that “behave” as living organisms or natural systems that accommodate the dynamic environmental changes. Alternative design approach to traditional kinetic architecture is to use shape changing materials` kinetic behavior depending on inner property.

1.4 Research Outline

The thesis seeks a convergence between adaptation challenges of a building and solutions found in nature, through bioinspired design, by using shape changing materials. To achieve this goal, this thesis will be supported by many research areas. They include kinetic architecture(chapter2) which enables the system to adapt and move, bioinspired design(chapter3) which provides solutions inspired by natural principles, and shape changing materials(chapter3) which will realize adaptable behavior with minimum energy based on material property (figure 1.1).

In chapter four, by integrating research from kinetic architecture, bioinspired design and shape changing materials, a bioinspired adaptaive component has been proposed. The component is inspired by the stomata of leaves which adapts to environmental change such as temperature, humidity, CO2 level and air pressure. The component will respond to interior environment factors: CO2 level and temperature. It will adapt its porosity according to the heat level and occupant condition to provide natural ventilation which will reduce energy consumption and dependency on HAVC systems of buildings. Working principles of the component and several application scenarios is presented.

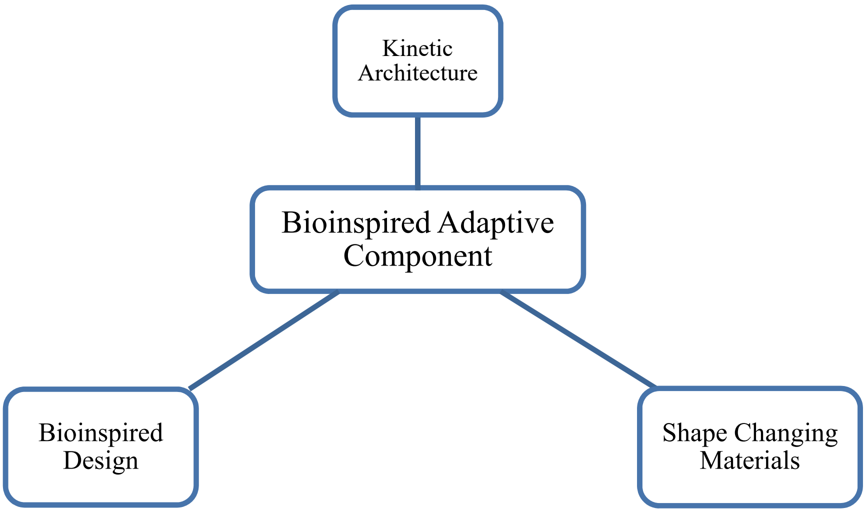


Figure 1.1Structure of The Thesis

CHAPTER 2

KINETIC ARCHITECTURE

From early period of human history, human beings are searching for solutions to adapt building to changing exterior whether conditions. Early Egyptians used the wind tower to achieve interior comfort. The tower runs from the underground level to the roof and uses the pressure difference between inside and outside to air circulation[5]. To adapt to climate change, during the nomadic period, people have built light weighted transformable tents, such as Mongolian yurt and tipi of the North America natives. Most of these structures were made of linear wood covered with rigid and/or flexible fabric, capable of being carried by animals and erected directly in the field. Nomadic tribes always have to move from one place to another to seek for food or water for survival. So the ability to build portable and transformable dwellings is the main factor for their survival.

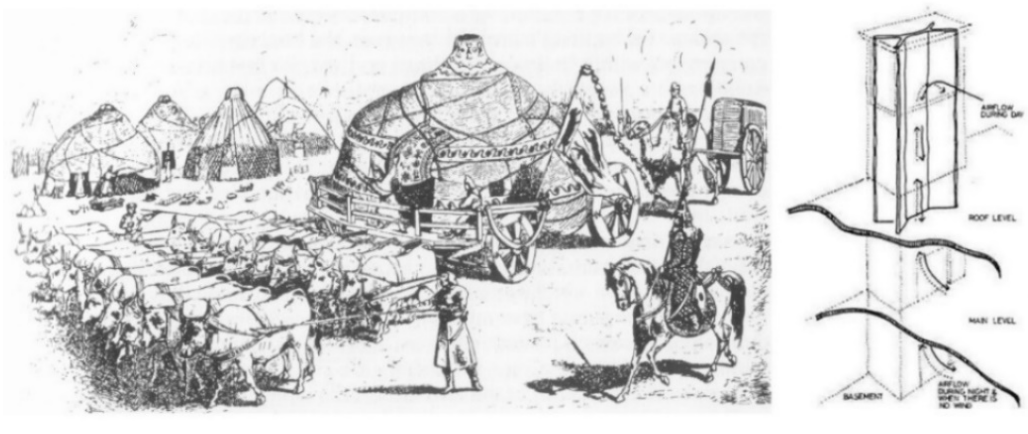


Figure 2.1 Mongolian Yurt and Ventilation with Wind Tower In Egypitian House[5]

Since the industrial revolution, with the development of mechanics, electronics, and robotics, the implementation of kinetic architecture has been increased strongly[6]. Modern kinetic architecture uses complex mechanical actuators for movement, such as

Chuck Hoberman’s Iris Dome and Santiago Clatrava`s Kuwait pavilion. After all, peoples are always looking for ways to adapt to environmental change.

In this chapter, literature review has been conducted about objective and benefits of kinetic architecture and the definition and recent researches about kinetic architecture is explained. Some build and conceptual projects are shown to have better understanding of conventional mechanic-based kinetic architecture.

2.1 Objectives and Benefits of Kinetic Architecture

At the moment our world is going through great technical, social, economic change with accelerating pace. With fast and cheap communication and fast transportation, human beings are experiencing new nomadic life. Human beings are incredibly flexible. They move around the world and manipulate objects, interact with the environment in various ways. Should not our buildings be flexible as we are?

Despite the fact that the surroundings and user needs are changing, the main design solutions are static and unadaptable. The fact, that the majority of buildings fall into this static, non-adaptive category, implies that a vast number of people are living and working in buildings which are too difficult and costly to modify, but don't meet their spatial and programmatic performance requirements. So the building should have kinetic ability to adapt to these varying needs and changing environmental conditions to provide optimal performance with less energy. The method to reach this goal is kinetic and adaptation[7]. Kinetic building is the main approach for achieving sustainability with flexible adaptive solutions by using less energy and providing better interior environment comfort. The overall space efficiently of kinetic architecture is much better than static buildings.

Kinetic systems can be used in different situations for satisfying different requirements. Firstly, kinetic architecture provides better space reconfiguration and customization both for users’ needs and changing surrounding conditions (figure 2.2). The application of kinetic architecture would provide possibilities such as interior space reconfiguration, transformation or deployment of the whole building structure. Kinetic systems can be used to turn a single space into a multi-function space that can occupy different activities by spatially reconfigure itself to truly accommodate each particular function when needed. Kinetic architecture system are used for large open spaces that accommodate many different activities by providing different configurations[8]. Transformable shelters could be design with kinetic systems. They are easily constructed, reassembled and transformed to other locations.

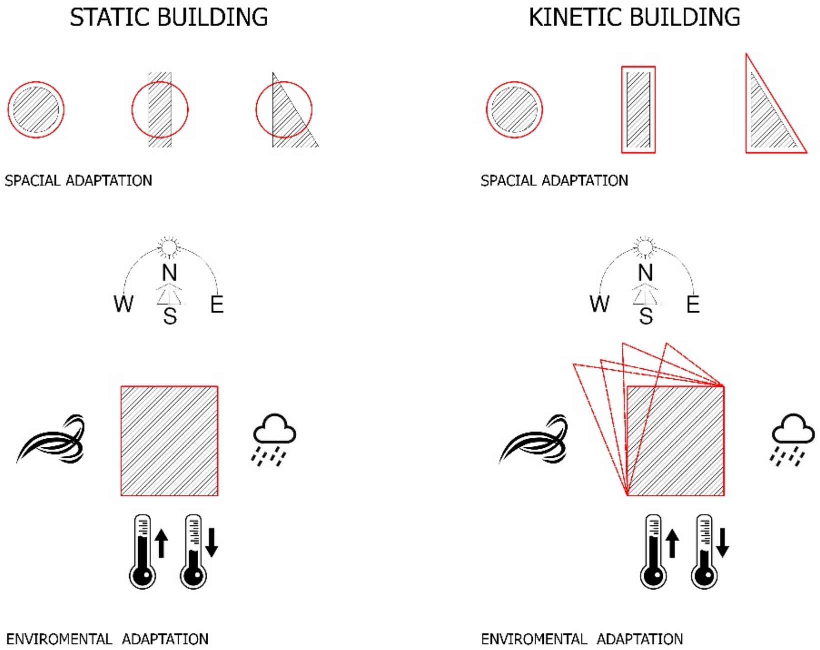


Figure 2.2 Response of Kinetic and Static Architecture to Environmental Change and Spatial Requirement

Secondly, kinetic architecture could provide better indoor environment quality with less energy. The aim of the architects is to design buildings that respond to as much environmental effect as possible however the problem here is the environmental factors is always changing and the buildings we design are respond to static environmental pressure (figure 2.3). Kinetic architecture is adaptation of building elements to changing environments to reduce the effect of environmental fluctuation to interior. These environmental factors include solar radiation, wind, light, temperature, air quality and so on. The kinetic building envelope could adjust itself according to sun radiation to regulate the interior luminous level, which is important for productivity and visual comfort. Air quality of the building could be also adjusted by kinetic elements.

Finally, Kinetic Buildings could have longer life cycle and suits the future needs better. These adaptations are ecologically and economically feasible[9].Kinetic architecture enables new buildings to adapt to environmental pressure also answers to the space requirement of today's constantly altering life style. Kinetic systems can be applied to existing buildings as a renovation solution. Those building which seems not satisfying user needs can be restarted new life cycle. With the development of technology and new materials, the kinetic architecture is supposed to adapt to varying users need of today and future. Kinetic architecture also adapts to the changing social needs of the space and interact with the user. The objective of kinetic architecture is to innovate kinetic structures and building elements which are adaptable to new needs[10].

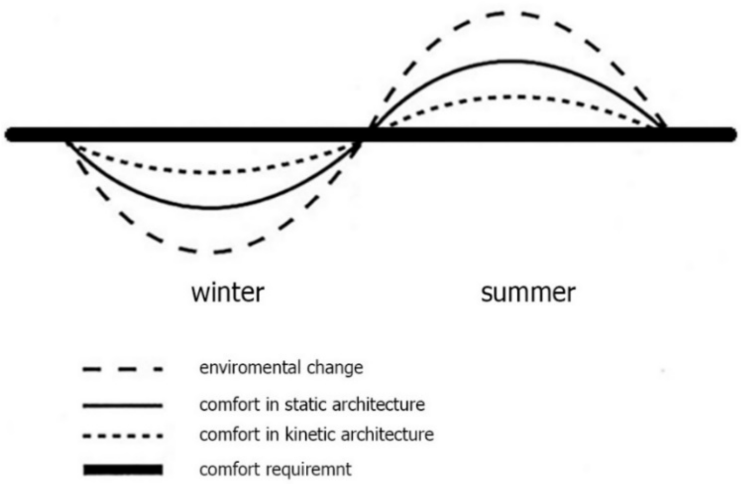


Figure 2.3 Comfort Level Fluctuation in Kinetic and Static Buildings

2.2 Kinetic Architecture in Literature

The word kinetic comes from the verb “kineo” means movement in Greek. So it is possible to interpret kinetic architecture as architectural movement or moving architecture[7].

Kinetics in modern architecture is not new. First relevant design is started as early as the first quarter of the 20th century. However, the term kinetic architecture was first introduced to literature in the book “kinetic architecture” by Zuk and Clark. Zuk and Clark in 1970s. The book investigated the relevant projects and prototypes and discussed the mechanism to achieve kinetic movement. They discussed about Natural forms which are the result of adaptation to the environmental factors. Zuk and Clark suggest that architectural form should have the capacity to adapt to different environmental pressure [11]. In artificial forms such as buildings, designers are analyzing these environmental factors and try to answer to most of the stimulus. But, the environmental factors are in continuous change. These form generating pressure sets would lead to the change of building elements. The relationship between architectural form and pressure has been illustrated by a schema in figure 2.4. The form is the response to these pressure, and technology is providing engineering solutions for efficient response. The architectural form should build an equilibrium with these changes. Zuk and Clarke characterize the kinetics as “the architectural form could be inherently being displaceable, deformable, expandable or capable of kinetic movement”[1].

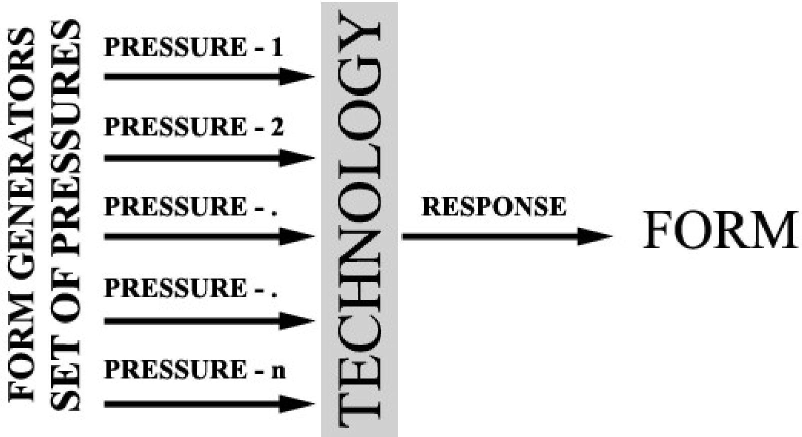


Figure 2.4 Basic Pressure-Response Diagram Showing Relationship Between The Set Of Pressures And The Form[1]

In the book, they also provide eight helpful architectural applications—kinetically controlled static structures, dynamically self-erecting structures, kinetic components, reversible architecture, incremental architecture, deformable architecture, mobile architecture, and disposable architecture[1]. They explain every types with built project or research experiment. This classification only focus on the application direction of the kinetic systems, but the scale of the project, structural characteristics and control mechanics is overlooked.

Later on, Kinetic architecture is defined by Michael A.Fox, founder of the KDG at MIT, simply as “buildings or building components with variable mobility, location and/or variable geometry”[12]. This is the most accepted definition of kinetic architecture. Kinetic movement may be achieved by “folding, sliding, expanding and transforming in both size and shape” through “pneumatic, chemical, magnetic, natural, or mechanical” means[12].

In “Intelligent Kinetic Systems in Architecture”, Michael A. Fox and Bryant P. Yeh try to classify kinetic structures from different angels. In the kinetic architecture typologies section, they evaluate the kinetic architectural structures according to their dynamic scale. Michael Fox categorize kinetic architecture into three general categories: (1) embedded (which means the kinetic structure is part of a fixed building), (2) deployable (which builds for temporary use and can be easily transported to other locations), and (3) dynamic kinetic structures (which is also part of the architectural whole, but could move separately response to the larger context) (Figure 2.5)[12].

Figure 2.5 Subdivision of Kinetic Architecture by System Configuration[12]

Fox and Yeh divided kinetic architecture into six subdivisions according to the techniques used to control/enable the motion.

1.Internal control: systems in this category are capable of kinetic movement without needing for sensors or other mechanisms (figure2.6).

2.Direct control: which is connected to an energy sources for the actuation of the kinetic system responding to environmental factors (figure2.6).

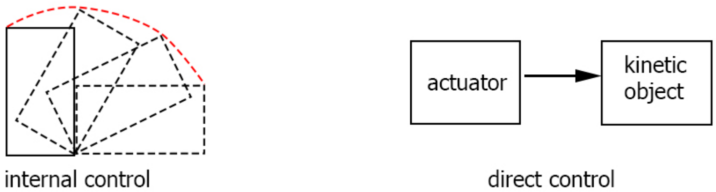


Figure 2.6 Internal Control and Direct Control[13],[14]

3.In-direct control. The sensor receives data from the environment and actuates the movement (figure2.7).

4.Responsive in-direct control. A control program is added to the in-direct control mechanism. The microprocessor will receive data from sensors and trigger the movement accordingly (figure2.7).

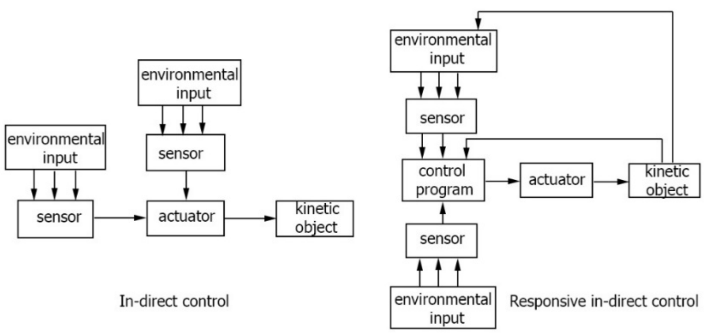


Figure 2.7 In-Direct Control And Responsive In-Direct Control[13],[14]

5.Ubiquitous responsive in-direct control. There more than one sensor actuator relationship in one control mechanism. They have a feedback algorithm

6.Heuristic Responsive In-Direct Control. This system could be just responsive control or Ubiquitous responsive in-direct control. But the system has learning or developing ability[13].

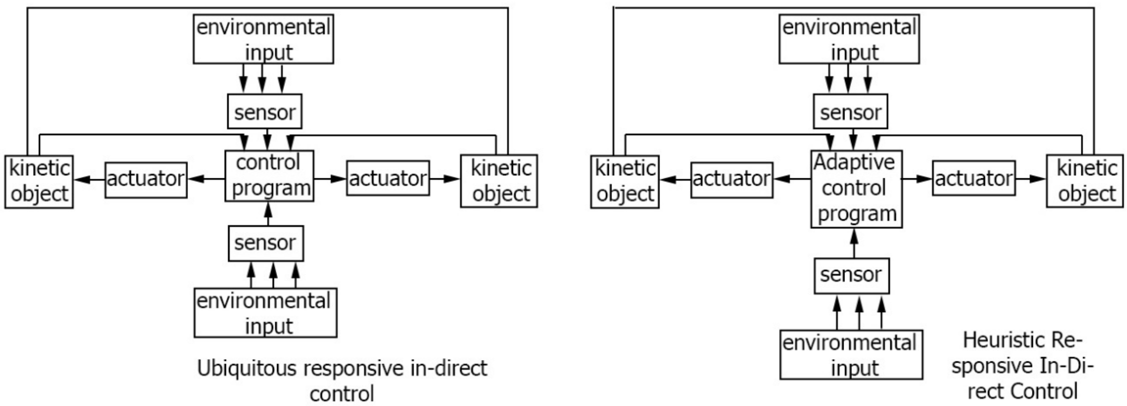


Figure 2.8 Ubiquitous Responsive In-Direct Control And Heuristic Responsive In-Direct Control[14],[13]

Chuck Hoberman gives another definition for kinetic architecture. According to his definition, kinetic architecture is capable of creating transformable environments or responsive building elements[11].

According to all the sayings above, we could conclude that kinetic architecture is buildings or building systems that respond and adapt to pressure sets which include environmental factors or user`s changing needs(Figure2.9), by utilizing different control/enable techniques, to create adaptive environments and responsive interactive space.

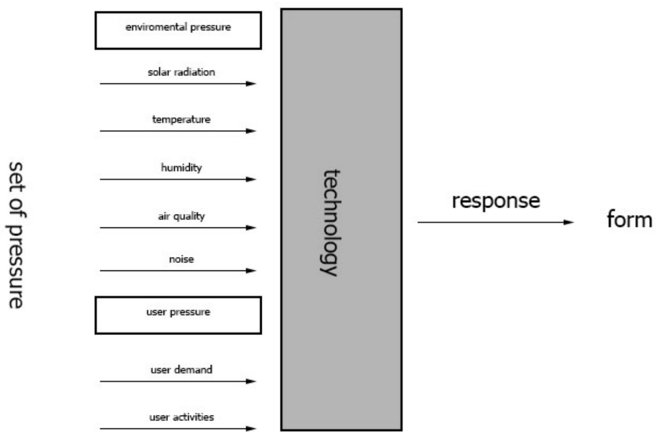


Figure 2.9 Environmental and User Pressure to Kinetic Architecture

According to the responsive mechanism of the kinetic architecture, we could categorize kinetic architecture systems into three types: passive systems, active systems and hybrid systems (figure 2.10). Passive system reacts instantly to external stimulus like control systems in lower level organisms. This system uses materials' property as sensor and actuator. However, the sensors in active system detect the changes and control mechanism process the information and defines the action to be executed. The user can interfere with the system and control the output reaction. The hybrid system combines the attribute of the both system, it could passively react to changes and also could be controlled by control mechanism.

