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EXPLORING NEW FORMS THROUGH PARAMETRIC PATTERNS IN RESPONSIVE FACADES

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Mahina REKI

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The thesis study titled “EXPLORING NEW FORMS THROUGH PARAMETRIC PATTERNS IN RESPONSIVE FACADES" is submitted by Mahina REKI in partial fulfillment of the requirements for the degree of Master of Science in the Department of Architecture, Gazi University by the following committee.

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ETHICAL STATEMENT

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- All data, information and documents presented in this thesis have been obtained within the scope of academic rules and ethical conduct,
- All information, documents, assessments and results have been presented in accordance with scientific ethical conduct and moral rules,
- All material used in this thesis that are not original to this work have been fully cited and referenced,
- No change has been made in the data used,
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Mahina REKI

25/07/2018

TEPKİMELİ CEPHELERDE PARAMETRİK ÖRÜNTÜLERLE
YENİ FORM ARAYIŞI
(Yüksek Lisans Tezi)

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ÖZET

Bina kabukları ya da cepheleri bina ve çevre arasında bir arayüz olmuştur. Çevre koşullarına uyum sağlamak için tasarlanan etkili ve akıllı cepheler, pencerelerin ve hava akımı sağlayıcıların, çevre koşullarına duyarlı olarak tasarlandığı zamanlara kadar uzanmaktadır. Son birkaç on yılda, teknolojinin gelişmesi ve binalarda her zamankinden daha fazla yeni malzemenin kullanılmasıyla, enerji tüketimi ve tasarrufuna verilen önem büyük ölçüde artmıştır. Cephelerin üstlendiği; ısı yalıtımı, estetik, akustik, aydınlatma gibi birçok önemli rol nedeniyle, yüksek performanslı bina cepheleri, araştırmacıların ve tasarımcıların odağı haline gelmiştir. Bu tez, 3 temel çalışma konusunun kesişimi üzerine temellendirilmiştir; (i) dekoratif olarak kullanımından ziyade mimari jali/kafes elemanlarının işlevsel önemine odaklanarak, İslam dünyasında kullanılagelen pasif serinletme tekniklerinin araştırılması, (ii) Büyük Mughal İmparatorluğu'na ait sanat ve mimari örneklerine odaklanarak, jali başta olmak üzere mimari cephelerde kullanılan İslami geometrik örüntülerin evriminin araştırılması, (iii) bu bilgilerin parametrik tasarım yöntemleri ile entegrasyonun sağlanması yoluyla cephe tasarımında yenilikçi çözümlerin araştırılması. Mevcut uygulamalardan bilgi toplamak, geleneksel uygulamaları ve geometrik örüntüleri modern tasarımlara taşıyan kafes/jali kullanımının olduğu çalışmaları analiz etmek bu tez için önemli bulunmuştur. Sonuç olarak, jali kavramı aracılığıyla kinetik cephelerin nasıl tasarlanabileceğini göstermek amacıyla, basit geometrik örüntülerin kullanıldığı iki tasarım temrini gerçekleştirilerek modüllerin kinetik olma potansiyelleri araştırılmıştır. Bu çalışmadan elde edilen sonuçların, kafes/jali üzerine araştırma yapan tasarımcılara, parametrik araçlar kullanılarak kinetik duyarlı cephelerin geliştirilmesinde, yeni ufuklar açması beklenmektir.

Bilim Kodu	:	80111
Anahtar Kelimeler	:	Parametrik örüntü, Mughal Sanatı ve Mimarisi, Pencere kafesi, geleneksel metotlar, modern yaklaşımlar
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EXPLORING NEW FORMS THROUGH PARAMETRIC PATTERNS
IN RESPONSIVE FACADES
(M. Sc. Thesis)

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GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
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ABSTRACT

Façades or the building envelopes have always been the interface between the building and the environment. The effective and smart facades that are designed to adapt the environmental conditions date back when windows and ventilators were designed carefully in response to the site conditions. In the last few decades, the emphasis on energy consumption and reduction has increased drastically, as technology has evolved and more new materials are used in the buildings than ever. Due to the numerous significant roles that a facade plays that are the thermal comfort, aesthetics, acoustics, lighting *etc*, high-performance building facades have become one of the main focuses for researchers and designers. This study is based on intersection of 3 main subjects of interest; (i) investigation of passive cooling techniques in Islamic world focusing on the importance of the jali/screens, as decorative architectural elements along with their functional significance, (ii) the role geometry on jalis and façades and the evolution of geometric patterns in Islamic world focusing on The Great Mughal's art and architecture, (iii) integration of this knowledge with parametric design methods to achieve new design solutions in façade design. Collecting information from the existing data and analyzing case studies using screens that revived the traditional practices to modern designs is crucial for this study. As a result, to demonstrate the basic understanding of the concept of a kinetic façade through a jali, two design exercises that have been carried out and explored their kinetic systems, with the potential of a simple geometric design used as a module to generate the skin and its kinetic response. The investigations from this research opens a gateway for further explorations in the field of screen design, using parametric tools for the development of kinetic responsive skins.

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I dedicate this dissertation to my children Yahya and Zaha.

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1. INTRODUCTION

Jali (Urdu word) is an architectural element found in Indian subcontinent and Islamic architecture. A jali is an ornamental perforated screen which has been a significant architectural feature in Mughal architecture for decades. As it is one of the major architectural elements commonly found in the region, the designs of the jali's were usually geometrical patterns carved out on red sandstone or marble.

The use of geometry is not only for ornamentation purposes in Islamic art and architecture but also as a unifying concept. It unifies the composition regardless of the diversity of materials and forms. These complex patterns have several features and principals they are based on, foremost being the symmetry, having a harmony and balance of proportions. The second major principal is the repetition of the unit, forming the base of the geometric patterns. Later scalability, adaptability and coverage are the focus depending on the elements, material and the object itself, whether it's a small vase or a wall. Movement, the illusion of continuity and framing of the patterns on pre-calculated surface are also major aspects of these geometric patterns in Islamic art and architecture.

The Mughals artisans and architects used jali's not only as ornamentation but considered it as one of the major architectural elements in a building's design. These intricate and highly crafted screens are remarkable decorative pieces of art and play a vital role in the ventilation of the building. They admit air to pass, at the same time they are very efficient in tempering sunlight and eliminating glare, making the interior spaces more comfortable. Other than these properties jali's are also essential for privacy, majorly in the context of *purdah* (veil), as it acts as a buffer between the inside and the outside. Due to the contrast, the view of the outdoors or the street is possible, whereas the interior view is limited.

<u>Research problem</u>

The numerous examples of the effectual use of jali's in the Mughal architecture that can be found in Pakistan and India, is of great importance. Understanding the significance of these jali's as building elements and "how they can be used efficiently in the modern.

Research aim

The aim of this research is to explore different strategies for Islamic geometric patterned screens, designed for kinetic facades, in response to the existing environmental conditions. The goal of this design process and research is to explore possibilities for modern day use of screens on existing structures or new designs.

Research design methodology

Stage I: Preliminary literature review (goals and objectives) In this stage, the main concepts of facades and its significance are understood by reviewing the related literature. The second stage that is the understanding of passive cooling techniques and the significance of jali's are identified through preliminary review literatures. With the help of the understanding of the responsive facades, Islamic geometric patterns and jali's, the relationship between the concepts is highlighted and goals and objectives of the study are formulated.

Stage II: Literature review (setting up a theoretical framework) The second stage of the study that is reviewing of the literature, by understanding the concepts, importance and relationship of the responsive facades and the patterns of screens through in-depth review of the relevant literatures, journals, reports, international case studies and desktop research. The in-depth literature review helped to formulate a theoretical framework of the study.

Stage III: Design Process; Amalgamation of screen and façade In this stage, after the literature review related to the topic were understood in the context of case studies and formulating a better understanding, two design exercises are performed in order to explore the possibilities

Stage IV: Analysis and Recommendations The last stage of the study is the conclusion of the research, attempts to analyze the findings from the study of responsive facades through design by using computer aided design software, against the backdrop of the literature review and theoretical framework, presenting potential areas for future research on jalis and kinetic facades.

Significance of the study

The significance of this study is to understand the merits of traditional/vernacular architectural elements for environmental and aesthetical purposes and their potentials for the today's architectural design practices. In the case of this research, the significance of jali's as building elements is revealed and the question of how they can be used efficiently in the modern architectural practices for passive cooling techniques and design purposes is exemplified to demonstrate the significance of the subject.