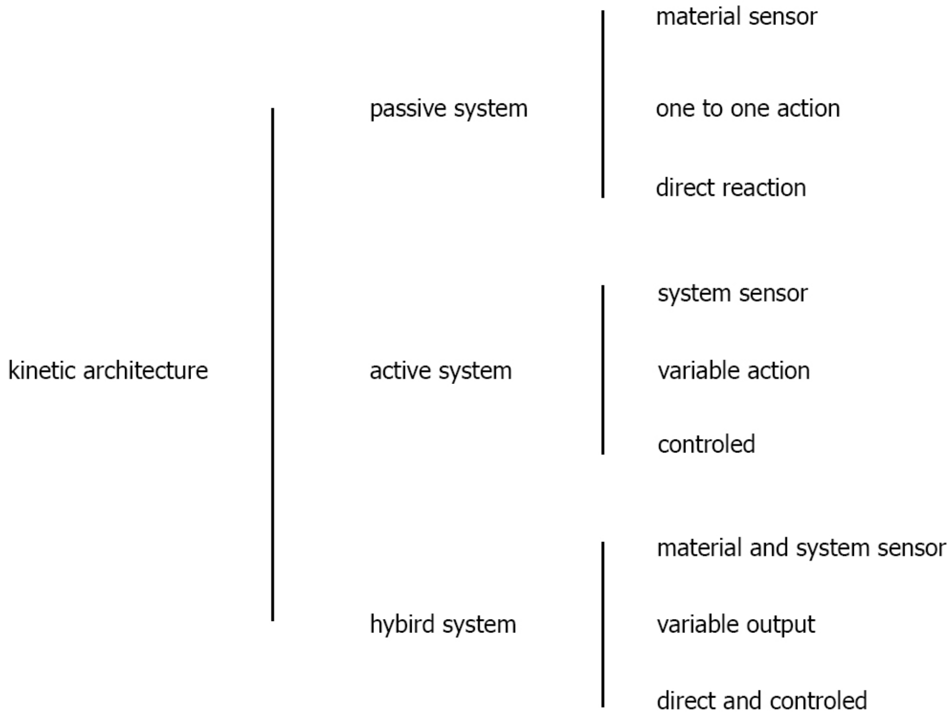


Figure 2.10 Active, Passive and Hybrid Kinetic Systems

2.3 Recent Developments

Although the kinetic architecture could be traced back to much earlier times, the widely practical implementation of kinetic architecture starts in 20th century. For a few decades, kinetic architecture remains on the paper or only theoretically[15]. But with the development of interdisciplinary research and development in mechanics, material engineering and computer aided design(CAD), some engineers and architects such as Buckminster Fuller and Santiago Calatrava and other research groups as Archigram, Futurism and Metabolism, have opened up new dimensions of kinetic architecture both in research and architectural application.

The selected projects are analyzed according to their stimulus factor and control mechanism.

a) Villa Girasole

The rotating villa designed to constantly capture sunlight, by Angelo Invernizzi, is one of the early designs of kinetic responsive architecture. As Girasole means sunflower, the front façade of the building always tracks the movement of the sun. There is no sensor or controller involved in this building, so it belongs to the direct control system. This house is designed for the mother of the architect, who has illness and cannot move her body. So the architect design this house to track the sun light to cure his mother`s illness. The architect not only transforms the static building to kinetic architecture, but also changes the dwelling function of the building to clinic function.

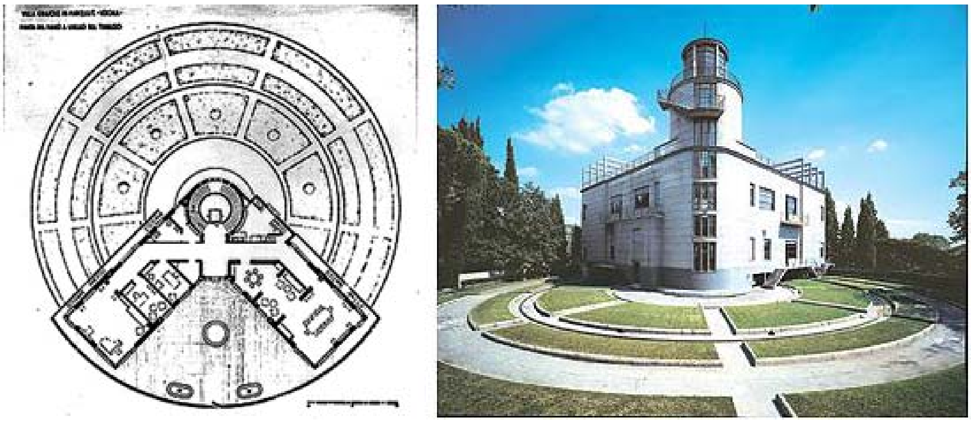


Figure 2.11 Villa Girasole[17]

b) Arab World Institute

Arab World Institute is designed by Jean Nouvel in 1987. The south façade of the building, which faces the large public square, is equipped with kinetic metal screen. It is the technical interpretation of the traditional Arabic sun screens in intergraded panel systems. The façade is controlled by 240 motors. This screen acts as sun shading device to control light penetration and creates shadows in the interior space. This façade is responding to solar value and adjust its opening on an hourly basis. The kinetic movement of the façade is trigger by light sensors and it is controlled by In-direct control mechanism.

This is the most widely known example of a building with climate adaptive building shell. This project not only the pioneer of kinetic facades that response to external environment, but also inspiration for many architects. However, this façade is not working duo to its complex mechanical system`s fatigue failure and high maintain cost[16].

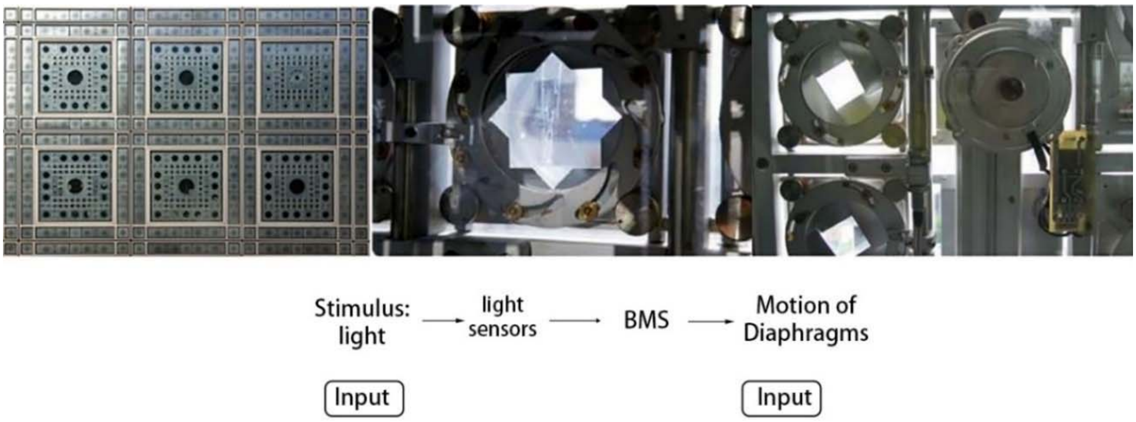


Figure 2.12 Arab World Institute And Its Response Diagram[16]

c) Santiago Calatrava Kuwait Pavilion

The Kuwait Pavilion for the Expo 92 in Seville, Spain, by Santiago Calatrava is an example of dynamic kinetic structures inspired by nature. The kinetic roof shading system could protect the users from sun during the day and opens at different angles during the night for different activities[7]. This building response to light and belongs to Responsive in-direct control.

Santiago Calatrava has designed many kinetic projects which includes kinetic systems. He always takes inspiration from nature. He investigates the movement of birds and plants then apply their mechanism to design.

Figure 2.13 Kuwait Pavilion[7]

d) Media-TIC

The Media-ICT building designed by Cloud 9 is an example of a highly energy efficient building, achieved through the implementation of kinetic architectural skins[16]. Façade is made of inflatable ETFE bubbles acting as an external mobile screen opening in winter to afford heat savings and closing in summer to control sun. Multiple temperature sensors embedded into façades and offices, are used to collect outdoor information. The system mostly responds to sun radiation and belongs to Ubiquitous responsive in-direct control.

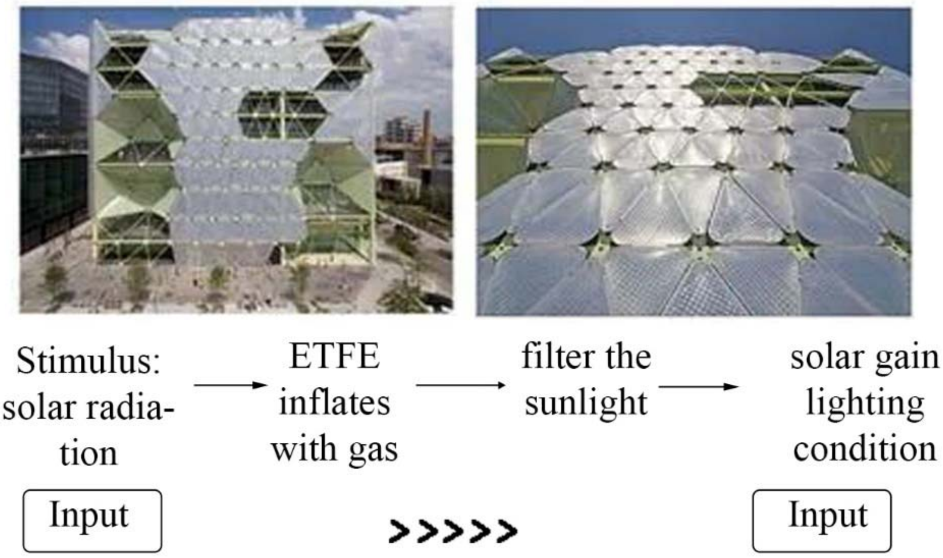


Figure 2.14 The Media-ICT Building And Its Response Diagram [16]

e) Qizhong STADIUM

Qizhong stadium is a tennis arena in Shanghai, China. The design was inspired by the flower of the city, a blooming magnolia. The roof has eight steel petals like in the magnolia flower. This stadium could host indoor and outdoor sport events by opening and closing its roofs[8]. The roof could protect the interior space during bad weather conditions. This roof is opened in good weather conditions and not responding to any environmental factors. This belongs to the direct control system.

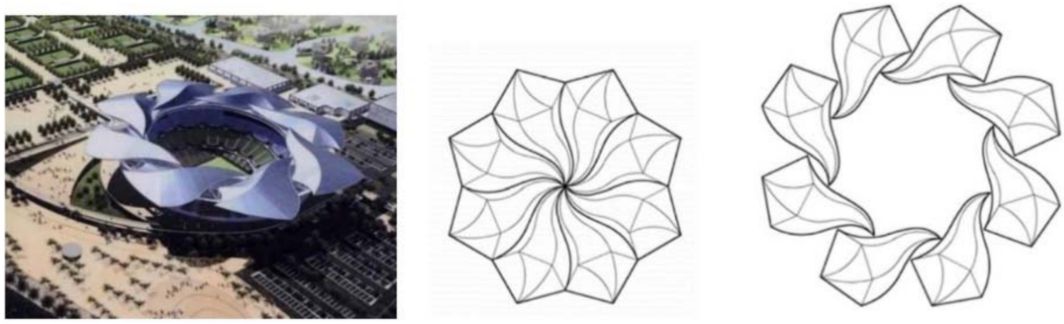


Figure 2.15 Qizhong Stadium[8]

f) The Aegis Hyposurface

The Aegis Hyposurface system consist of transformable triangulated metal plates, actuated by 896 pneumatic pistons. The real-time response of the surface is based on various stimuli, such as whether, people's existence or sounds. The surface interacts with the user by adapting its shape according to people movement. This surface uses high tech mechanical solutions to achieve transformation[16]. This system uses Ubiquitous responsive in-direct control.

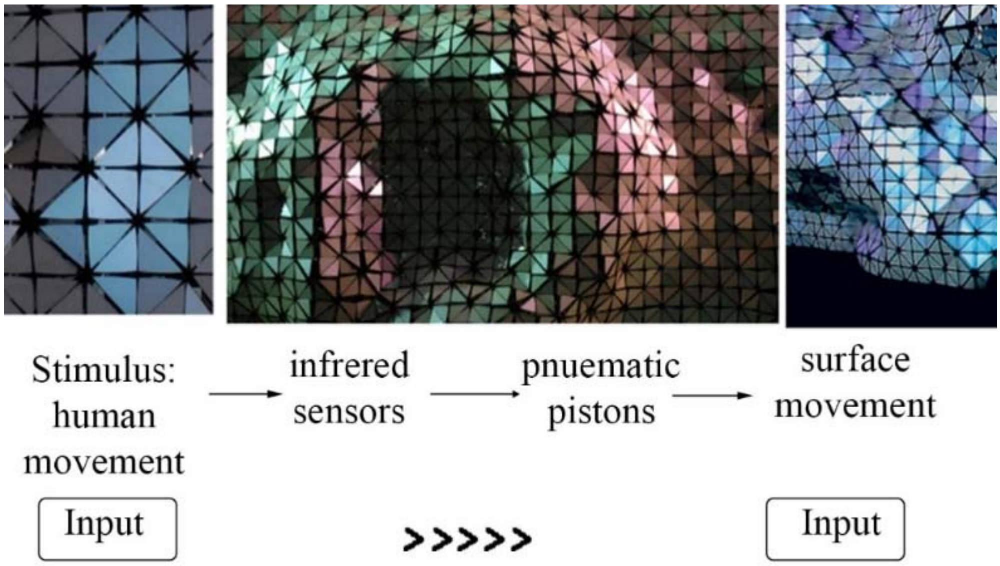


Figure 2.16 The Aegis Hyposurface[16]

g) Tessellate

Tessellate is a sun shading device designed by Adaptive Building Initiate. The dynamic perforated patterns on the wall has different layers of stacked panels, the shift of the layers results in dynamic façade elements. The kinetic behavior of the element could regulate the light penetration and heat gain ratio, also could provide privacy and views [18]. The Tessellate could be used for exterior walls, glass facades, or as separation wall for interior space. the layers of panels move and overlap, which leads to the pattern change of the façade and creation of light-diffusing mesh. The tessellate behave like a leaves on a tree adapting to different environmental conditions, blocking the sunlight during the summer, allowing the sun penetration during the winter. The system mostly responds to sun radiation and belongs to Ubiquitous responsive in-direct control.

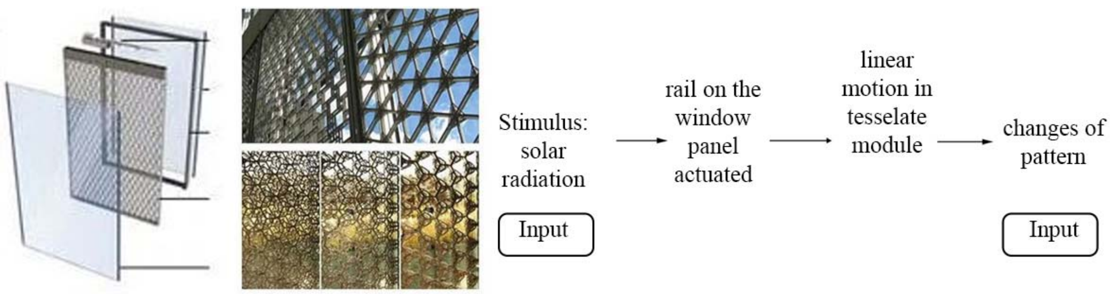


Figure 2.17 Tessellate Sun Shading Device And Its Response Diagram [18]

h) City of Justice, High Court of Justice and Supreme Court, Madrid, Spain 2006

Hoberman and Norman foster have developed a shading system for the city of justice building. the developed unit is hexagonal shading unit with kinetic capacity. When fully opened, it will cover the entire central atrium as well as eight peripheral atria for sunshade. When the unit is retracted, it will disappear behind the roof structure not affecting the light penetration of the space. [19]. A special algorithm which combines historic solar gain data with real-time light level sensing has been developed to control the shading units. This system uses Ubiquitous responsive in-direct control.

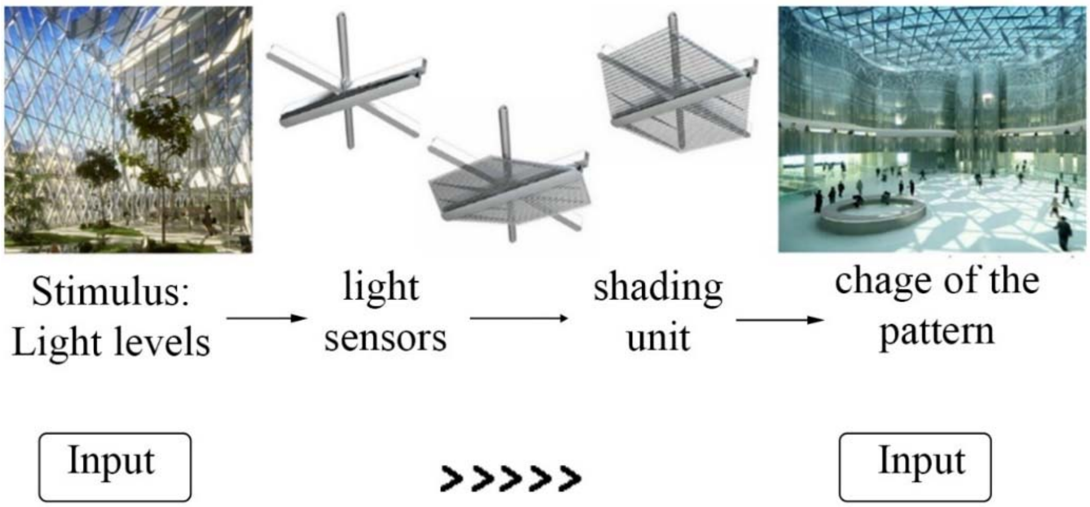
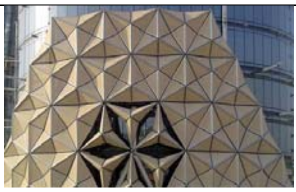
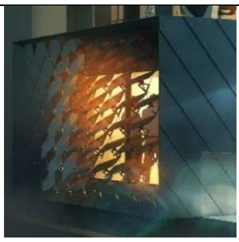
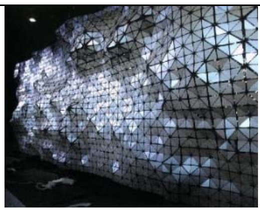


Figure 2.18 High Court of Justice and Supreme Court And Its Response Diagram [20]

In the examples mentioned above and projects in the table1, the transformations are realized by the change of position of mechanical elements such as joints and gears. This type of systems is the most commonly used in kinetic systems for their easy to access and scalability to large building skins. These transformations often require complex energy consuming electromechanical devices such as motors, sensors, and electronics[16]. These elements used to sense and actuate are generally borrowed from mechanical and electrical engineering discipline. However, with the recent development of smart materials and researches on natural material`s kinetic behavior, many kinetic systems which utilize material inner property have been developed. These materials possess the ability to change their shape without mechanical parts. According to the movement actuation mechanism, kinetic architecture could be categorized into two types: mechanical based and material property deformation based. (figure 2.19). Material actuated kinetic systems will be discussed in detail in section 3.4.

Table 2.1 Lists of Mechanical Actuated Kinetic Projects

Project name	Control systems	Stimulus	image	Active/passive response
Villa Girasole	In-direct control	Sun radiation		passive
INSTITUT DE MONDE ARABE	In-direct control	Solar radiation		passive
Abu Dhabi Investment Council Headquarters	Ubiquitous responsive in-direct control	Solar radiation		active
MEDIA ICT BUILDING	Ubiquitous responsive in-direct control	heat		active
The Adaptive Solar Facade (ASF)	In-direct control	Solar radiation		passive
TESSELATE™	Ubiquitous responsive in-direct control	View, light, heat		active
AEGIS HYPOSURFACE	Ubiquitous responsive in-direct control	Human movement		active

Project name	Control systems	Stimulus	image	Active/passive response
Wind veil	In-direct control	Wind		passive
Thematic pavilion	Responsive in-direct control	light		active
lumenhaus	Responsive in-direct control	Solar radiation, air		active
Showroom kiefer technic	Direct control	view		active
CITY OF JUSTICE	Responsive in-direct control	Solar radiation		active
sonomorph	Responsive in-direct control	Sound		active
WIND SHAPED KINETIC PAVILION	Responsive in-direct control	wind		active

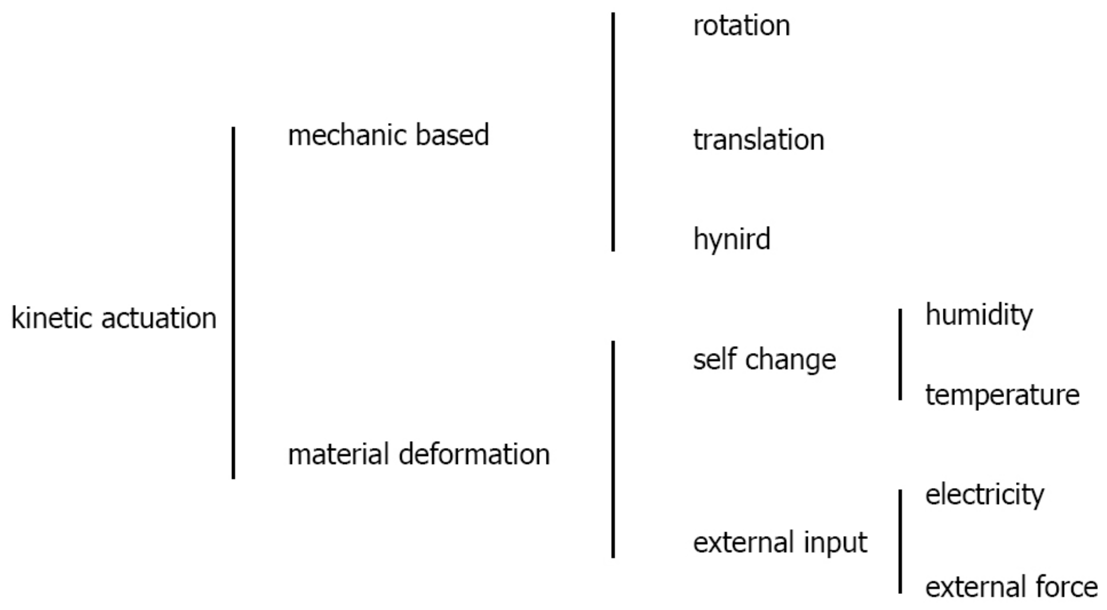


Figure 2.19 Kinetic Architecture Movement Actuation Mechanism

2.4 Conclusion

In this chapter, background knowledge about kinetic architecture is given. Firstly, objective and benefits of kinetic architecture is explained. Kinetic architecture is the new design method to achieve sustainability by adapting to variable environmental conditions. Kinetic architecture also answers to the changing social needs of the space and interact with the user. Then the concept of kinetic architecture is explained based on the relative literature. Kinetic architecture is new architectural methodology that is not static, as has traditionally been the case, but one that has the capability of adapting to ever-changing requirements and conditions with variable geometry or movement through kinetics. Finally, projects and researches are explained to obtain a better understating of the kinetic architecture development.