Thesis structure

The thesis is structured in six chapters as follows;

i. The first chapter of the report structures the thesis. It forms the foundation of the research and helps in analyzing the context which is the main idea of this study.
ii. The second chapter focuses on the significance of the façades. Is discusses its evolution with the passage of time, and focuses on the modern-day smart façade, which is a resultant of the changing and advancing technology and new materials. In this process of understanding the new methods of façade designing, the research highlights the use of parametric design tools and its role in designing kinetic façades.
iii. The third chapter of this report is a brief study on the geometric patterns and its significance and evolution in Islamic architecture. Since geometry is essential in the parametric design process, this chapter focuses on the different patterns and their tessellations. The major focus of the study remains on the Mughals screens which are taken as an inspiration for this study.
iv. The forth chapter focuses on the energy efficiency of the architectural elements from earlier practices to the present day responsive facades. The chapter gives an in-depth analysis of the vernacular practices and architectural elements, which are used in modern day responsive façade as found in the case study presented in this part of the research.
v. Chapter five is the case study designed to explore the findings of this research exercise. In this chapter two screens are designed and analyzed, based on the concept of responsive Facades play a significant role in regulating the waste of energy in constructions in general. But, most of them are made to offer solutions that require a

lot of energy to reach internal comfort levels. However, the biological adaptation solutions are complex, multifunctional façade. A basic Islamic geometric pattern is used to develop a screen or a second skin of a façade with the help of parametric design.

vi. Chapter six presents the evaluation and the conclusion of the research. In this chapter the attempt is to analyze the findings from the research and the design exercise that was done in Chapter five. Analyzing the results of the screen design for responsive facades with the help using computer aided design software, against the backdrop of the literature review and theoretical framework, this chapter aims to present potential areas for future research on jalis and kinetic facades.

2. LITERATURE REVIEW AND THEORETICAL BACKGROUND

Façade, (a French word) is usually referred for the elevation or exterior of the building (not only the front elevation, but since its literal meaning is face or frontage, so it's taken as the front elevation of the building). A façade holds great importance and is considered a significant aspect in architecture design, as it not only acts as the envelope of the interior spaces it also has the aesthetic value, which makes the image of the building, making it an icon or landmark. On the other hand, as per the engineering aspect, it's the major element of the building as it has impacts on the energy efficiency of the building.

Building façades earliest records suggest the use indigenous materials such as clay, mud and wooden logs for the building and its exteriors, earliest of which are said to be found in Japan. Decades later, the Europeans started using these materials along with stone and glass to build sturdy and more durable building structures.

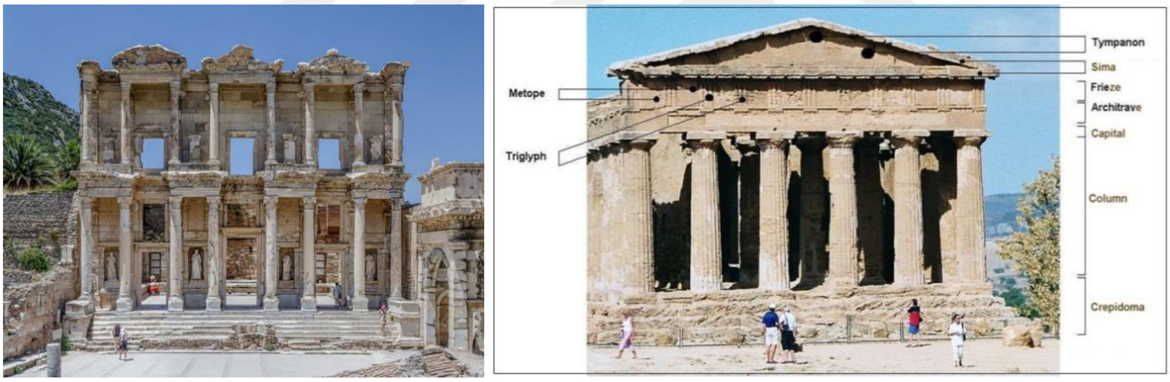


Figure 2.1. Celsus Library façade, Ephesus. Temple of Concordia, Agrigentum (Lieu, 2010; Pastorino, 2005)

In earlier times the façade was considered as main decorative element of the building and in many great empires it was very significant and highly ornamented. These ornamentations and the precision with which these façades were designed were based on classical order, where the proportions and particularities were defined. These characteristics of the façades have been a great source of information for us to study and categorize them according to their eras. For instance, if a building is from the Greek period or the Roman civilization, it is recognized at once because of the classical order. As shown in Figure 2.1, the ruins of the library and a temple clearly show these buildings belonged to the Greek era.