Regardless of prevalently used, these mechanical systems often are brittle and vulnerable and actuators of these transformations needs high energy costs. These mechanical machines are energy consuming and in some aspect polluting the environment. Buildings are in a need for more efficient kinetic adaptation. When looking to nature, living organisms' own material structures that adapt to external environmental conditions to keep inner pressure balance. So nature could be taken as inspiration source for architects to develop better adaptable kinetic architecture.

CHAPTER 3

BIOINSPIRED DESIGN APPROACH IN KINETIC ARCHITECTURE

I am not trying to mimic the nature; I am trying to find the principles she`s using.

Buckminster fuller

During the 3.8 billion years of adaptation and evolution, animal and plants have developed the best solutions for adapting to environmental change. Nature has been taken as inspiration source by many architects and designer. Plants are best inspiration for architecture because of their static position. When the environment changes, the plants have to adapt to protect themselves against excessive whether condition such as wind, drought, heat and light. In this chapter, solutions inspired by nature is explored, some adaptation principles of plants are abstracted and shape changing materials are introduced.

3.1 Solutions Inspired by Nature---Bioinspired Design

3.1.1 Definition of Bioinspired Design

Stone sickles invented by Chinese farmer during the new Stone Age could be considered as early example of biomimetic design. The earliest example of biomimetic design could date back to the study of bird flight by Abbas Ibn Firnas (810-887) and then by Leonardo Da Vinci. However, in terms of modern science, Otto Schmitt, is the person who coined the term biomimetic in 1950`s in his PhD dissertation. According to him, biomimetic refers to the transformation of nature`s biological ideas to solve engineering problems. During 1960, Jack Steele defines bionics as using natures function system to solve the problem of engineering. After that biomimicry is generally used in disciplines such as aerospace, car design, product design. In 1997, Janine Benyus published the book "biomimicry: innovation inspired by nature". In the book, she gives the widely accepted definition of biomimicry and explains the way how biomimicry research is conducted. Biomimicry is defined in the book as a "new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems"[3]. she expands the scope of biomimicry and she also points out that the ultimate goal of biomimicry is to achieve zero-energy buildings.

Different terms have been used in different literature, such as bio-inspired, biomimetics, biomimetics biomimicry and bionic, but they all means the same. In this thesis, bioinspired design is chosen to use as accepted term. Combining the definitions above, Bioinspired design is not about nature imitation, but the observation of their properties and principles, and the transformation and the development of these principles into sophisticated technological solutions.

3.1.2 Levels of Bioinspired Design

Bioinspired design has three levels, which shows the depth of the understanding of natural principles: form, process and ecosystem. On the form level, the shape or the form of the organism is taken as resource, however on the process level the behavior of the organism and its relationship to other organisms is learned. On ecosystem level, the whole ecosystem and its functions and principles is mimicked[21].

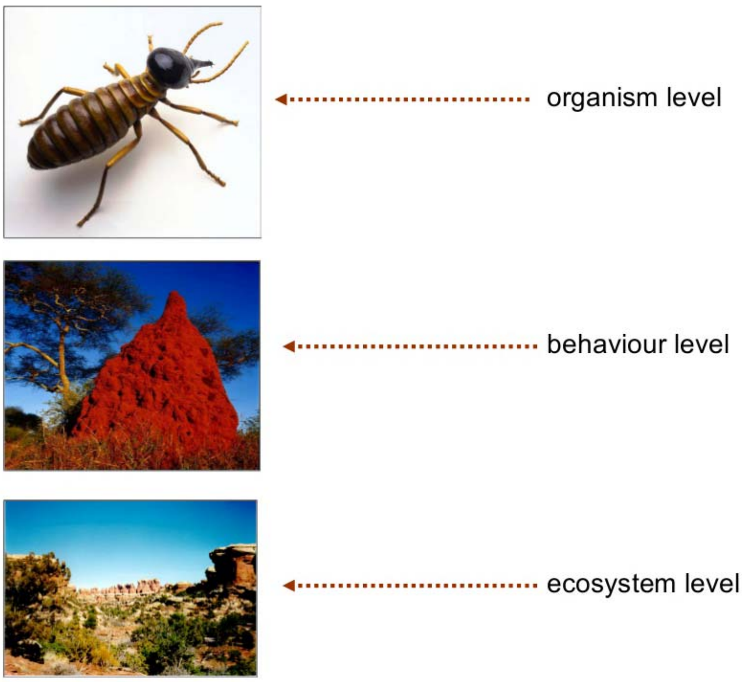


Figure 3.1 Three Levels of Bioinspired Design[21]

Mimicking form: this level of mimicking nature, designers directly takes natural form for only external characteristics. This kind of design method would result in visual beauty but may not result in sustainable design. There are many examples of this level of bioinspired design. For example, Beijing Olympic stadium is the mimicking of bird nests (figure 3.2). Except form its seasonal behavior and disposability, the designers only take its form during the design process.

Figure 3.2 From Bird Nest to the Olympic stadium[22]

In some cases, mimicking the form of organisms in architecture leads to funny designs, such as a duck, an elephant, a banana, a pineapple, a human being, etc.(figure3.3). These forms mimicked from nature not really match the function they perform in organisms so these designs not representing successful biomimetic designs. However, there also many successful applications of form mimicking. In the first design of the Japanese Shinkansen bullet train, there is a problem that every time the train came out of tunnel there is loud bang. The engineers observe the kingfisher diving from air to water with no splashing, then applied the shape of the beak of the kingfisher. The new model train is much quitter and much faster and used less energy.

Figure 3.3 Funny Designs Of Form Mimicking[23]

Mimicking process and principle: the behavior and principles behind the form are analyzed and transferred into design solutions. For example, the adaptation principle of the organisms could be learned and applied to architectural solutions.

Inspired by the principles found in termite mounds, The Eastgate Centre have a natural and passive ventilation and cooling system with particularly designed hooded windows, uneven thickness walls and light colored paints to decrease heat observation[21]. Eastgate has achieve sustainability by reducing energy use by 90% compare to a similar size conventionally cooled building[21].

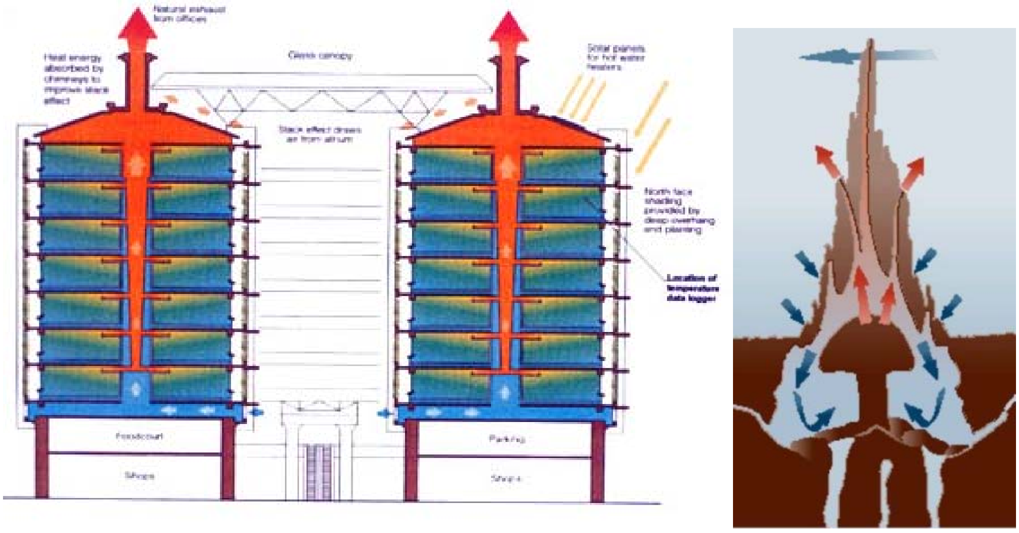


Figure 3.4 Working Principle of Eastgate Center[21]

In the realm of this thesis, process level of mimicking is aimed. In particular, the variability of the material systems in plants and its capacity to adapt is analyzed and integrated into adaptable architectural component design process.

Mimicking the natural ecosystem: in this level, the relationship between organisms are analyzed and each organism`s function in the ecosystem is learned. Mimicking these relationships leads to sustainable solutions for cities. On the ecosystem level design, the relationship between elements are the primary factor and usually works on urban level or some mega projects involving multiple elements. One of the examples that could be categorized into this is the Llyod Crossing Project by Mithün Architects and Green Works Landscape Architecture Consultants. The architects estimate how the existing ecosystem is functioning on the site, and tries to develop a project that perform as the existing ecosystem for long period of time[21].

In her paper “Biomimetic approaches to architectural design for increased sustainability”, Zari further develop this design method. Under these three level, she develops five elements: from (what it looks like), material (what it made of), construction (how it is constructed), process (how it works) and function (what it can do)[21]. Taking termite as an example, she builds the structural frame of Appling biomimetics into architecture.

Successful biomimetic designs are limited. There are many challenges to implement biomimetics into design. Firstly, nature provides large database to select and it is not easy to select the appropriate one to use in the design process. Secondly, the scales are different, the ones that work in a molecular scale may not be working in a building scale.

3.1.3 Bioinspired Design Approaches

According to the literature, there two main approaches in biomimetics: problem-driven approach (top-down, biology to design, biomimetics by induction) and Solution-driven approach (bottom-up, challenge to biology, biomimetics by analogy)[24].

The problem-driven approach is mainly seeking to solution from nature to predefined human needs or problems. This approach requires designers to identify the problem and its parameters. An example from industrial field is the bionic car deigned by Daimler Crysler (figure3.5). To build an aerodynamic body, the boxfish is observed and abstracted principles applied to design process. Also for the structure of the car, the trees growing process is animated by computer program. During the growth process, the concentration stress is minimized. The bionic car is the lightest but strongest car ever. More material was lay down where the loads are greater. With this mimicry from nature, the car has better aerodynamic performance and efficient structural configuration.

According to literature, there are many ways to apply problem-driven bioinspired design. according to Zari, problem-driven design should follow steps flow. However, these steps ate not linear, results from the later steps would influence the previous steps. So it is in an interactive feedback loop.

Step1: Problem Definition

Step 2: Reframe the Problem

Step 3: Biological Solution Search

Step 4: Define the Biological Solution

Step 5: Principle Extraction

Step 6: Principle Application[21]

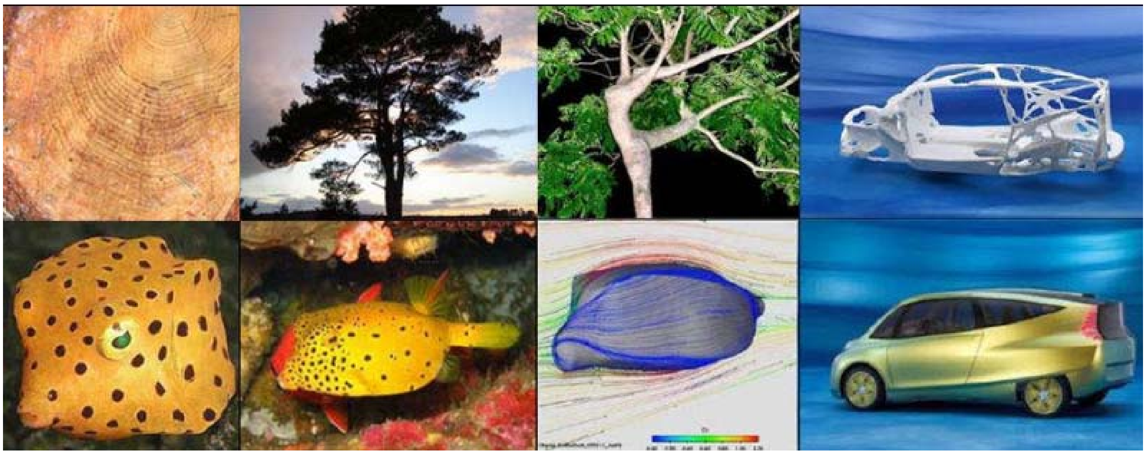


Figure 3.5 Inspiration Source and Design of Bionic Car[21]

Solution-driven approach follows opposite flow of knowledge. The principles of natural design are acquired by biologist, then designers and engineers use these knowledge as guidelines for design. Design process starts with relevant information about biological and ecological research on the related topic, instead of design problem. By starting with, analyzing nature`s solution, this approach brings forward the advancement in the specified fields. For example, the flippers of a whale have bumps on them, which help them glide through the ocean with greater ease. This feature was used to make more efficient blades for wind turbines. Turbines with the bumped blades can generate energy at much lower wind speeds, when traditional wind turbines fail.

Figure 3.6 shows the general structure of biomimicry. In this research, we use problem-based approach to solve buildings adaptation problem to specific requirements, such as ventilation, temperature. We transfer biological adaptation principles of plants to architectural kinetic adaptation.

3.2 Bioinspired Design in Architecture

In the field of architecture, biomimicry is much less developed than the engineering field. When we look at the bioinspired designs it is all about the product and material, not related to architectural systems. Although, there are many architects take biomimicry as a new design method, most of the designs are about architectural form and beauty[21].

The earliest structures that mimics the formation of natural process are the Eiffel tower and crystal palace. Crystal palace is designed by Joseph Paxton in 1851, based on his research on lotus flower. Inspired by the structure of veins of the giant water-lily leaf, the crystal palace is constructed by large span steel structure covered by glasses(figure3.7).

The Eiffel tower was designed by Gustave Eiffel and built in 1880. The structure of the tower is inspired by the human bone (figure3.7). with this bioinspired approach, the tower has an unshakeable structure [25].

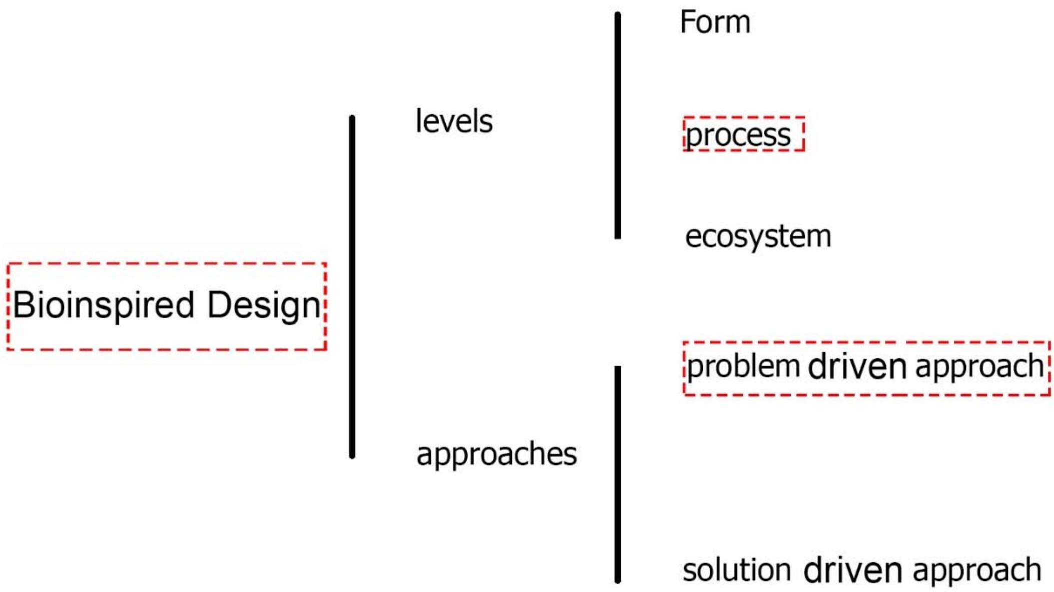


Figure 3.6 Levels And Approaches Of Biomimicry

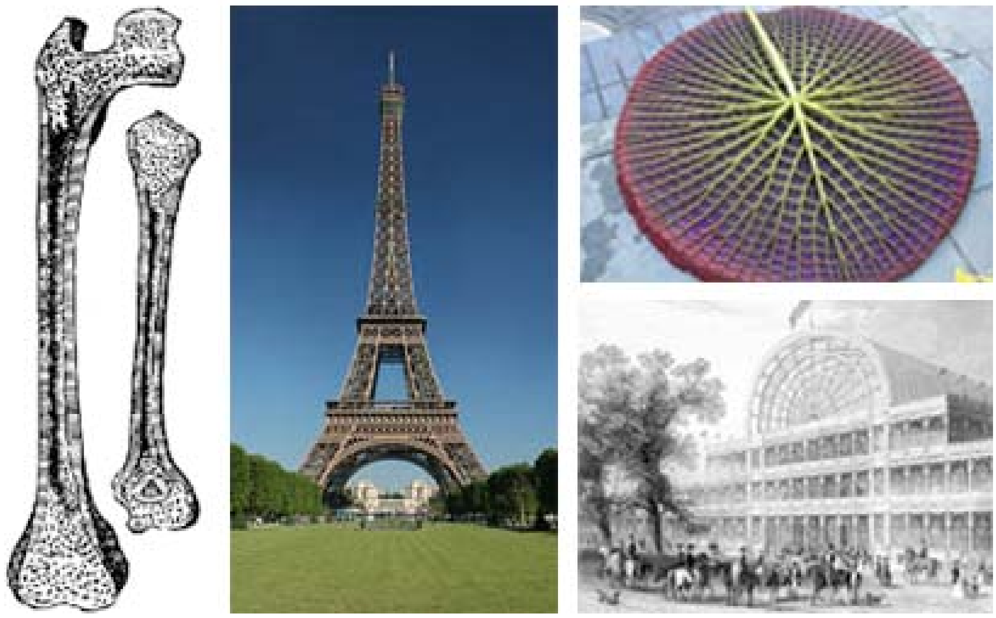


Figure 3.7 Eiffel Tower and Crystal Palace[14]

At the same period, Antoni Gaudi`s projects start to draw attention duo to its mimicking nature`s principle approach. He tries to mimic every plants and animals around him. Not only the total form of the building is miming the nature, also the small parts are intergraded to mimic nature`s principle. He also tries to uses the color of the nature, like in his project Park Güell which is finished by colorful mosaics. Although it seems that Gaudi is trying to use natural form in his design, in reality he understands the functional benefits of these form to architectural performance.

In his book “natural house”, Frank Lloyd Wright introduce organic architecture and he claims that every element that used or will be used in the building should be designed together. Just like in nature, every parts even the decoration should be integrated in one system. In 1962, Eero Saarinen designs TWA Terminal based on the research of Felix Candela about see shells structure and Hyperbolic paraboloid surfaces. Santiago Calatrava and Frei Otto flowed the way of organic architecture and opens the door to biomimetic architecture.

With the arrival of 21. century, biomimicry lead to even more development in architecture. The reason for this is that global warming and reduction of energy resources requires building to be more energy efficient and sustainable. Santigao Calatrava is one of the architects who adds kinetic ability to architecture. Milwaukee art museum quadracci pavilion not only mimics the form of bird wings but also adds functional attributes by kinetics. The iconic roof of the museum can also inform the visitors whether it is open. There are sensors on the wing which can calculate the speed and direction of the wind, measure the temperature and sun light strength. The wings will be open during the day to control the sunlight interring the space and close during the night and harsh environments.

Figure 3.8 Milwaukee Art Museum Roof Structure Open and Close Movement [7]

In architecture, biomimicry can be used in a way that a design problem or user requirement can be solved by observing the nature. An organism or natural system can be investigated and turned into architectural system. In this research, I focus on the biomimetic transfer and integration of functional principles of organisms into building to adapt to changing environmental conditions. The design method seeks a convergence between adaptation challenges of a building and solutions found in nature, through biomimetics.

3.3 Plant's Adaptation Principle: Homeostasis

"It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to changes."

Charles Darwin

Adaptation strategies and principles for kinetic architecture can be learned from living organisms in nature. Adaptation is the evolutionary process whereby an organism becomes better able to live in its habitats. Living organisms have developed through their evolution various strategies to cope with the different climatic conditions. The adaptation of organisms to environmental factors such as light, temperature, humidity and wind are called Biological Acclimatization. Biological Acclimatization could be happened on plants, animals and humans. What makes this process possible is the characteristic of the organism called homeostasis, which is the mainspring of adaptation and response. Homeostasis is in charge of the maintenance of the liquid pressure balance and internal environment of the body[26]. Homeostasis is the property of the living organism which regulates the organism behavior so that internal conditions remain stable and relatively constant[26].

Homeostasis is one of the fundamental characteristics of living organisms. There are different types of adaptation depends on time scale: throughout the day, throughout a season and throughout evolution. different levels of organism have different adaptable systems. There is coordination between stimulus and response. One-to-one response of the organism is the simplest type of response. This kind of response exist in lower level of organisms. In the case of lower level organisms, adaptable behavior depends on the inner pressure of the organism. So, the sensing and actuation process of these organism is integrated with inner material property. The adaptive behavior emerges through the strategic definition of the fiber material hierarchies in multiple scales[27]. However, higher level organisms respond to multiple stimuli in a controlled mechanism(figure3.9). Adaptive behavior is the result of the synchronization and integration of different stimulus, control mechanism or controller and response. Higher level organism holds much more advanced and intricate system for environment sensing and actuation. To keep inner balance of the organism, the sensor sends singles about environmental change to the control mechanism, which will activate the response mechanism[27].

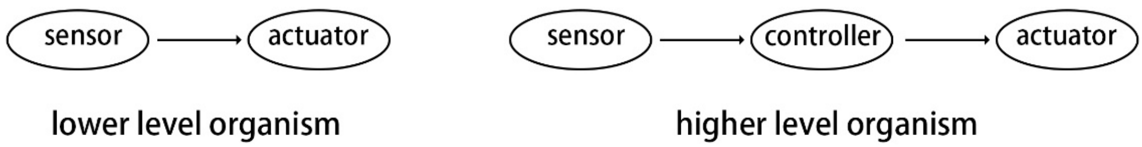


Figure 3.9 Adaptable Mechanisms in Nature

Plants are best inspiration for architecture because of their static position. When the environment changes, the plants have to adapt to protect themselves against excessive whether condition such as wind, drought, heat and light, on the other hand animals could immigrate to other environment to keep their body safe, like birds fly to how clime during winter, some animals stops their metabolism during the winter to avoid the cold winter.

Adaptation strategies found in plants are good role model for designing kinetic adaptable buildings which behave like living organisms. A few examples of plant adaptation that are able to regulate the environmental changes is presented to have better understanding of homeostasis. The challenge here is to transfer these adaptation strategies into successful solutions for buildings adaptation.

Leaves: distribution and orientation

Through evolution, plants have developed unique shapes and mechanisms to adapt to local climate conditions. Leaf distribution and orientation to the sun has a significant influence to photosynthesis and exposure of the plant[28]. These mechanism determines the amount of sun radiation received by the leaves.

Distribution: Leaf arrangement and density are the factors that influence photosynthesis efficiency. Some plants have adopted compact and dense packing of leaves, which could be described by mathematical laws. In the figure 3.10, the leaves are arranged in horizontal way that maximize expose area by adopting Fibonacci series. Plants have different leave distribution in different climate even in the same climate. Some plants have monolayer leave distribution with high density, others have multi-layer leaves with loosely distribution. In shaded environments, species tend to have taller stems while understory species tend to expand horizontally with less height than canopy species.

Orientation: Tracking the sun is the one of the most significant movements in plants, because it affects sun radiation dynamics. In plants, sun tracking is achieved in two ways: move leaves perpendicular to the direct sun rays, which are called diaheliotropic leaves, and move leaves parallel to direct sun rays, are called paraheliotropic[29]. Light interception could be regulated by plants by changing their inclination. At hot and dry climates plants leaves face east, by that they maximize the leaves surface for light interception in the early morning and while at noon keeps a minimum interception by changing inclination parallel to the sun radiation.

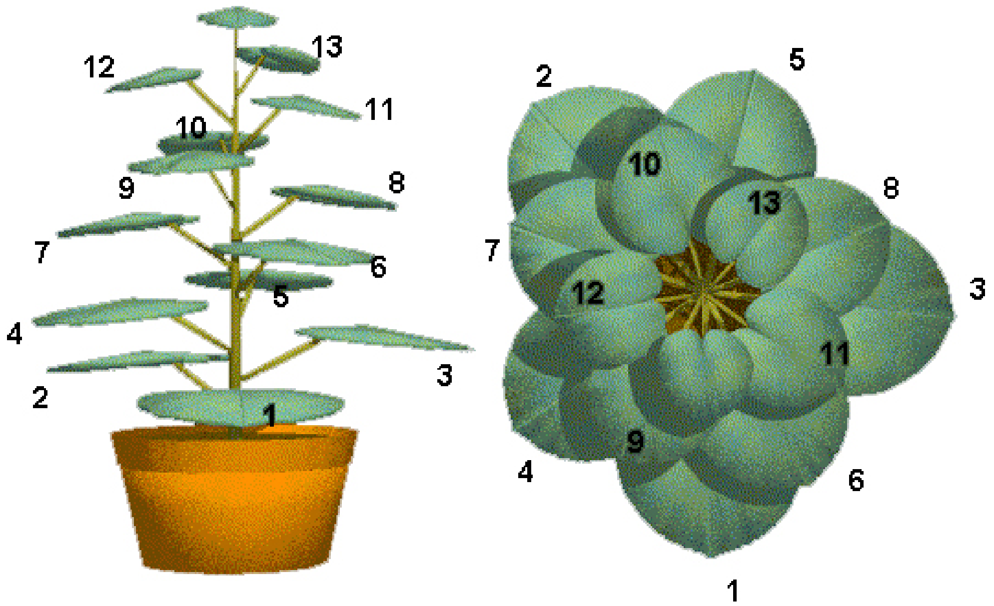


Figure 3.10 Fibonacci Series in Leaves Distribution[30]

Flower openings of Lily

When the humidity and temperature is suitable for the flower, it will bloom, the pedals perform a bending motion which opens the flower bud and thus makes the reproductive organs accessible for pollination. The underlying mechanism is based on a differential growth rate that occurs between the pedal's inner lamina and its outer edges. More precisely, while the inner lamina retains its length during blooming, unidirectional changes along its edges cause a significant expansion of the pedal's periphery, which forces a bending motion of the plant organ and an opening of the flower bud(figure 3.11)[29].

Sunflower

With the process of heliotropism, sunflowers always track the sun. Heliotropism means moving toward the sun. in order to maximize the photosynthesis, all the parts of sunflower (flowers, stems and leaves) faces to the sun. During the day, the side of the stem that is away from the sun will elongate results in the inclination of the leaves and flowers towards the sun. Throughout the day, the flower and leaves tracks the sun and ends up facing to west at sunset. During the night, it works exactly opposite direction. The other side will grow and tilting the leaves and flowers to east facing the sun at sunrise. The sunflower actively photosynthesizes more efficiently that sitting still plants. Heliotropism enables the 15%more sunlight during the day[31]. However, when the flower matures, it will end up facing east.

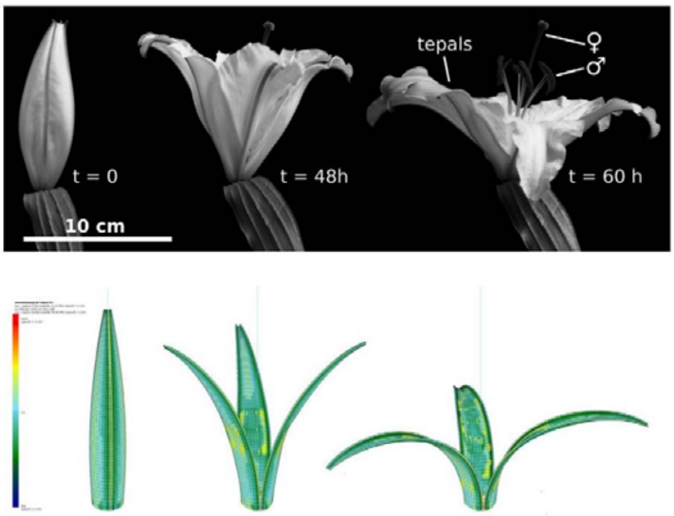


Figure 3.11 Lily Flower Blossoms and Kinetic Models[29]

Figure 3.12 Sun Flower tracking the sun[30]

Stomata: the breathing of the plants

Air exchange are significant functions in nature, because oxygen is crucial for survival of organism. Organisms have developed various approaches to maintain the required gas concentration levels in their bodies. The stomata are one of the most important plant homeostasis mechanism on our planet and among the best-studied by the scientific community. Stomata are structures found on the surface of plant leaves to control gas exchange. The stomata distribution various in different plants and different locations of the same plans. There more stomata on the bottom of leaves and less on top of the surface. On most floating plants stomata locates on the upper level of the surface. The stomata consist of two pairs of specialized cells called guard cells. When the amount of the water changed inside the plant, the guard cell will regulate its openings. This movement is based on multidirectional changes of two expanding cells[29]. Environmental stimuli, such as humidity, temperature, carbon dioxide will actuate plant hormones to intricate the guard cells to open or close. This kind of homeostasis mechanism is very important for plants to photosynthesis and survive.

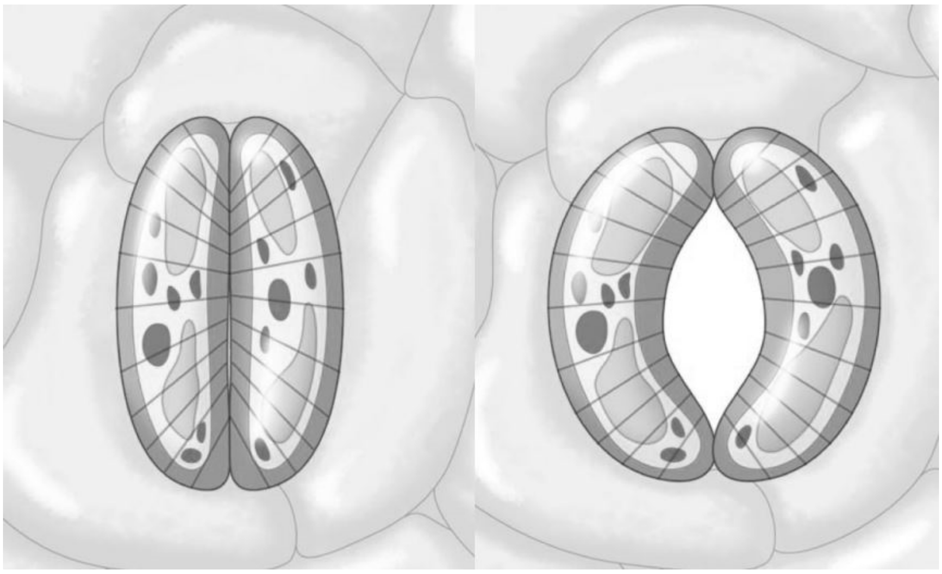


Figure 3.13 Open and Close Configuration of Guard Cells[29]

The stomata response to varying environmental factor differently. When the CO2 level decreases, the stomata will open to obtain more CO2 for photosynthesis. They will close responding to CO2 level increase. During high temperature weather, the stomata will open due to high CO2 consumption. Water percentage inside cell also trigger the opening and closing of the cell to control water evaporation. With the mechanism of stomata, plants can fulfill too tasks. First one is exchange gas to conduct photosynthesis and respiration. Second one is transformation of the water from ground to leaves. This will decide the survival of the plants.

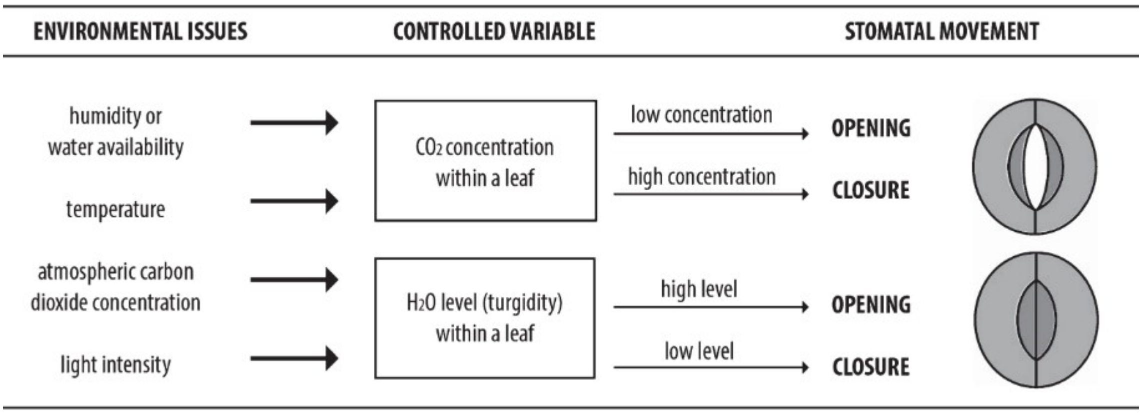


Figure 3.14 Diagram Showing the Mechanism of Stomata [32]

Many living organisms seek physiologically tolerable conditions, in the same way that architects and engineers try to maintain a comfort state inside the buildings despite the changes of the environmental conditions. It is mentioned that biomimicry should be focused on the process and principles of the mechanism in the nature instead of the forms. These adaptation principles and solutions could be transferred into architectural design for providing interior environmental comfort with few energies. It is important to understand the principles of adaptation to transfer them in artificial system rather than just simply copying them.

3.4 Shape Changing Materials

As mentioned above, all the adaptation in the plant world is realized by the inert property of materials. Material systems in nature don't distinguish between material and structure[33]. Plants are role models for architecture to achieve adaptability and mobility with minimal energy, because plants integrate sensing and actuating mechanism into their materiality[34]. By mimicking the passive adaptation principles in plants, architecture would reduce dependency on complex expensive mechanical system and will achieve sustainability.

Current material advancement allows new materials to be act as plants in terms of kinetic response. Materially embedded responsiveness could be achieved by integrating shape changing materials. Shape changing materials refers to unique materials which has the capability to morph shapes in response to stimuli. Shape changing material could be optimal alternative actuation and sensor system of traditional kinetic system, which allows kinesis and transformation happen through changes in material properties rather than changes in how different mechanical elements connect together.

Integration of shape changing materials can help designing of climatically adaptive architectures with materially embedded responsiveness providing occupant comfort and welfare. Researchers like Achim Menges have developed innovative solutions to actuation of kinetic systems by utilizing natural material`s property with computational techniques. At the same time, various environment responsive active smart materials have developed which are of great advantage to kinetic architecture (figure 3.16). With these material`s sensing and actuating capability without external energy, sustainable zero-energy building seems possible. The main idea is smart material`s capacity to adapt can bring us closer to the seamless material integration and greater environmental responsiveness found in biological organisms.

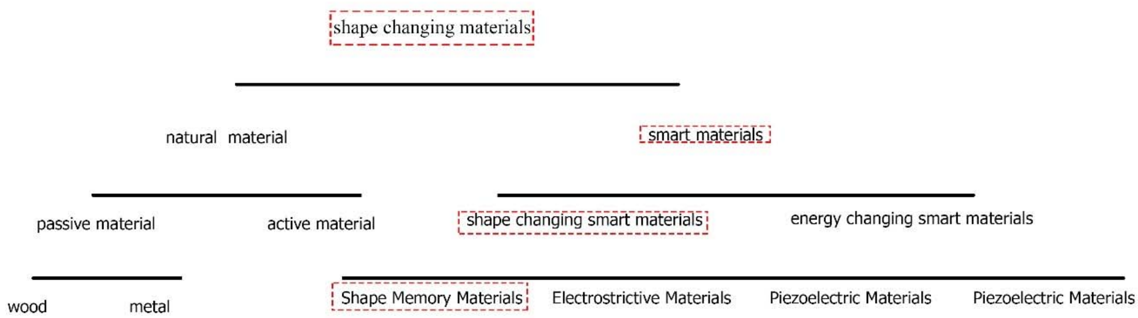


Figure 3.15 Categories of Shape Changing Materials

3.4.1 Natural Active Materials

Wood

Although wood is traditional static material, hygroscopic and anisotropic properties turn wood into humid responsive active material. Wood has moisture equilibrium in its special cellular structure. So its shape constantly changes responding to fluctuations in relative humidity[35].

Hygroscope demonstrates a material inherent actuated responsive skin. HygroScope by Achim Menges is one of recent projects which utilizes inherent behaviors of wood in a novel way to achieve kinetic skin. spruce cone is taken as an inspiration source duo to its exact control of movement response to the humidity. Change in the relative humidity results in opening and closing of the surface. The surface enlarges its openings size to breathe and ventilate when the humidity level rises (figure 3.16). the climate directly triggers the response behavior without mechanical systems. Material itself is the mechanical system. The wood utilizes its embedded hygroscopic ability to behave kinetically[35]. This purely passive approach suggests that zero-energy responsive architecture is possible. However, one of the shortcomings of this approach is that passive behavior of the material properties is fixed and unchangeable.

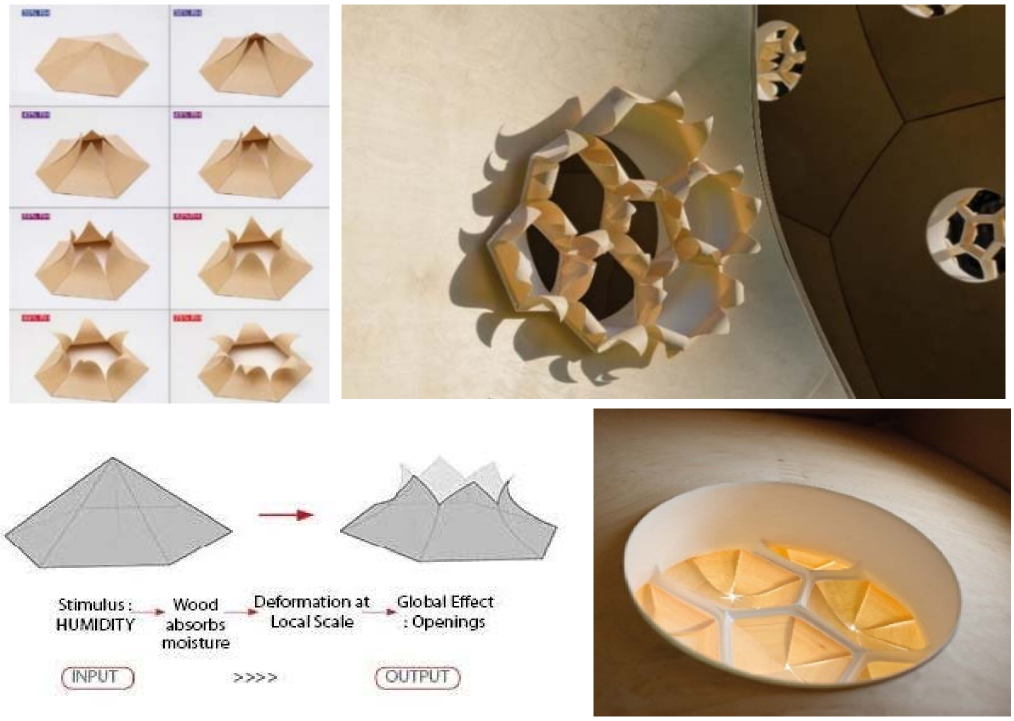


Figure 3.16 Working Principle of Hygroscope [35]

Thermobimetal

Thermobimetal is another example of natural active materials. Thermobimetal is two sheets of metal with different thermal coefficients rate. When the thermobimetal heated, they expand at different rates, so the thermobimetal will bend to one direction. It could provide material imbedded responsive behavior activated by the temperature change in the environment.

The project Bloom is designed by Doris Kim Sung using thermobimetal. It is made of different 14,000 tiles which is only possible with digital technology. This is an architectural installation for sun shading and air ventilation for the space covered by this canopy. When the material is exposed to the sun, movement is caused by the temperature change results in differentiated extension of metals which triggers the opening of the surface to “breathe”[36]. When the thermobimetal is heated by the sun radiation, the fins of the surface will curl to open up to let the air escape. Every tiles are specific to its location to the angle of the sun. When the temperature goes down, the metal return to initial geometry. It requires no control no energy. Bloom adopts a “passive” type of system, but the material response to the sun and temperature makes this surface active[16]. This kind of research project has a lot of implications to actual future application in architecture.

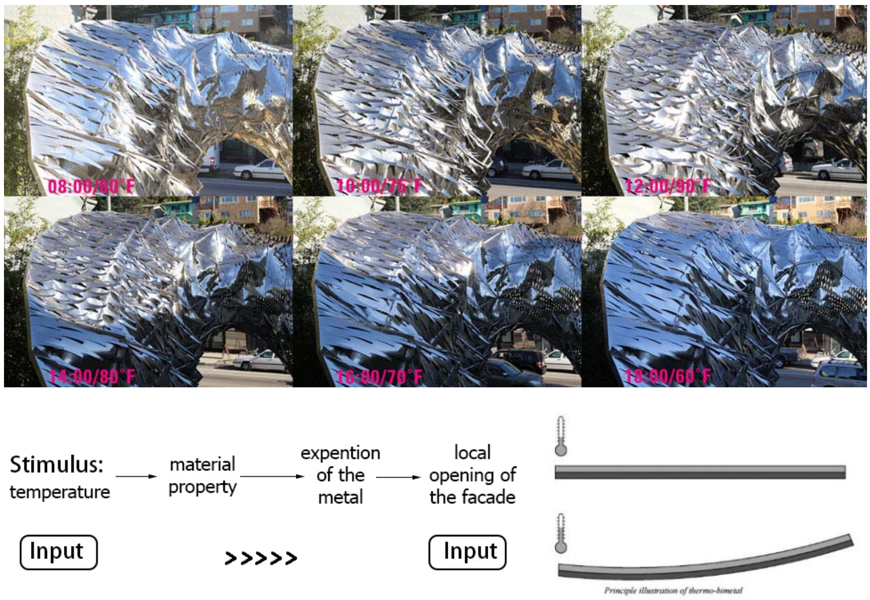


Figure 3.17 Working Principle of Project Bloom [36]

3.4.2 Smart Materials

Smart materials have great development in recent years, which has the capacity to change phase and energy react to the changes in the environment. Smart materials usually able to sense environmental change and respond to it actively [2]. These kinetic behaviors are not based on mechanical complexity butt rather on chemical, electronic even biological reactions and process. The material response results in a significant transformation of their properties, such as a change in color, luminosity, shape, volume, or the production of an electric current. Due to these capabilities, architects both in research and practice started to include them in their proposals.

Smart materials do not require sophisticated sensory, control, and actuation systems to produce a dynamic response to changing environmental conditions; instead, they cleverly exploit the embedded, intrinsic properties of the materials. So they are best materials solution to achieve climate adaptive kinetic building systems. The shape or the dimension of the materials are able to reversibly under stimulus. These deformation depends on the inherent properties of these materials. The material has both sensing and actuating capability. They can take input from their exterior environment and respond with an output. They can also perform as an actuator.

According to Addington and Schodek, there two types of smart materials: property change smart materials and energy exchange smart material[37]. Property change smart materials refers to the materials that adapt their metaphysical, chemical, electrical properties in response to environmental conditions. Energy exchange smart material exchange input energy into other forms of energy in accordance with the First Law of Thermodynamics. These materials obey to the first law of energy, so also called "first law materials"[37]. There are different types of energy changing smart materials such as shape memory alloy, shape memory polymer, piezoelectric materials and light emitting materials. These materials provide the opportunity to replace mechanical kinetic systems with active systems utilizing material behavior and deformation. This will provide much durable and cheaper architectural solutions for kinetic architecture.