Façades or the building envelopes have always been the interface between the building and the environment. The effective and smart facades that are designed to adapt the environmental conditions date back when windows and ventilators were designed carefully in response to the site conditions. Table 2.1 shows the architectural movements and each era had its own significant style of façade design.

Table 2.1. Architecture evolution timeline (prepared by the author)

Timeline of Architectural Movements	
850 BC- AD 476	Classical
700- 323 BC	Greek
323- 146 BC	Hellenistic
44 BC- AD 476	Roman
527- 565	Byzantine
500-1200	Romanesque
1100- 1450	Gothic
1400- 1600	Renaissance
1600- 1830	Baroque
1650- 1790	Rococo
1730- 1925	Neoclassicism
1720- 1800	Georgian
1730- 1925	Gothic Revival
1840- 1900	Victorian
1860- 1900	Arts and craft movement
1890- 1914	Art nouveau
1895- 1925	Beaux Art
1905- 1930	Neo- Gothic
1910- 1924	Expressionism
1925- 1937	Art Deco
1900- present	Modernist styles
1972- present	Post-modernism
1997- present	Neo- modernism and parametricism

With the passage of time, due to constant research and development, architectural tools and materials have evolved which has resulted in major changes in façade design and structures.

Industrial Revolution marked a completely new era in the construction world, the whole structural system and concept of façade changed, as load bearing building structural frames were covered with non-load bearing façades. This revolution gave birth to skyscrapers era where the façade acted as a curtain wall, hung over the structural frame (steel or concrete).

The Table 2.2 represents the brief history of the evolution of façades from 19th century onwards.

Table 2.2. Evolution of façades 19th century - 21st century (prepared by the author)

Evolution of façades
from 19th Century to 21st Century

		Industrial Revolution 1760-1840
First metal framed with glass curtain façade	1800's	Jayne Building, Philadelphia
First Grand-Plate- Glass Structure		Crystal Palace London
First Public building lit entirely by electricity		Savoy Theatre, London
Masterpiece and a revolution in architecture		La Sagrada Familia, Barcelona, Spain
First Skyscraper		Home Insurance Building, Chicago
Tallest structure till 1930		Eifel Tower, Paris
All steel framed buildings	1900's	Rand McNally Building, Chicago
First reinforced concrete skyscrapers		Ingalls building, Cincinnati
Free facade, pilotis		Villa Sovoye, France
Tallest building till 1931		Chrysler Building, New York City
Tallest building till 1974		Empire State Building, New York City
First solar building		Bridgers And Paxton Solar Building, Albuquerque, N.M.
Architectural marvel		Guggenheim Museum, New York City
Architectural marvel		Sydney Opera House
Responsive Kinetic façade		Institut du Monde Arabe, Paris.
First Passive House-Rated Building		Kranichstein Row Houses, Germany
First Major Bim-Designed Building		Matitone, Genoa, Italy
First Living Machine System	2000's	Lewis Center For Environmental Studies, Ohio
First Leed Platinum Building		Philip Merrill Environmental Center, Annapolis, Md
World's First Twisting Skyscraper		Turning Torso, Malmö, Sweden
Structural Engineering Marvel		Cctv, Beijing: "3d Cranked Loop"
World Tallest		Burj Khalifa, Dubai
Flowing abstract forms, engineering marvel		Heydar Aliyev Centre, Baku, Azarbaijan
Worlds successful kinetic responsive façade		Al- Bahar Towers, Abu Dhabi
First 3d-Printed Commercial Building	⋮	Winsun Apartments, Shanghai

The table shows how the architectural façade design has evolved with the passage of time as a resultant of advancing technology and new materials. It can be observed that the new materials gave more confidence to the architects and designers, to experiment with the forms. The buildings that we see in the early phase of industrial revolution which were achieved due to the use of metal frame and glass curtain walls were growing vertically and had a static form, with the passage of time these forms grew taller and leaner. As more experimentation and engineering techniques advanced the forms and facades became more abstract and as we see more dynamic forms take birth.

This evolution in designing the skin of the buildings gave the architects control over the form design, making them more responsible and aware of the buildings impacts on its surrounding. This resulted in their growing concerns towards the environmental impacts on the buildings and the buildings impacts on its surroundings. The focus of the façade designs was shifted from just being the face of the building to the living skin, where the design can reduce the carbon footprint, be more sustainable, less energy consuming and more responsive to its context.