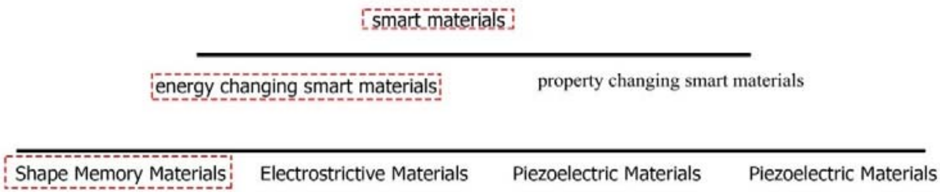


Figure 3.18 Smart Materials

Researchers and architects have developed many projects using different kinds of smart materials. Although most of the projects are still in research period, they show great potential for architectural application for future use. Some projects using these materials is presented below no to draw a definitive conclusion but to communicate initial concerns about this field

Pixel skin

Pixel skin is design by Anshuman using smart materials to regulate soar gain and view. This surface also could be used to display images. Matrix of interconnected pixel tiles are controlled interactively via embedded controllers. The system utilizes two-state martial SMA wires for actuating each pixel in one of 255 potential states. This pixel tiles are created to realize dynamic windows to control view and light conditions response to internal conditions. SMA alloys are actuated by electric to change shapes. When the electric current heated the SMA wires it will open the pores of the surface to let more light in. this surface can also be used to generate dynamic low resolution images, patterns or videos. This surface successfully handled the confliction between signature on the faced and internal light condition. This surface achieves a communication wall as well as the integration of illumination[38].

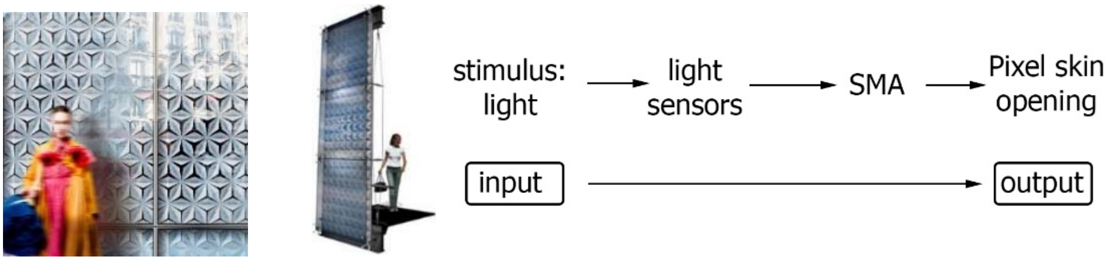


Figure 3.19 Pixel Skin And Its Working Principle[38]

Living glass

Living glass is a new smart material that comprised of polymers. This project is developed by Architects Soo-in Yang and David Benjamin. This project is inspired by the gill, the respiratory organ that controls the absorption of oxygen in most aquatic organisms. The system could provide different ventilation solution to monitor the air quality of the room. The living glass responds to the human presence and carbon dioxide levels. When the CO2 level is high, the sector will detect the condition and electricity will be sent to the polymer wire which will allow the grill to open to breathe and regulate the air[39].

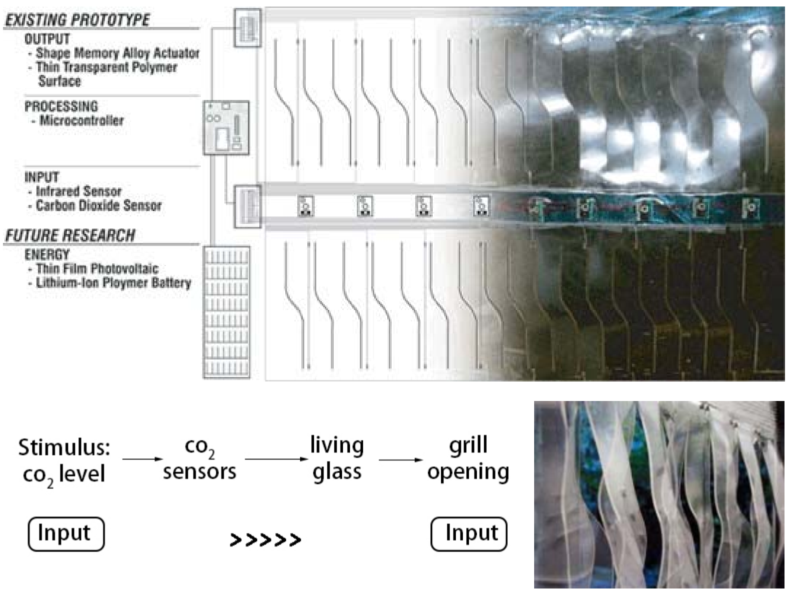


Figure 3.20 Living Glass and Its Working Principle[39]

Shape shift

ShapeShift is an experiment to develop the architectural-scale application of smart materials for responsive kinetic architectural skins. It produces a variable building skin for shading and air control. The students from ETHZ uses electro active polymer to develop this project [40]. It performs actuation by an electro-mechanic process within the materials' properties. To actuate the EAP, small amount high voltage current is needed[40]. EAP has great potential for architectural application because it is light weighed flexible material that has shape changing capability not needing mechanical actuators. This project has achieved the combination of advanced material techniques with architectural design pushing academic research for real world application

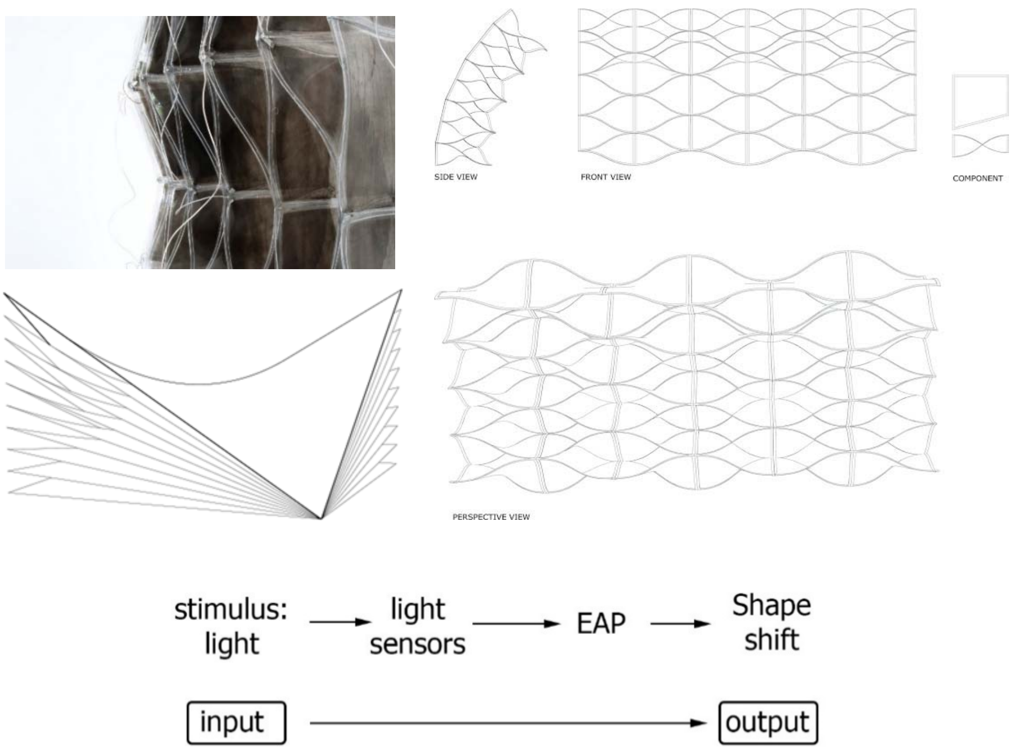


Figure 3.21 Shape Shift And Its Working Principle[40]

The Aır Flow(er)

The Air Flow(er) is designed for ventilation of the space which is thermos active. It behaviors like flowers. The four petals of the flower open when exposed to high temperature. This project is inspired by the thermos nastic behavior of yellow crocus[41]. Based on natural behavior principle, the petals work without electricity. its main benefits are regulating interior air quality and temperature. This system could be used for exterior surface or interior separation. During the summer, the Air Flower is actuated by the high temperature, which will lead to opening of the petals for ventilation.

Habitat 2020

Habitat 2020 is designed for the future by using biomimetic approaches. This building works like a live organism. This concept explores the possibility of using sensitive textile skins on buildings to create energy independent structures. The membrane is used as transporter for collecting and channeling air, water and light, from the outside feeding into the inside space. Like a plant, the building could open its pores to breathe or ventilate to adapt to environment. the skin of the building not only allows the light to enter the space, also air and water could be exchanged between interior and exterior. The skin works as the stomata on the surface of leaves.

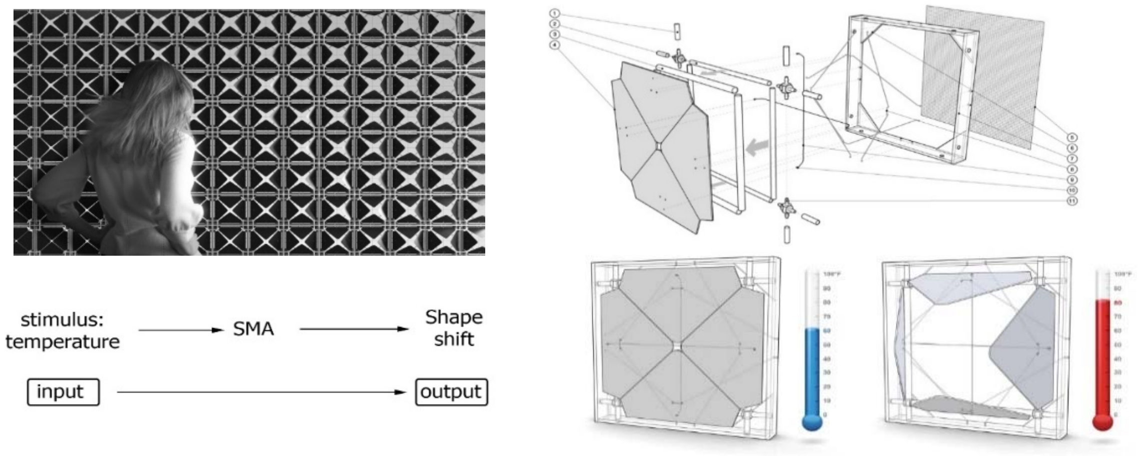


Figure 3.22 THE AIR FLOW(ER) and Its Working Principle[41]

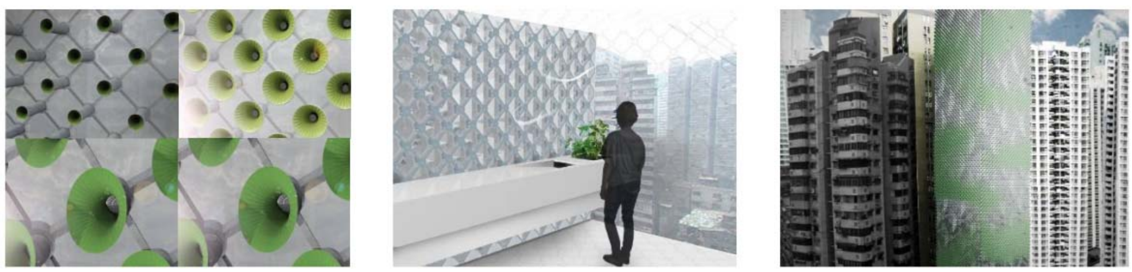
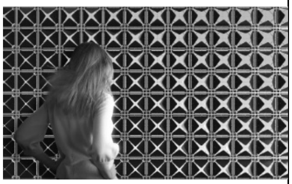


Figure 3.23 Habitat 2020[42]

Based on the projects above and table 2, it could be learned that most of the material used in these adaptive kinetic projects are shape changing materials. Shape changing materials are the most attracted one for architects. Shape changing smart materials are in some aspect similar to material systems in plants.

Table 3.1 Kinetic Projects Using Active Materials

Project name	image	material	Active/ passive/ hybrid	Control system	stimulus
Hygroscope		wood	passive	Internal control	humidity
bloom		Thermos bimetal	passive	Internal control	heat
Living glass		SMA	active	In-direct control	CO2
Homeostatic Façade		silver-coated elastomers	passive	Direct control	heat
PIXEL SKIN		SMA	active	Responsive in-direct control	Solar radiation

Project name	image	material	Active/ passive/ hybrid	Control system	stimulus
Shapeshift project		electroactive polymer	active	In-direct control	
The air flow(er)		SMA	hybrid	Responsive in-direct control	Temperature
SmartScreen		SMA	active	In-direct control	Heat
HABITAT 2020		SMA	hybrid	Heuristic Responsive In-Direct Control	Air Heat Humidity Solar radiation

Shape changing smart materials could react to different stimulus. Temperature and electricity is the most used stimuli to activate these materials. there are also photostrictive smart materials, piezoelectric smart materials, magnetostrictive smart materials and so on[43]. The table below shows some shape changing smart materials and their properties.

As has discussed in the examples above, shape changing materials can potentially serve as actuators, as well as structural components, for adaptable kinetic architectural designs. Table 3 lists several selected shape changing materials that can be applied as actuators which can change shape and transform under stimuli, and studies their individual properties. This list is in no way extensive and I am only listing here a few of the more common materials to compare their main properties. Based on this comparison, it can be seen that most materials with the potential for architectural applications are either not commercially available or are not strong enough for actuation purposes. These shortcomings are obvious disadvantages in architectural-scale transformation. Shape memory alloy (SMA) is one of the most appropriate shape changing materials to apply to the design investigation of this thesis because of its accessibility, durability strong activation force.

Table 3.2 Shape Changing Smart Materials[44]

Material Name	Direct or Indirect stimulus	Keep shape when stimulus is removed	Displacement	# of 'memory' states	Force	Consistency
Shape Memory Alloy	heat	no	large	1 (potentially 2)	high	solid
Magnetic Shape Memory Alloy (Ni_2MnGa)	magnetism		large	2	high	solid
Shape Memory Polymer	heat	yes	large	1	weak	solid
Piezoelectric Ceramic	electric	no	small	2	high	solid
Dieletric EAP (e.g. Dielectric Elastomers (DEs))	electric	yes	large	2	high	solid
Ionic EAP (e.g. Ionic Polymer Metallic Composite (IPMC))	electric	no	large	2	high	solid
Magnetostrictive (Terfenol-D)	magnetism		large	2	high	solid
Electrostrictive (Lead Magnesium Niobate (PMN))	electric field	no	small		small	solid
Thermoplastic	heat	yes	large	1	weak	solid
Ferrofluid	magnetism	no	large	indeterminate		viscous

Shape memory alloys are the most known shape changing smart materials since the 1960s. An SMA is a unique metal with two novel properties that have interchangeable phase capacity at its molecular level: martensite and austenite. Martensite is a soft phase that is deformable with applied force in the normal temperature condition (< 30°C). Austenite is a strong and 'memorised' phase that occurs when heating (> 50°C) takes place[37]. They have shape memory property which refers to the ability to revert back to a memorized shape. Shape memory alloys has very common application in other disciplines, such us product design, aerospace design[37]. The eyeglass frames which resistant to bending are example of shape memory alloy application. SMA has great potential for architectural application due to its actuation happens at low temperature and can exhibit the same behavior millions of times without occurring fatigue failure.

3.5 Conclusion

Environmental conditions include elements such as temperature, humidity, natural light, rain air pressure, which are in continuous change in daily and hourly bases. Biological system has developed acclimation method based on homeostasis mechanism. Based on these homeostasis principles, using biomimetic design methodology and utilizing smart materials, we could achieve kinetic buildings that adapt to the environmental change and user demands. In the next chapter, SMA is used to develop an adaptive component which reacts to air quality and temperature.

CHAPTER 4

BIOINSPIRED ADAPTIVE COMPONENT PROPOSAL

Smart materials and advance control systems enable architects to develop kinetic building skins that are capable of reacting to environmental changes to maintain stable indoor comfort levels and reduce dependence to mechanical climate control systems. The future building envelopes will behave as human skins or plants. Most of recent researches focus on the adaptable shading devices. However, indoor air quality is very important aspect of human comfort. So in this research, indoor CO2 level and temperature is considered as a main environmental factor to react.

This research tries to work out a component that are able to change its shape to adapt to different environmental conditions. Bioinspired adaptive component has the ability to adapt its aperture size according to the temperature and CO2 level of the space. The bioinspired component which takes the stomata as role model is realized by utilizing shape changing behavior of shape memory alloy. It serves to achieve better thermal comfort, acceptable indoor air quality and facilitate daylighting performance in some cases. In the following section, the development process of the component and several application scenarios are presented.

4.1 Development Process of the Adaptive Component

Criteria: demand controlled ventilation (DCV)

Indoor environmental quality, which includes thermal, visual, acoustic and air quality, has significant effect on occupant’s health, comfort and productivity[45]. Major part of time of the human beings are spent in indoor spaces, so indoor air quality is the most important factor for users [45]. Failure to provide optimized indoor air quality can rise the possibility of long-term and short-term health issues, such as sick building syndrome.

When thesis topic is selected, the environmental adaptability of the kinetic façade is taken into consideration. The new façade system should be able to adapt to variable environmental conditions and user needs. Indoor air quality, CO2 level in particular, and temperature is chosen as the environmental factor that the adaptive component is reacting to.

Despite the fact CO2 is not harmful, in indoor environments high levels of CO2 concentration can reduce the amount of oxygen for breathing. To achieve indoor air quality and energy consumption, ventilation should be provided according to the occupant number. So demand-controlled ventilation (DCV) is chosen as the design criteria. CO2 is mostly produced by occupants, so it could be chosen as an indicator of interior occupancy. Therefore, CO2 is an effective parameter for controlling ventilation based on occupancy level[46]. So, to provide controlled ventilation based on occupancy level, CO2 is an affective parameter.

To provide better air quality, passive and active ventilation is required. Mechanical systems for ventilation is energy consuming and produce toxicant gas. Form the early history of human beings, natural ventilation has been the main method for keeping interior comfort. It is energy efficient and reduce the energy need of the building. with proper design, the air quality and thermal comfort of the building could be satisfied by natural ventilation.

So the temperature of the space and CO2 level is considered as the primary factor for this adaptable kinetic component. The component module will achieve natural ventilation to adapt to temperature change and regulate air quality. The component will provide demand controlled ventilation by adapting its opening size according to the CO2 level and temperature of the space.

Methods: problem based biomimicry approach at process level

It is concluded from second chapter that the conventional kinetic architecture depends on heavy, complex, energy consuming mechanical system, which is the reason why adaptive kinetic architecture is not commonly accepted as a new design approach among architects. However, in the natural world the plants and animals have developed many mechanisms to survive and adapt to changing environmental factors by utilizing material property. Human beings mimics these processes consciously or even sometime unconsciously to build structures better suits to the environment. Homeostatic mechanisms in plants are driving force for adaptation, because they are accountable for the regulation of internal environment of the body[26]. Plants are recognized as examples of systems that perform mobility with minimal energy use, due to the fiber elasticity composition, and integrating sensing and actuating capabilities into their system. It is mentioned that biomimicry should be focused on the process of the mechanism in the nature instead of the forms. So in the development process of the module, the stomata of plants are taken as role model. These principles are going to be transferred into adaptable kinetic architecture solutions with biomimicry method with process level and problem based approach.

Inspiration source: stomata

The working principle of the stomata is analyzed in chapter 3. Opening and closing of the stomata is one of the most important plant movements and among the best-studied by the scientific community. Stomata of the plant leaves are chosen as the role model for the development of the modular component. It responses to CO2 in the air, temperature, sunlight and humidity. So it is good example for our project to develop breathable component The principles of the stomata are analyzed and transferred into this project. Adaptive component works as a stomata cell on the skin of the building to control the air and temperature comfort of the space. The efficient active and passive solutions in nature might promote the design of innovative hybrid ventilation systems for building envelopes, and result in better indoor air quality with less energy consumption.

Material: SMA wire

Every design in some phase has to consider materiality to realize or construct in the three-dimensional world. If we mimic behavior and principles in plants with smart materials, it is possible to develop an adaptable kinetic module to react to changeable environments and user needs. SMA wires are commercially available, has better reliability and could be actuated with lower temperature or low electric current. It is a great alternative to conventional mechanical actuators with its light weighted strong actuation power. So SMA is chosen as the actuating material for adaptive component.

4.2 SMA Wire Behavior

As briefly mentioned in previous chapter, SMA is capable of recovering from temporary shape without permanent deformation and remember its original shape. The shape memory effect(SME) indicates the capacity of the material to deform at low temperature and revers bac to its original shape when heated. There are two types of SME: one-way shape memory and two-way shape memory. The two-way shape memory alloy also revers to its second shape upon cooling which allows the material to be cycled between two different shapes. The SMA used in this thesis is two-way shape memory alloy. The below mentioned SMA refers to this type unless otherwise indicated.

The SMAs are deformed at high temperature (called M_{gh}) to memorize its permanent shape. For most of the SMAs, M_{gh} is around 200^0C[47]. When cooled, it could be transformed into any shape with little power. When the SMA heated again, A_s is temperature at which SMAs starts to recovers to its permanently deformed shape, and A_f is when it finishes (figure 4.1). When cooled again, SMA will goes back to its temporary shape. The transformation between permanent shape and deformed shape could be happen millions of times without fatigue. Scientist have developed some SMAs that could bounce back to its original shape more than 10 million times with very little fatigue[48].

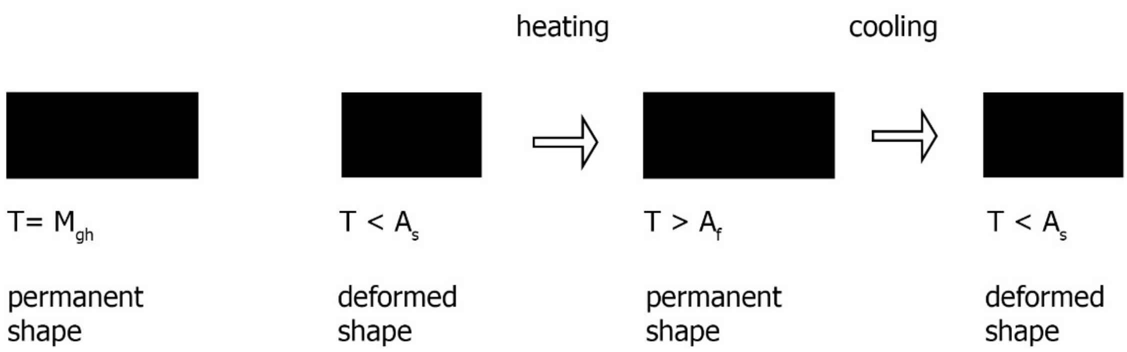


Figure 4.1 Shape Memory Effect of SMA

The transformation temperature, react time and elasticity of the SMAs are depend on the materials selected and their ratio in the alloy. In the case of this project, special SMA will used which transform at indoor temperature level. This is the very important factor of the material to achieve passive natural ventilation. The special SMA wire has an A_s of 25°C, which means that when the temperature is higher than 25, it will start to recover to its memorized shape. This temperature change can also be undertaken directly via electricity, which results in Joule heating or resistive heating. SMAs have a high capacity for elastic deformation (up to 15 per cent in some cases)[49]. So in the case of 50cm length SMA alloy, during the transformation process, the SMA wires have 15cm length change.

The figure 4.2 shows the shape change behavior of the wire under different temperature situation. When the temperature is higher than 25°C, the wire starts to recover to the memorized shape by bending. When the temperature arrives 40 °C, the materials will totally go back to its permanent shape. The response time of SMAs are depend on heating and cooling rate of the material. So under indoor climate condition, the change of the SMA will be very slow due to slow temperature change. However, when heated by electricity current, the deformation from temporary shape to permanent shape could be very quickly, but the cooling process will depend on the material.

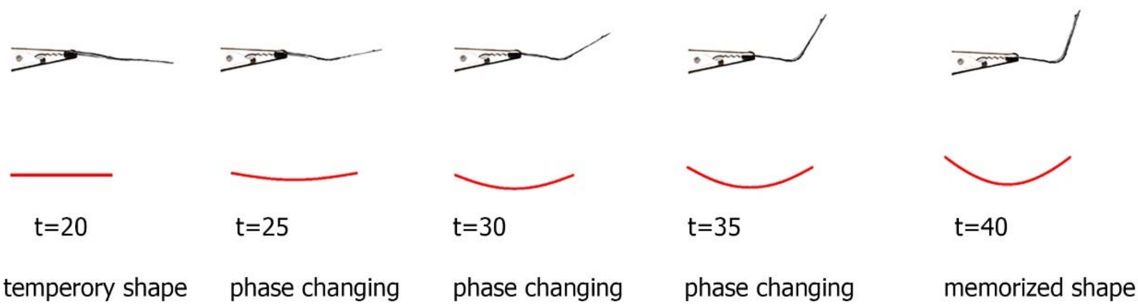


Figure 4.2 Transformation Temperature of Shape Memory Alloy

Material inherited capacity to actuate minimizes the dependence on motorized operations in order to achieve similar kinetic functions. This shape changing process of the SMA wire can be used as the actuator for the adaptive component. The SMA wire is embedded into the adaptive component module to generate kinesis and deformation.

4.3 Working Principles of Adaptive Component

When designing the adaptive component module, stomata is taken as the role model at process level of biomimicry. However, for the shape of the module, we could also look for plant leaves arrangement in plants. As discussed in chapter 3.3, plants have different patterns depend on environmental conditions and the sun radiation required. In nature, plants exist with three leaves, four leaves or six leaves. Here, the patterns of the leaves are analyzed and different patterns have generated (figure 4.3). Depend on these patterns, surface tessellation with triangle grid, rectangle grid and hexagonal grid could be created. The SMA behave the same in different surface patterns for actuation. Among these patterns, triangular pattern has been chosen due to its applicability to different surfaces, planer or double curved.

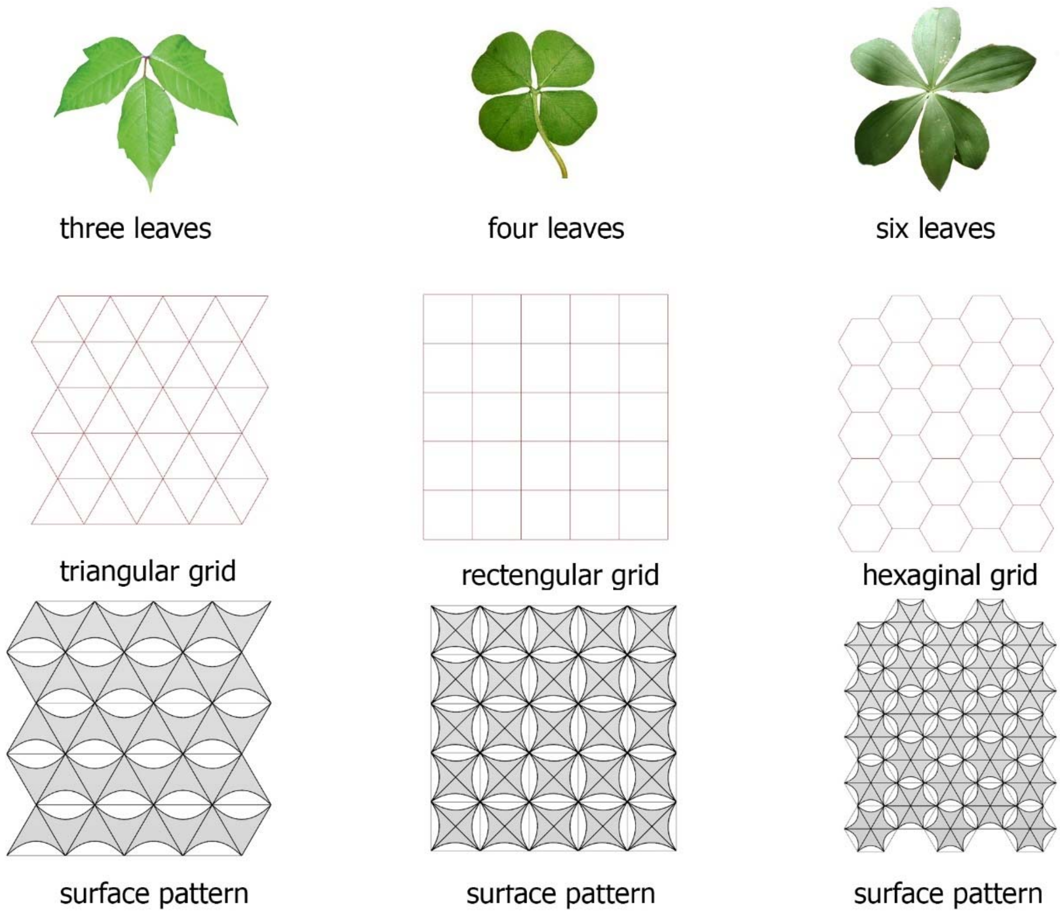


Figure 4.3 Patterns of The Module Inspired by The Plant Leave Arrangement

Basic module of component is shown in the figure4.4. A combination of two triangles is used for the module. The module consists of four parts, SMA wire, elastic polymer, frame and electric wires. The frame is made of aluminum and contains electric wire inside to actuate the shape memory alloy with electricity current. The SMA wire changes its shape according to the stimuli form temperature and CO2 level, which will actuate the elastic polymer and results in the opening and closing of the component. Sensors are located inside the space which sends signals (through a control system) to the component to activate the SMA wire.

The different response of the module towards temperature and CO2 level has been shown in the figure 4.5 and figure 4.6. When the temperature raises the SMA wire will passively reacts to the change and goes back to its memorized shape which will results in the opening of the module to ventilate the interior space. this is the passive system mentioned in chapter3. When the temperature is higher than 25^{0}C, the component starts to open and when the temperature arrives 40^{0}C, it will fully open to better ventilation. However, the CO2 level fluctuation will be detected by the CO2 sensor, and single will be send to the controller. Although the requirements for CO2 level vary from space to space, the transformation of the component is based on the requirement of the classroom. However, it could be easily adjusted to other spaces with control mechanism. The micro controller analysis the data and will send electricity to the SMA wire to regulate the air quality of the space. this is the active system. By combing these two with a responsive in-direct control mechanism, a hybrid system has been created. In the new system, the module could passively response to temperature, or actively response to air quality, or controlled by the user by sending information to the controller. The module will react to the environmental information depends on analyzed single from the micro controller.

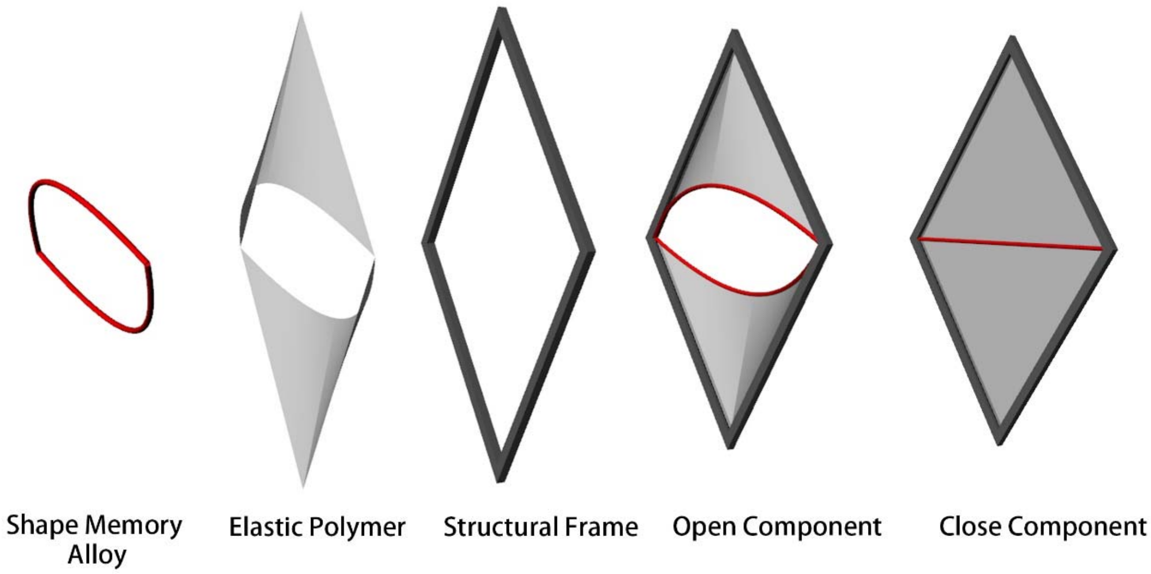


Figure 4.4 Material Layers of the Component

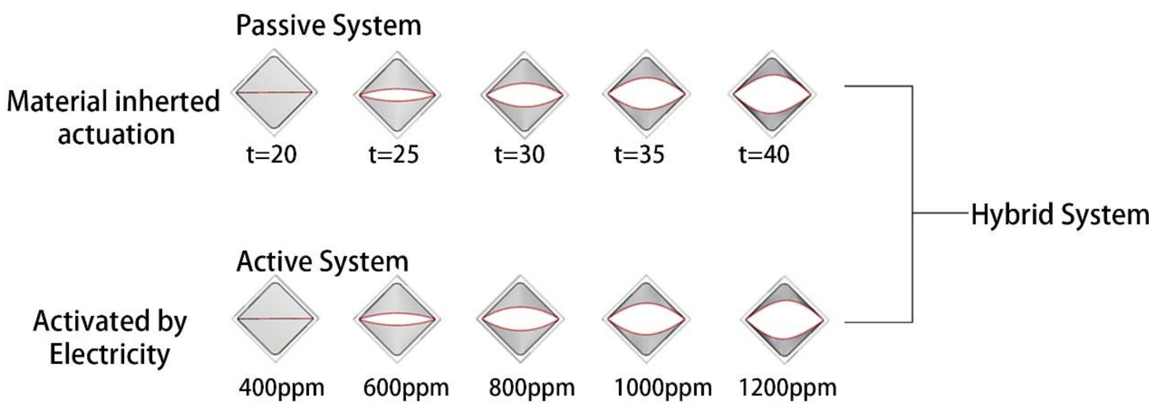


Figure 4.5 Material Response to Environmental Change and Hybrid System

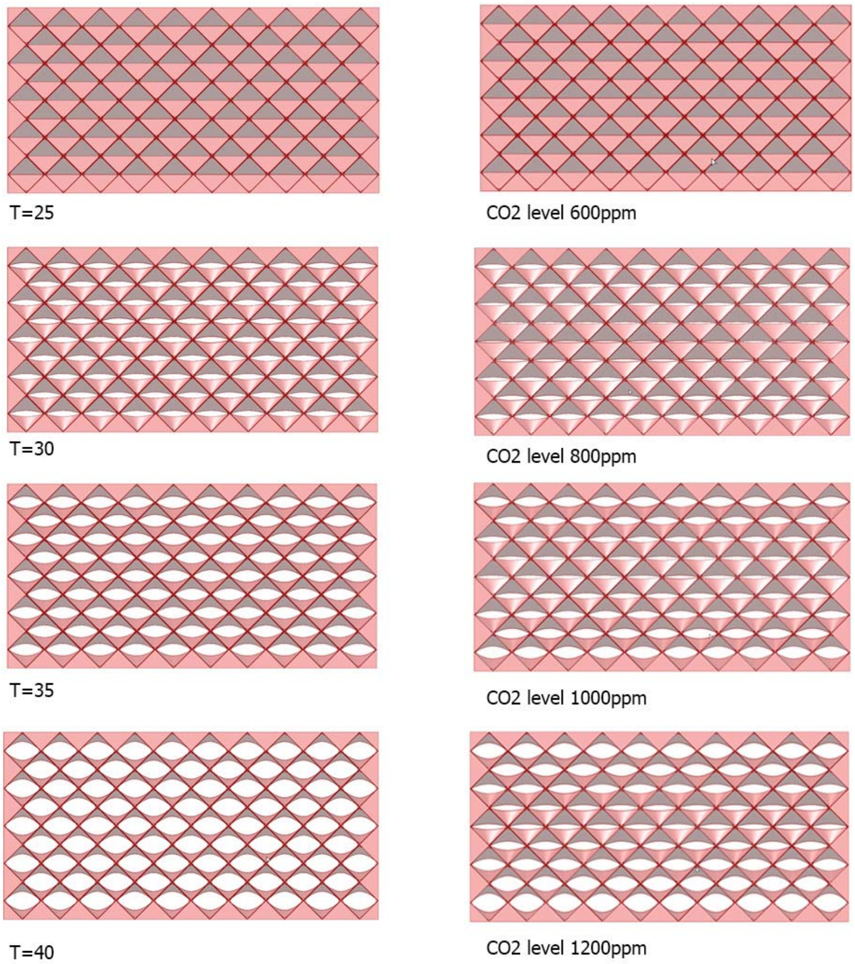


Figure 4.6 Different Behavior of the Component on the Façade Level

Responsive In-Direct Control mechanism (figure 4.7) is chosen for this project to control the input data from different environmental factors, temperature and CO_2. The adaptive kinetic component could response to the environmental factor directly, or indirectly by the controller. The module passively response to the temperature change or actively adapt to air quality by changing its surface porosity to breathe and ventilate air. It is also possible that the overall movement of the system could be controlled by the user input to achieve some desired façade pattern.

4.4 Application of the Module

This adaptive component module is most effective in environments such as classrooms, theaters, auditoriums, data centers, stadiums and mosques where the occupancy is intermittent and often well below the maximum design occupancy. In those spaces to save energy while not reducing the comfort level, demand controlled ventilations is required. In the following section, three application scenario has been shown in detail.

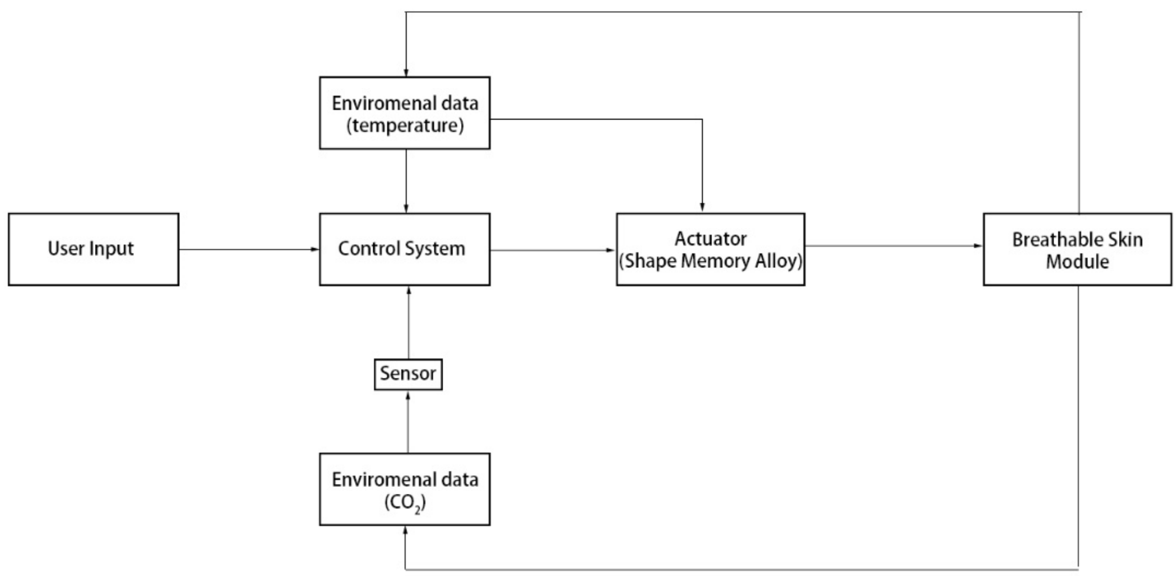


Figure 4.7 Responsive In-Direct Control mechanism

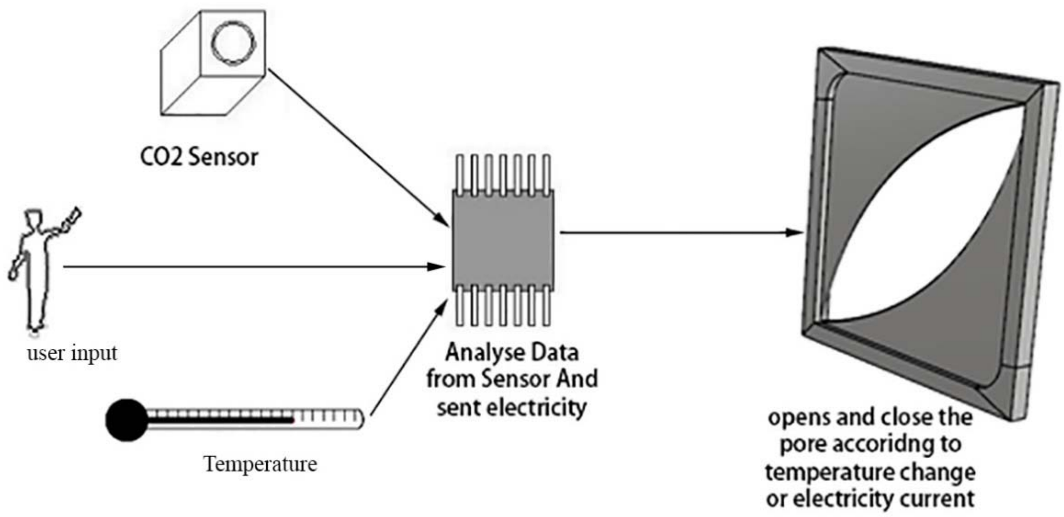


Figure 4.8 Flow of Environmental Information

4.4.1 Application of the Adaptive Component for Classroom Acclimation

Classroom indoor air quality is very critique issue for students' concentration and mental health[50]. According to ASHRAE standard, when the CO2 level in the classroom exceeds 1000 ppm, it is considered to be under ventilated. High levels of CO2 have been shown to cause a negative influence on pupils' learning ability[51].

When we look at the classrooms in YTU architecture faculty main building, we found that most of the classrooms are not equipped with ventilation systems. However, according to some research, the indoor comfort level is not reached. Some students reflect that during the peak hours, they have experienced some levels of headaches. This will affect student's concentration and study level significantly. So we take one of the classrooms at the third floor to improve the indoor air quality by applying adaptive component to replace the windows and corridor wall. Figure 4.9 shows the existing situations of the classroom and corridor in between. There is no ventilation system for the classroom, so in order to keep the better air quality, the windows have to kept open. However, during the extreme environments, opening the windows will reduce other comfort indicators.

Figure 4.9 Existing Situations of the Classroom

This classroom has 80-person capacity. However, during the day the occupant number is changing from class to class. So the need for air ventilation is changed accordingly. One research has been conducted to calculate the CO2 level change of the classroom during the day based on student number in the classroom. Based on the measurement on site, the length of the classroom is 14m, the with is 8m, the height is 3.5m. So the volume of the classroom was approximately 400m^3. In the outdoor environment, the concentration level of CO2 is 400ppm. So when there is no occupation of the space, initiate value of the classroom CO2 level is 400ppm. For the simplification of the research, other factors which produce CO2 is taken into consideration. The amount of CO2 exhale out by each person is 0.25L/min[52]. Based on these number, the CO2 level change is quite predictable and exhibit linear change based on the occupant's number. However, during the calculation process, the windows are considered closed and any type of air flow except when the adaptive component module opened is not taken into consideration. Figure 4.10 shows CO2 concentration changing difference based on occupant number during the one-hour class duration. Although in the 10-person scenario, after one hour of usage the air quality of the space is still under acceptable limit, in 80-person scenario, serious CO2 level is reached in ten minutes.