2.1. Evolution of Façade in terms of Environmental Concerns

In earlier times building façades were considered as barriers between the exterior and the interiors, like an outer shell protecting the users from external environmental conditions and maintaining thermal comfort. After the industrial revolution, the 20th century architecture was a product of industry and technology. Not only the building material and building techniques changed, due the technological advancements, building services techniques also improved resulting in enhanced mechanical thermal comfort techniques, such as the HVAC systems (heating, ventilation and air-conditioning). Due to these mechanical means of controlling the indoor environmental conditions, the external skin, the façade or the envelope is overlooked as a protective shell. The façades are considered merely as an outer surface of an aesthetic significance, losing its main role as a buffer of comfort and energy, resulting in highly energy consuming built structures, thriving to maintain optimal indoor environment comfort and contributing more to the greenhouse gas emissions.

In 1920's, a modernist architect Le Corbusier's 'new epoch' brought a drastic shift in the architectural practice. Other modernist architects namely, Mies van der Rohe and Walter Gropius, along with Le Corbusier pursued this new ideology and presented this minimalist, rational approach to architecture, setting it free from nationalist, class or region-based distinction. They used new technology, materials and industrial forms which became known as the International Style. The modernist architects aimed at achieving transparency, lightness, spacious and sleek forms, which gave rise to the use of concrete, steel and glass to achieve their idea of industrial modernity. In the meanwhile, when the air-conditioning system was introduced, referred as "man-made weather", it further freed the architecture from its ties with nature, as nature was not considered as an obstacle anymore. It allowed Le Corbusier to dream of "one single building for all nations and climates," the machinelike structure independent of place (Yilmaz, 2006; Banham, 1984).

The modern architecture movement, under the name of internationalism and universality, took it for granted that architecture could be governed by architectural design indifferent to essence of place (Yilmaz, 2006; Banham 1984). Since then, the modernist approach designs were copied and reproduced around the world without any consideration of the climate, landscape or the surroundings. These designs are conceived in isolation, without any consideration of their context, be it climatic or cultural. This practice resulted in buildings high dependency on mechanical means for ventilation, lighting, heating and cooling, making the buildings more energy consuming than before.

In the last few decades there is a drastic shift in the role of architecture, as sustainability concerns have emerged. Emphasis on energy consumption and reduction has increased drastically as technology has evolved and more new materials are used in the buildings than ever. New architectural approaches have taken birth in order to design modern buildings in harmony with the context it is placed in (Frampton 1998 [1983], 27). To name a few starting with green architecture, biomimicry, sustainable architecture, responsive kinetic architecture, are all interconnected and focus on the same aspect, to learn from the surrounding and energy efficiency and optimization. Table 2.3 represents timeline of the evolution of façades due to environmental concerns.

Due to the numerous significant roles that a facade plays, it has become the focal point as it is responsible for the thermal comfort, aesthetics, acoustics, lighting of the building. As the architects and engineers worked more on the skin of the building, they started experimenting with the façade and since then high-performance building facades have become one of the main focuses for researchers and designers. The high-performance buildings are the new phenomena where the façade is not just a static elevation but it’s a dynamic building component. In high performance smart buildings, one of the main features is kinetic façades, not just for aesthetic purposes but is programmed to be responsive to the surroundings. These dynamic responsive façades have kinetic climate-adaptive elements including sensors and automation, along with the user or designers’ ability to dominate and control the settings.

Table 2.3. Evolution of façade in response to environmental concerns (prepared by the author)