Figure 4.10 CO2 Level Change of the Classroom by Occupant Number in One Hour basis

By applying adaptive component to the classroom, demand controlled ventilation will be achieved. The module is applied on the wall between corridor and classroom (figure 4.11) and also the windows will be replaced by this component. Triangulated grid strut was used to support the module. The modules are constructed on the frame. Electric wires can be hided inside the frame. One CO2 sensor are located on side of the desk for each four desks, which will equally measure CO2 concentration in the classroom. detail view of the wall system is shown in the figure4.12. The wall may be considered as the leaf surface having several stomata for air exchange. The permeability of the wall could be changed according to the temperature and CO_2 level of the space like plants. When the “stomata" of the module open, the air from corridor during the winter or the air from the outdoor during the summer will enter the space to regulate the interior environment comfort.

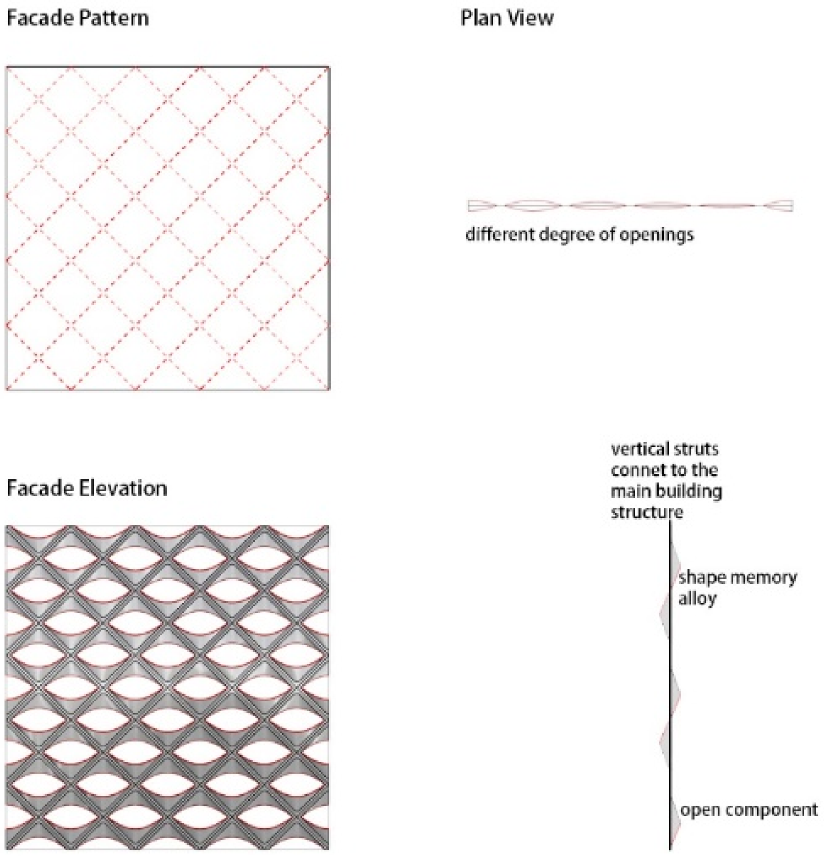


Figure 4.11 Detail View of Breathing Wall

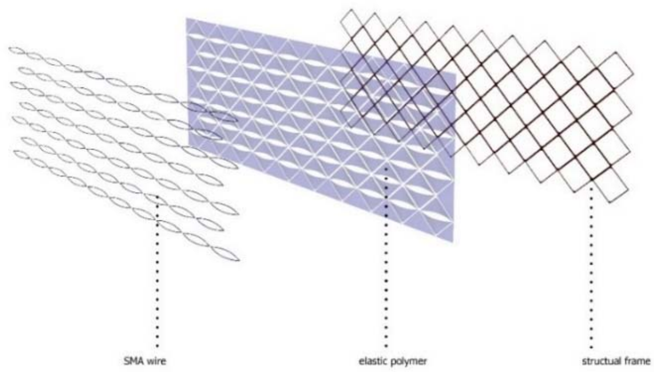


Figure 4.12 Exploded Axonometric Diagram of the wall

Figure 4.13 Existing Situations of the Classroom and Application of the Adaptive Component

As mentioned the above, the CO2 level of the classroom changes according to the occupant number, so the adaptive component will behave accordingly. The pattern on the wall is generated by the individual stomata-like openings that respond to temperature and CO2 level. For example, when the classroom is used by ten people, the CO2 level is still under acceptable level, so the stomata of the wall will mostly react to the temperature of the classroom. When the temperature arises to higher than 25 ^{0}C, the SMA wire will passively adapt to the environment and opens up the adaptive component of the wall to ventilate the space.

However, in other situations, CO_2 level will change rapidly. So the wall has to open some stomata to provide clean air to the classroom. The number of the openings and size could be controlled by the microprocessor of the module and will adapt to the occupant number and CO_2 level (figure 4.14). For example, when the classroom is fully occupied, the SMA will be actuated by electric to fully open every ten minute, to ventilate the space. When the CO_2 goes back to normal level, the controller will close these openings. And the wall goes back to its original shape. So the pattern openings of the adaptive component reflect the occupant situation in some way.

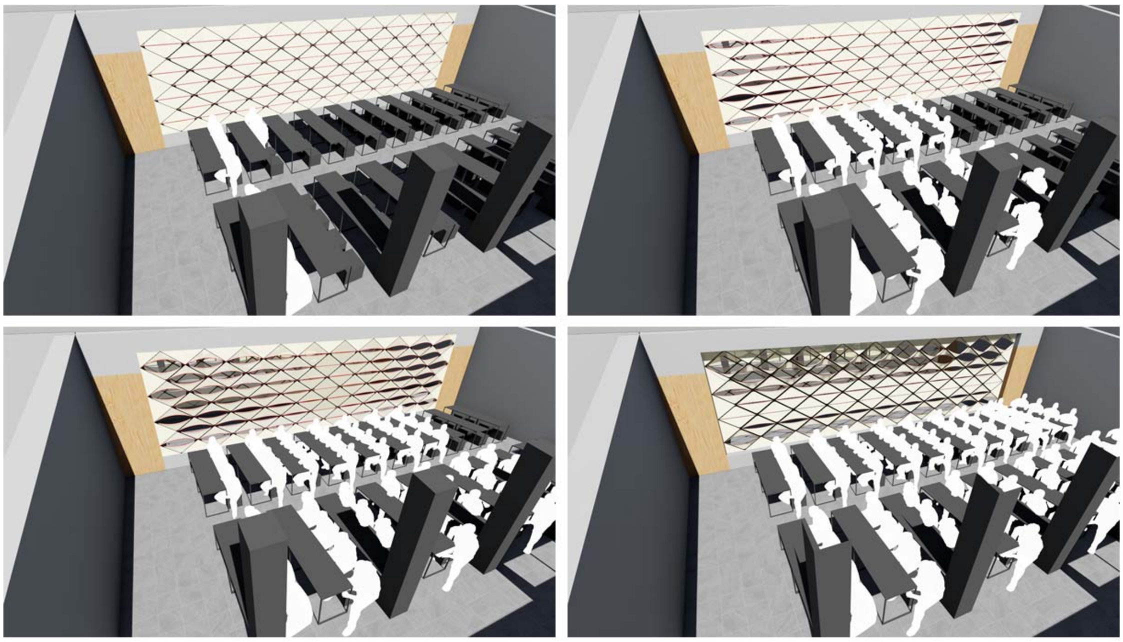


Figure 4.14 Different Patterns of the Wall in Varying Occupant Conditions

Different ventilation solutions are needed for winter and summer because of the great temperature difference. During the summer, the outdoor temperature is lower than indoor temperature and comfortable enough to cool the air inside by cross ventilation. The summer strategy brings fresh air from outdoor through the stomata on window side, then letting it exhaust out at high level through the stomata on the wall to the corridor. During the summer days when the temperature is higher than 25 ^{0}C, so the stomata opens passively. During the days the temperature is lower than 25 ^{0}C, when ventilation is needed for fresh air, the controller will send electricity to the SMA to breathe. Air flow during the summer is shown in figure 4.15. Opening direction and size of the adaptive component could regulate the air flow direction and speed. With the control mechanism we could control the open size and direction to regulate air temperature and quality. This allows the system to optimize the ventilation strategy for comfort and energy use.

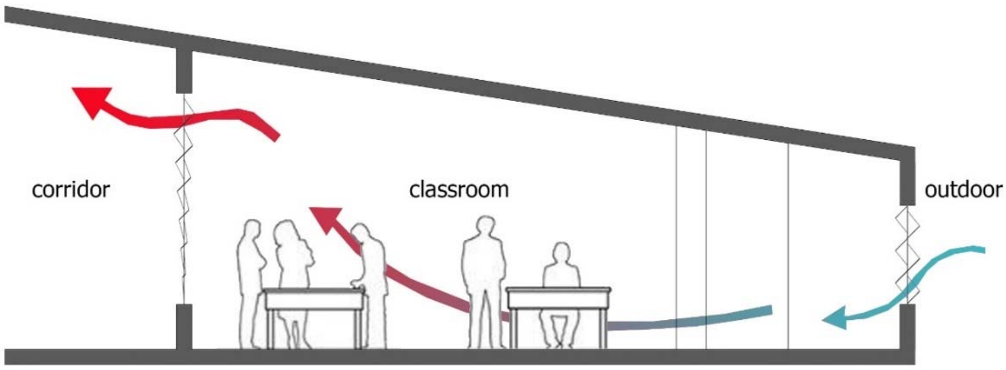


Figure 4.15 Summer Ventilation Airflow

However, in the winter, bringing fresh air from outdoor will cause cold draughts problem. The corridor is well ventilated and acclimated. So it will work as a lung to exchange air with the classroom. The temperature during the winter is too low to actuate the SMA. So the actuation of the adaptive component module is only affected by CO2 level. When the CO2 concentrates, the sensor will be activated and sent single to the control mechanism. According to the location of the concentration and level of CO2, Control mechanism analyze data and decide which part of the wall stoma will open to regulate the air. Part of the adaptive component module will draw air from the corridor to classroom, others modules will exhaust air from classroom to corridor (figure 4.16). The rate of the air flow is regulated by the controller based on the CO2 level During low occupation, less module will be opened and changing period is longer. When the classroom is fully occupied, more "stomata cells" will be opened frequently. Better air quality is provided with these demand controlled ventilation based on hybrid system.

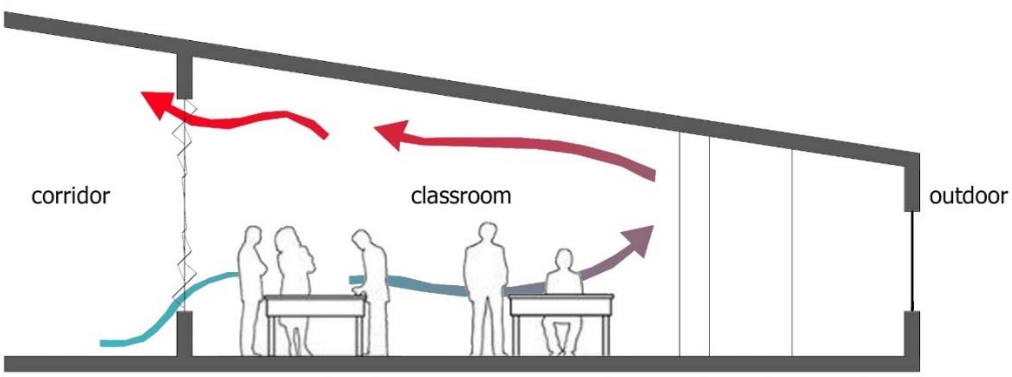


Figure 4.16 Winter Ventilation Airflow

By applying the adaptive component to the classroom wall and replace the existing window, the air quality of the classroom would have kept at a desired level without needing complex mechanical HAVC systems. Also, the temperature of the classroom could be controlled by natural ventilation. The wall is acting the same as leaves of the surface, which adjusts its stomata openings according to the environmental conditions. With the application of the bioinspired wall, the building could reduce energy consumption and greenhouse gas emission, also the productivity of students will be increased.

A new wall constructed with adaptive component module has been created that helps to passively cool a building space and also actively monitor the CO2 in the air by providing demand-controlled ventilation (DCV).

The benefits of this component is:

- Improved Indoor air quality (IAQ)
- Increased student concentration
- Energy savings
- Reduction of greenhouse gas emissions
- Occupant control ventilation
- Reduction in occupant illness associated with Sick Building Syndrome

Rhinoceros and grasshopper are used to build the digital model of this component and its reaction to the environmental factors. The surface that will be used to covered by adaptive component modules is modeled in rhinoceros and imported to grasshopper then it will be panelized into triangular shapes.

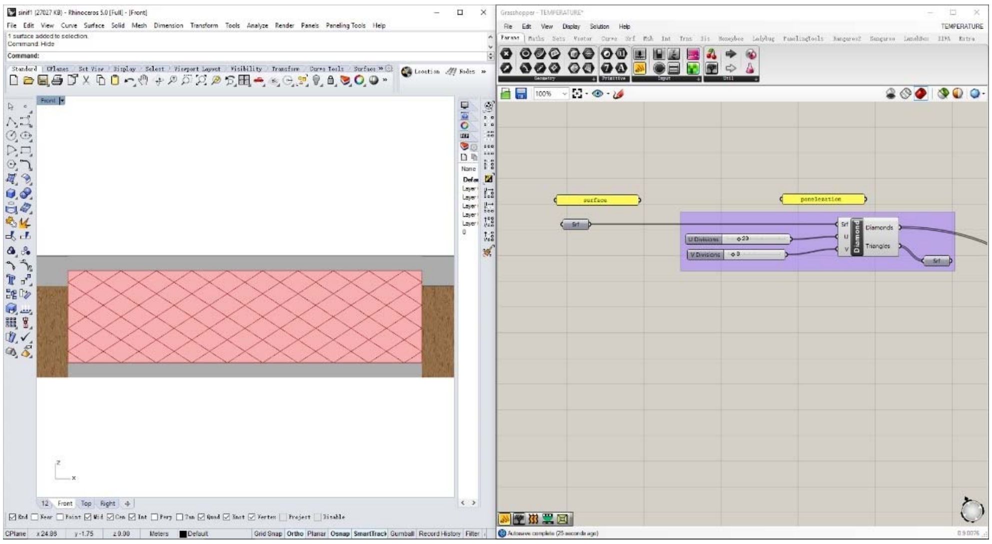


Figure 4.17 Import Surface from Rhinoceros to Grasshopper and Penalization

The temperature slider represents the real world temperature change. These data will be analyzed by this definition and transformed into the actuation data of the SMA alloys. When the temperature starts to go higher than 20^{0}C, the component starts to open. When it arrives 40^{0}C, it will totally open.

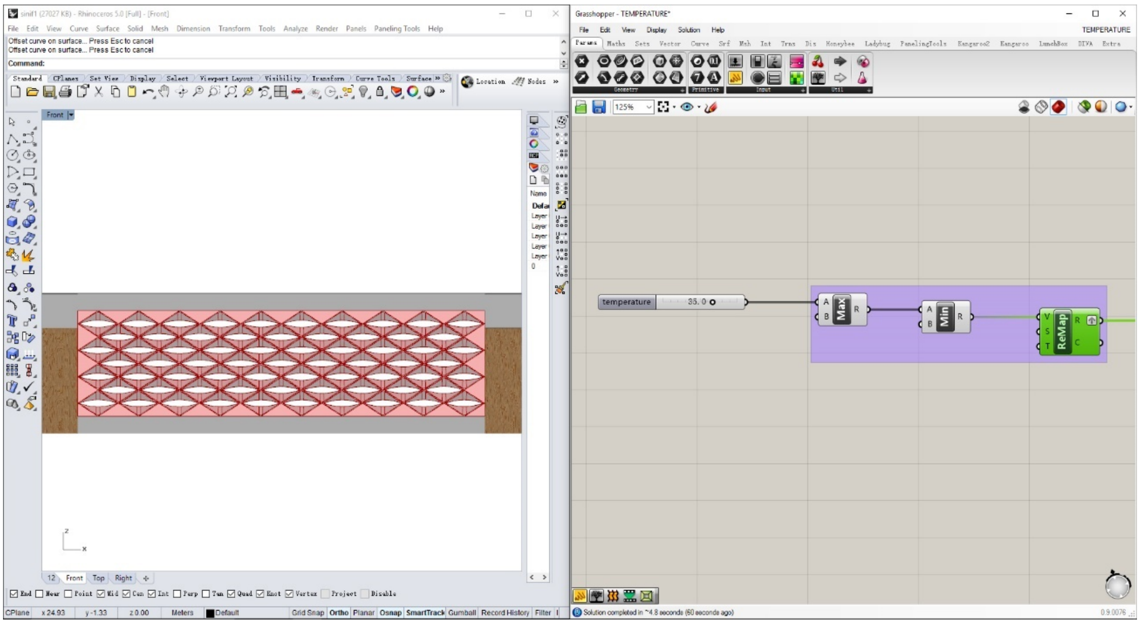


Figure 4.18 Temperature Parameter and Opening of the Component

The temperature slider value is transformed to the opening size of each module. The triangular pattern is replaced by the adaptive component. And this definition represents the overall application of the component. The higher the value of the temperature slider, the wider the component will open.

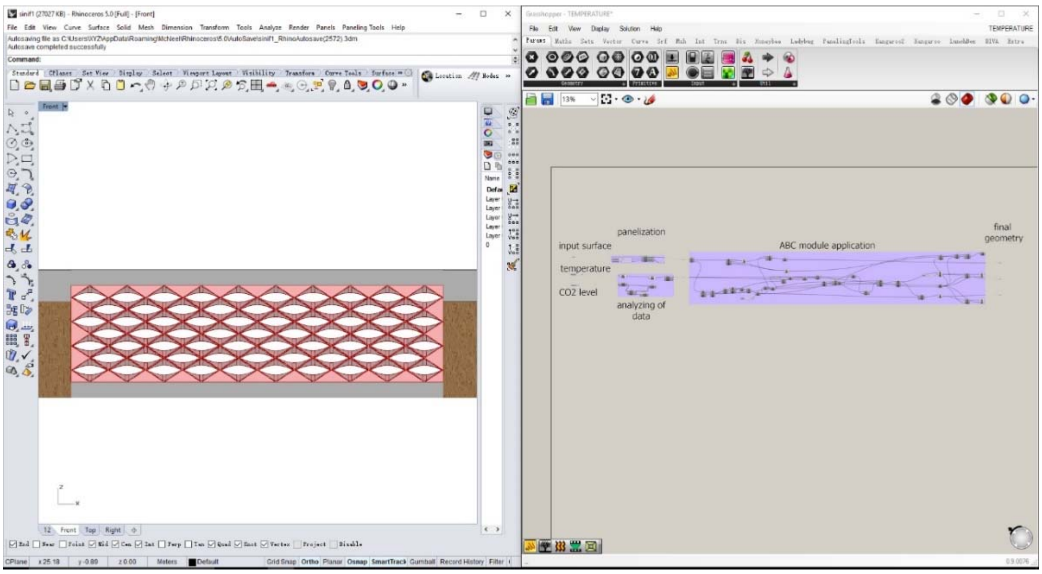


Figure 4.19 Grasshopper Definition and Behavior of the Component

In the grasshopper definition, CO_2 slider is also showed. It ranges from 400 to 1500, which represents the CO_2 level of the space detected by the sensors. The value of the slider is also transferred to the opening size of the component by the analysis definition. The SMA wire will elongate as the value goes up.

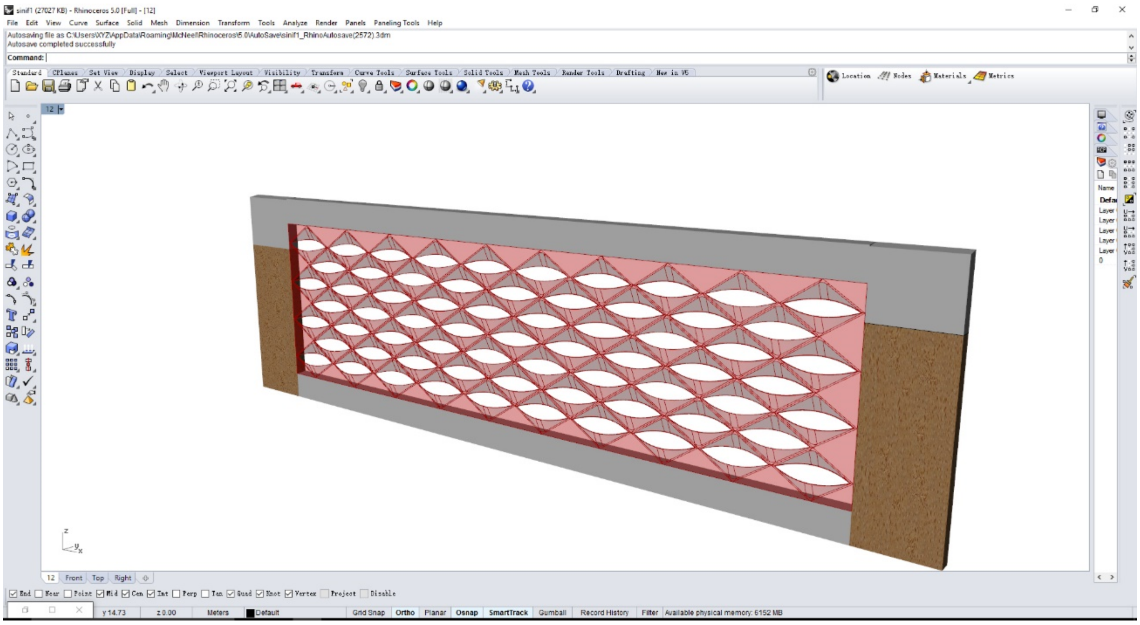


Figure 4.20 Perspective View of the Adaptive Wall

4.4.2 Application of the Adaptive Component for Mosque Ventilation

Mosques are of great importance for Muslims for religious activity. People come to the mosque for five obligatory prayers. The average time for each pray is around 20 minutes. The occupation percentage of the mosques are 5% constant occupation, 20% pray time occupation, 100% Friday pray occupation[53]. The interior air quality changes drastically during peak praying hours. It has been observed that well-ventilated mosques attract more prayers[54]. Maintaining indoor environmental quality in a mosque is a significant challenge whether buildings are naturally ventilated or using HAVC systems.

The Altunzade mosque is taken as an example to analyze and improve interior environmental quality. The existing ventilation system depends on mechanical system. It is energy consuming. Most of the under occupant situation is over ventilated and during the over occupation, the comfort level is not reached. The overall shape of the mosque is suitable for natural ventilation (figure 4.21). the mosque has fixed windows in the entrance level and on dome. If these windows are replaced by adaptive component module, natural ventilation with chamfer affect could achieved.

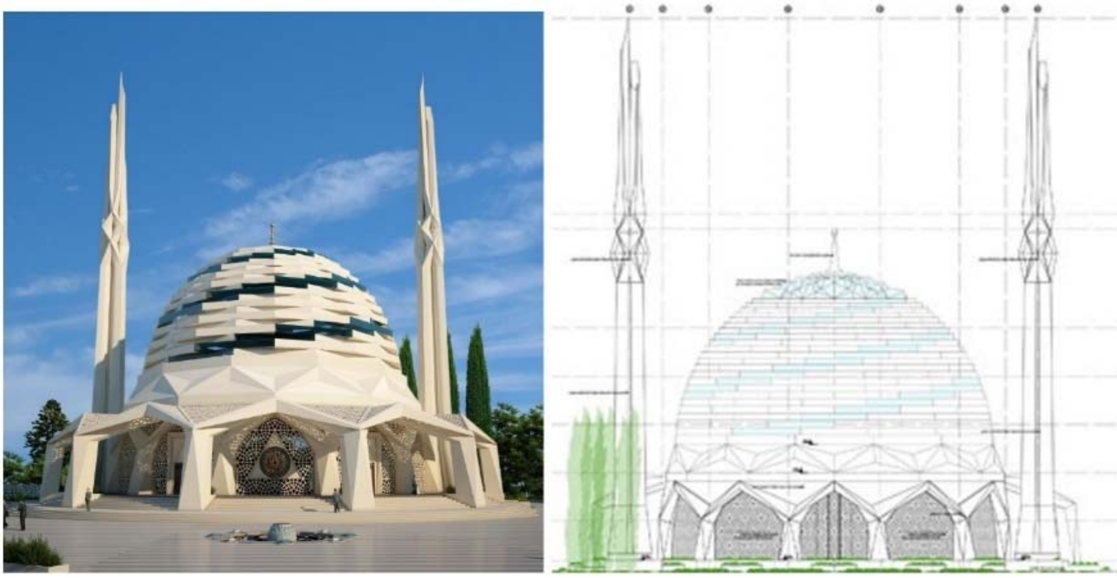


Figure 4.21 The Perspective and Section of Altunzade Mosque[55]

The pattern windows façade at the entrance level are fixed window. So if these facades are exchanged with the adaptive component module, the façade will response to environmental change to monitor air quality of the mosque. In the hot summer, the adaptive component module will passively open its stomata to vent in the colder air outside and exhaust the hot air inside to outside. During the peak prayer times, the CO2 level inside the mosque will increase drastically. This change will stimulate the CO2 sensor and singles will be send to the controller. The controller will actuate the SMA wire to increate ventilation rate. Also, if the glasses at the dome of the mosque are replaced by adaptive component module, based on the shape of the dome, it will increase the chimney effect (figure 4.22). In this case, the ventilation rate will be much higher. The interior comfort can be satisfied easily.

Mosque now has an integrated solution that monitors the temperature and air quality in the mosque's main praying hall (figure 4.23). Natural wind and temperature difference are used as the force to increase the air flow. The temperature difference between the entrance level and top of the dome increase the buoyancy affect (figure 4.24). the cold and flesh air form out door inter the praying hole through the façade openings. The hot air and CO2 in the praying hall raises. On the dome, adaptive component will be open to exhaust out the air. The natural ventilation reduces the bad smell during the pray time. The hybrid system works as a lung. By breathing in and out, the interior environment comfort is satisfied.

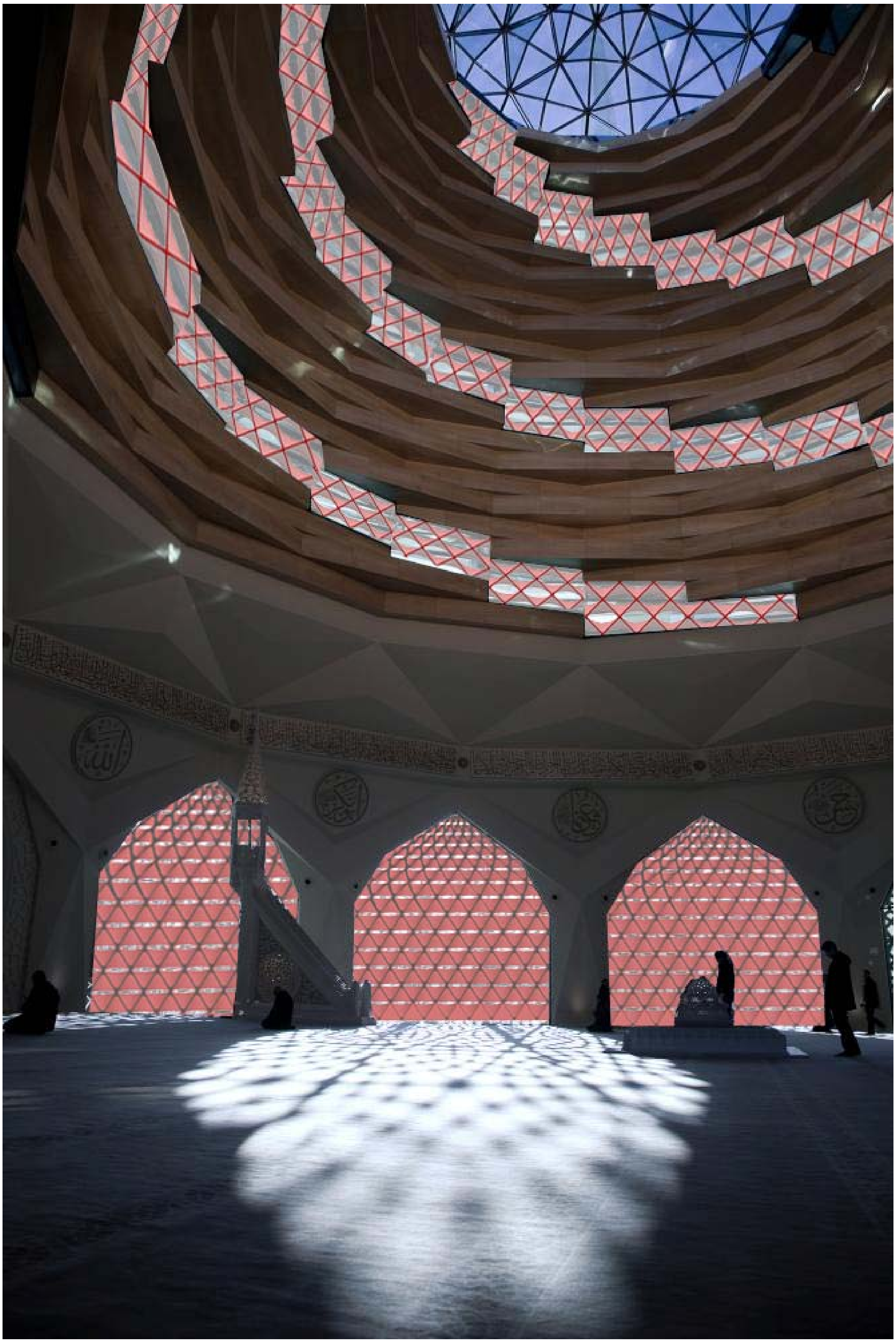


Figure 4.22 Application of Adaptive Component Module on the Mosque.

Without depending on complex mechanical system, the adaptable kinetic façade has been realized. The benefit of the adaptive component is improved air quality, environmental comfort for worshippers and increased energy efficiency.

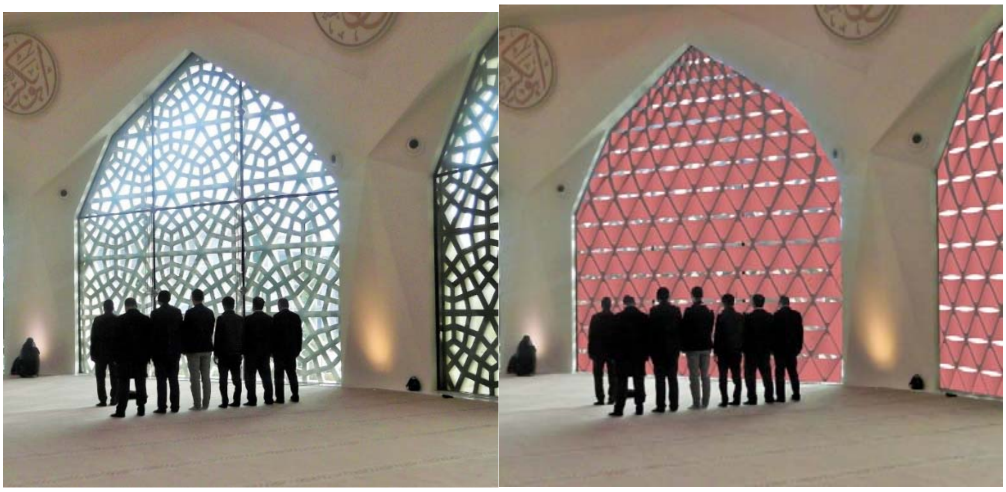


Figure 4.23 Interior View Comparison of Existing Situation and Application of Adaptive Component

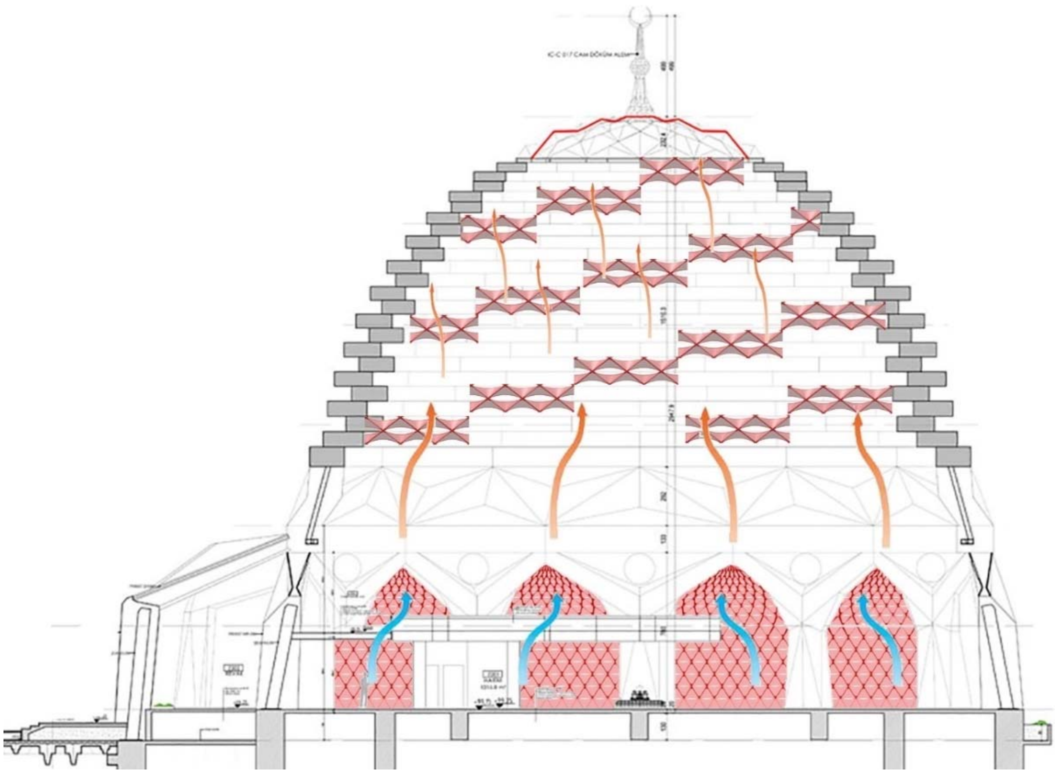


Figure 4.24 Air Flow Through the Praying Hall

Also, peak occupation time of the mosque is predictable. So the façade could be interactive wall by providing information about the occupancy of the space and praying time. By opening the adaptive component module during pray time, for outside visitors, showing the prayer time have arrived. By doing this, this façade not only reacts to environmental data by providing natural ventilation, but could also became an interactive kinetic system. Traditional mosques are known for their pattern on the wall and windows. So creating kinetic patterns would an interesting topic for designing modern mosques. With the application of this adaptable kinetic module for the mosque, we could have a dynamic pattern on the façade which not only response to environmental change but also could controlled by user input. Different patterns that could be achieve by this component is shown in the figure 4.25.

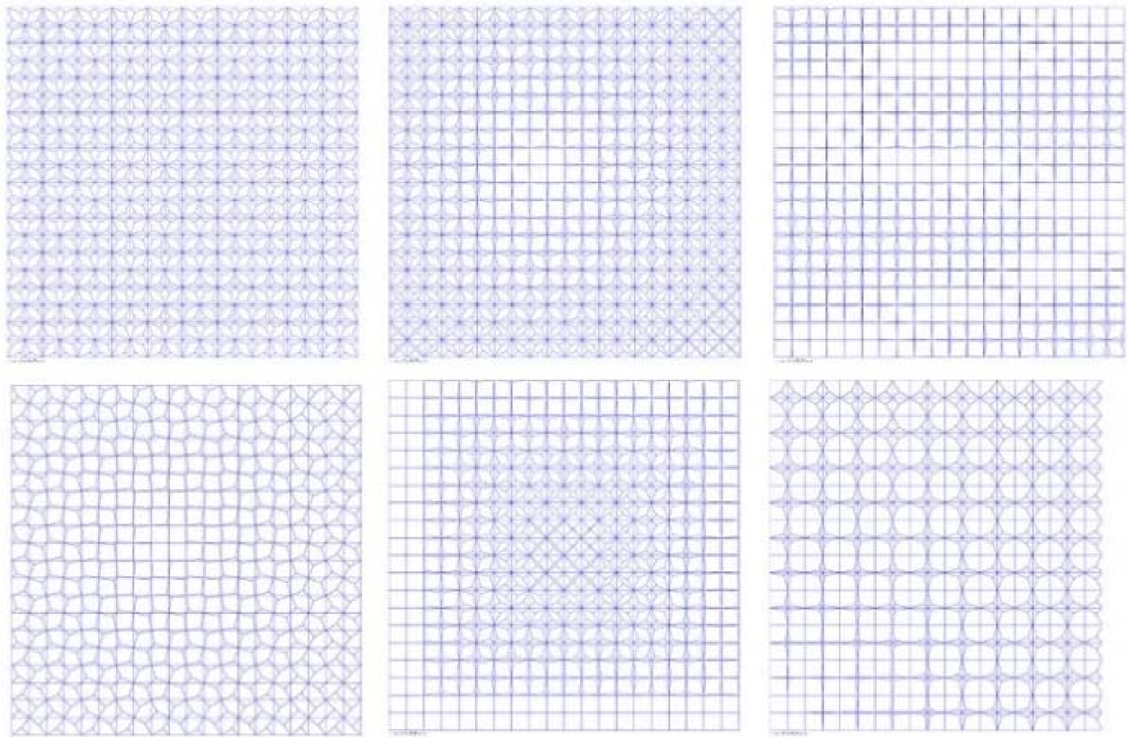


Figure 4.25 Different Pattern for The Mosque Façade

4.4.3 Application of the Adaptive Component for Stadium VIP Lobby

Indoor sports arena or closed areas in open stadiums could have occupants ranging from a few hundred to tens of thousands. So the interior air quality changes accordingly. To energy saving demand controlled ventilation is needed for these kind of spaces. Application of the adaptive component module could provide CO2 based demand controlled ventilation for these spaces.

Beşiktaş Vodafone arena is selected as case study. Although it is not an indoor arena, the space like lobby, coffee and other shops are intermittently occupied. So for these spaces, we could provide hybrid responsive ventilation system with adaptive component module. The heat reactive ability and CO2 sensor based actuation of the system provides natural ventilation for the space. The application of the module for the façade of VIP lobby is shown in the figure 4.24. the arena will have a kinetic adaptive façade with environmental adaptability. When the space is occupied during, the adaptive component will adapt its openings according to occupancy. Also, we could input data directly to the control system to control the opening pattern on the façade.

Figure 4.26 Existing Façade of the Beşiktaş Vodafone Arena

Figure 4.27 Application of The Adaptive Component Module for VIP Lobby

The application of the module could be extended to more spaces. But in this thesis, only three application scenario have been analyzed. With adaptive component module, by benefiting from material property of SMA and hybrid kinetic system, low-cost sustainable building could be achieved without reducing user comfort. This bioinspired design approach proved that bioinspired adaptable design solution could reduce the energy consumption of the building.

CHAPTER 5

RESULTS AND DISCUSSIONS

With the industrialization of architectural construction, similar architectural forms have occurred in different climate conditions answering different needs. To find better adaptation solutions, architects turn to nature which has developed adaptation principles over 3.8 billion years of evolution. Design ideas about buildings that are capable of adapting to user demands and changing environmental factors have occurred. One of main contributions of this thesis is using bioinspired design method to apply shape changing materials to adaptable kinetic surfaces.

The integration of different disciplines (biology, material science, robotics) in to architectural design process have changed the architect`s perspective to nature and design problems. Development of material science and computer aided design and biomimicry principles allows architects to develop innovative sustainable solutions. By transferring and integration of functional principles of plants through bioinspired design approach and utilizing SMA, a bioinspired adaptive component has been developed which adapts to changing environmental conditions to offer interior air comfort and user requirements without depending on complicated, energy consuming mechanical systems.

Literature review have been conducted about how the architects found solutions related to the above mentioned problems and new research areas about kinetic adaptation have been investigated. In this context, in the second chapter, the benefits and purpose of kinetic architecture are explained, definition of kinetic architecture and control mechanism of kinetic movement are introduced and its recent development in literature and real world projects have investigated and exhibited by projects. Apposed to its widely application, mechanical kinetic systems rely on sophisticated mechanical and electronic sensors, control mechanisms and programs and motors for actuation which leads to energy consumption, high complexity and cost, and reliability and maintenance problems.

In the third chapter, the new design approach – bioinspired design- have been discussed to find an alternative solution for kinetic architecture. Bioinspired design transfers abstracted solution form nature to architectural problems. The plants are chosen as role model for their homeostasis adaptation principles and static locations. The adaptation principle of plants responding to sun light, temperature, humidity and CO_2 level are analyzed and abstracted to apply for architectural applications. The plants are exhibiting kinetic behavior depends internal material properties without needing external energy consumption. To realize kinetic behavior similar to plants, shape changing materials (natural active materials and smart materials) are explored. The goal was to make some of the design trade-offs more apparent and help guide the material selection process. Shape changing materials allows kinesis and transformation happen through changes in material properties rather than changes in how different mechanical elements connect together. In this thesis, I purposely shift away from extensive material characterization towards a practical design approach in order to make this knowledge more accessible for architects. In chapter four, based on the plants adaptation principle, control mechanism and smart material technologies, the development process of the adaptive component are described. During the development of the adaptive component, stomata in plants leaves are taken as role module, CO_2 level and temperature is considered as the main environmental factor. The application scenario of the adaptive component is shown in three different examples. With the application of the module, demand controlled natural ventilation have been realized. Adaptive component module is inspired by the stomata principle of plants, and actuated by SMA. Through the outcomes of this design proposal investigation, it is illustrated the great potential of shape changing materials to full-scale architectural implementation in future research.

This bioinspired design approach proved that bioinspired adaptable design solution could reduce the energy consumption of the building. With application of adaptive component module, building envelopes are no longer the separator of interior with outdoor space, but a mediator of the indoor environmental quality. Buildings will have changing façade which will adapt to environmental change and respond to user needs. Application of shape changing materials with intrinsic sensitivity to climatic stimuli can help architects to realize development of zero-emission sustainable adaptable building skins with hybrid response. However, the production process of SMA is energy consuming and emits a lot of CO_2 to the environment during the shape memorizing period, and current available

SMAs are expensive which makes it hard to widely implicit in architectural industry. So its contribution to sustainable design could be measured during the future research in site application of the module.

As mentioned about architectural design is not defining of space any more, it requires the attendance of other disciplines to the design process. For the real world application of adaptive component, interdisciplinary cooperation is needed: for the control program of the system computer engineers are needed, for the exact actuation of the SMA material engineers are needed, for the application of sensors and electric current mechanical and electrical engineers are needed, to decide the size of the adaptive component and support frame construction engineers are needed. Before the application of the adaptive component, it would be beneficial to build a sample of the component according to the site condition and to test whether the require criteria is reached. Future work will include a series of experiments that explore the scalability of the modular system and implement it in an actual site context, and measuring the environmental benefit of the component for indoor air comfort. Cooperation with researcher from other disciplines will lead this research to new levels. Another future envisage of this research is integrating energy harvesting systems for self-sustainability by including technologies such as paper-based printed photovoltaic cells. It is supposed that with further development and exploration of bioinspired design approach and shape changing materials, a fully kinetic and adaptable architecture could be achieved.

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CURRICULUM VITAE

PERSONAL INFORMATION

Name Surname : AISA ATAWULA

Date of birth and place :1989.09.29, China/ Hotan

Foreign Languages : English, Chinese, Turkish

E-mail : eysa1989@gmail.com

EDUCATION

Degree	Department	University	Date of Graduation
Masters	Architecture	Yildiz Technical University	----
Undergraduate	Architecture	Hefei university of technology	2011.06

WORK EXPERIENCE

Year	Corporation/Institute	Enrollment
2014-2015	Loco Mimarlik	Architect
2011-2012	PTW Architects	Architect