Evolution of façades
Due to environmental concerns

First reinforced concrete skyscrapers	Early 1900's	Ingalls building, Cincinnati (1903)
Free facade, pilotis		Villa Sovoye, France (1929)
Tallest building till 1931		Chrysler Building, New York City (1930)
Tallest building till 1974		Empire State Building, New York City (1931)
First solar building		Bridgers And Paxton Solar Building, Albuquerque. (1956)
Rise of Eco awareness	Mid- Late 1900's	(1960- 1970)
the Rocky Mountain Institute		(1982)
one of the first civic icons for energy conservation		Environmental Defense Fund Building in New York City. (1985)
Responsive Kinetic façade		Institut du Monde Arabe, Paris. (1987)
First Passive House-Rated Building		Kranichstein Row Houses, Germany (1991)
First Major Bim-Designed Building		Matitone, Genoa, Italy (1992)
US Green Building Council		(1993)
Leadership in Energy and Environmental Design (LEED)		(1994)
William McDonough;s green building		the Herman Miller factory and offices (Holland, Mich., 1995)
William McDonough;s green building		the corporate offices of Gap, Inc. (San Bruno, Calif., 1997)
Nature inspired biomes- green principles of biomimicry	2000's	the Eden Project, (UK, 1998- 2001)
First Living Machine System		Lewis Center For Environmental Studies, Ohio (2000)
First Leed Platinum Building		Philip Merrill Environmental Center, Annapolis, Md (2001)
Worlds successful kinetic responsive façade		Al- Bahar Towers, Abu Dhabi (2012)
Using nature with architecture	...	BIQ, algae façade. (Bernadette Grimmenstein / IBA Hamburg GmbH 2014)

2.1.1. Passive cooling systems

The concept of energy efficiency and conservation is not a new phenomenon anymore. It is observed that in the last decade the idea of sustainability in design and passive cooling techniques have been very popular in architectural practices. Architects are aiming to introduce and design structures that use passive cooling systems to reduce the need of power consumption.

Passive cooling refers to any technologies or design features adopted to reduce the temperature of buildings without the need for power consumption (Hanan, 2014). Designers are using innovative ways for efficient systems or designs that eliminate or reduce the need to use mechanical heating or cooling and use renewable energy sources. The main focus of the designer is on thermal comfort of the users. By applying passive cooling techniques, they aim at improving and making the interior of any building more comfortable and reduce energy consumption and its negative impact on the environment.

There are four main approaches or methods of passive cooling, in order to achieve thermal comfort. These elements are basic yet very crucial in the design for passive cooling techniques (URL-5). These elements are: envelope design, natural cooling sources, hybrid cooling systems, and adapting lifestyle.

The first and foremost is the envelope design, as façade of the design covers the whole building, it's important to consider the form and material of this layer of skin to achieve maximum results in form of energy consumption and heat gain. The second important aspect is focus on natural cooling sources and designing good air movement and ventilation system aiming for maximum efficiency. Considering different techniques like evaporative cooling, courtyard effect and venturi effect. The third approach is hybrid cooling systems. In this approach the whole building has a variety of cooling solutions which includes the use of both, the passive and mechanical cooling. The main objective is to use both the methods where they are applicable and efficiently. The fourth approach, that is more user based, is about adapting lifestyle. In this approach the user has the control of adopting his living patterns to adapt with the climate. This approach encourages decreasing the use of mechanical cooling and living more sustainable lifestyle.

2.1.2. Traditional elements used for passive cooling

In earlier times, as can be seen in the vernacular structures, the design had all necessary architectural elements that were required to tackle the natural conditions of that particular region and provide indoor thermal comfort. Vernacular architecture has always focused on these methods and design elements, to achieve thermal comfort. The use of available material and simple techniques in respect to their region and the surroundings made their living spaces comfortable without the use of mechanical cooling technology as we have today. A few of the most successful passive techniques that have been used in the hot climatic regions are *mashrabiyas*, *malqaf* (windcatchers), *roshandaan* (a combined ventilation window/screen and skylight), *jali* (screens), courtyards and waterbodies.

Mashrabiya

The term *mashrabiya* is of Arabic origin, meaning 'a place for drinking'. In the past times, drinking water in clay pots was placed to cool down in a *mashrabiya*, by evaporative cooling technique. When winds passed through the intricate shaded wooden lattice screen and then the porous clay pots surface, the water temperature decreases inside the clay pots placed there. Figure 2.2 shows the mashrabiya and its section which explains the mechanism.

They were typically carved out of wood. The artisans would patiently dovetail the pieces together without nails or glue to allow the wood to shrink and warp under high temperature and adjust itself (Feeney, 1974; Kamath and Daketi, 2016).

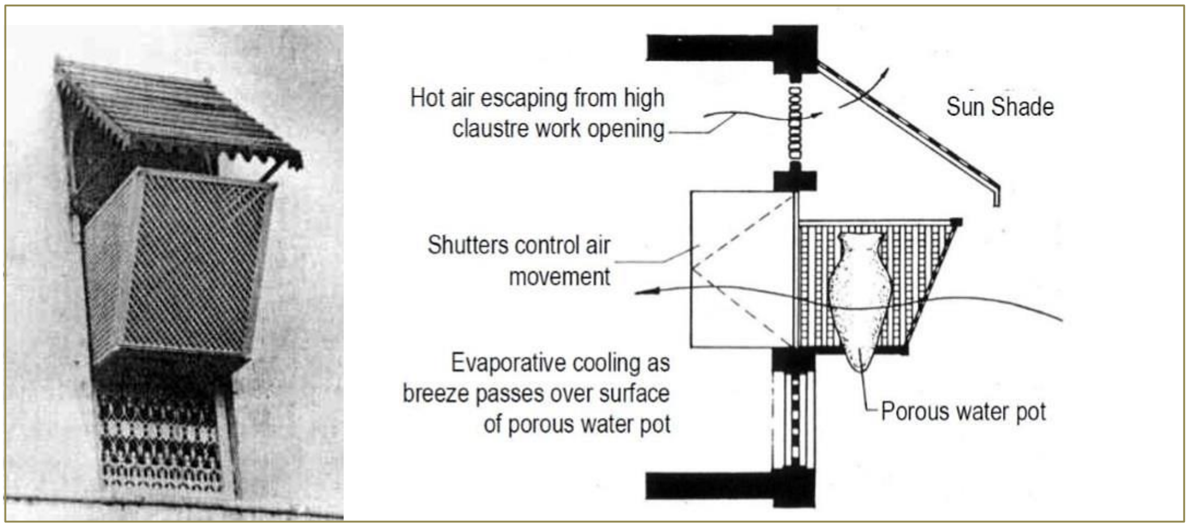


Figure 2.2. A mashrabiya that was commonly used in Muscat. The section of a mashrabiya showing its mechanism (Schiano, 2007)

Malqaf

The *malqaf* (windcatchers), can be found in Asian regions which were historically influenced by the Persian Empire, where it is referred as *badgir*. It takes the form of a tower, usually built in fixed position on the roof.

The *badgir* tower is like a chimney whose end is in the underground and the top is set over a specific height on the roof and were built at the entrance of the house over underground water reservoirs or ponds built inside the house. (A'zami, 2005). Due to the difference in air pressure on the wind side and leeward side of the house, air circulation is constant resulting in removal of stale humid air and cooling effect is achieved by enhanced evaporation caused by the airflow. Figure 2.3 and 2.4 show sections of different windcatchers in Iran and Egypt and its function.

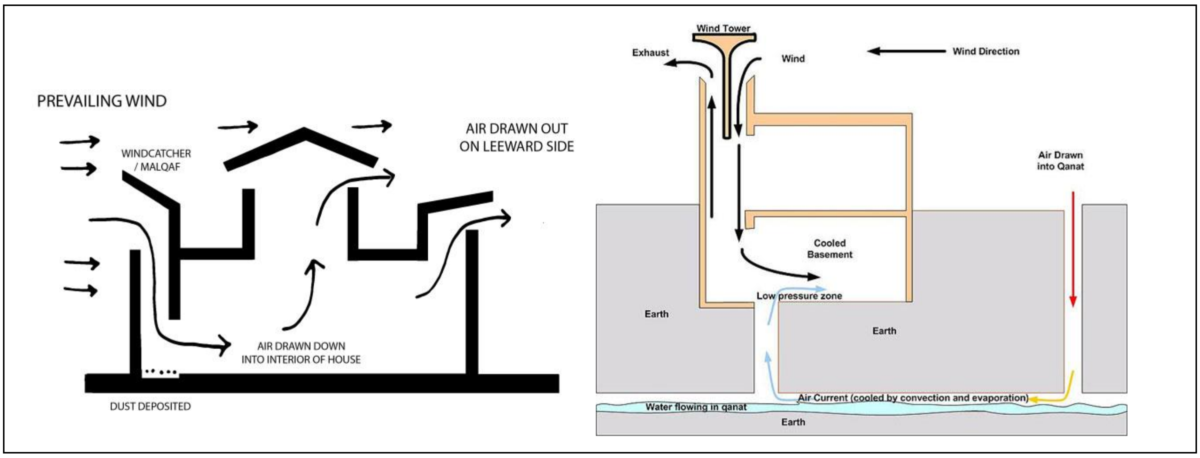


Figure 2.3. Windcatchers section, conventional windcatcher used traditionlly in Arab and Persian vernacular architecture (Kohlstedt, 2017; Mohammadi, 2009)

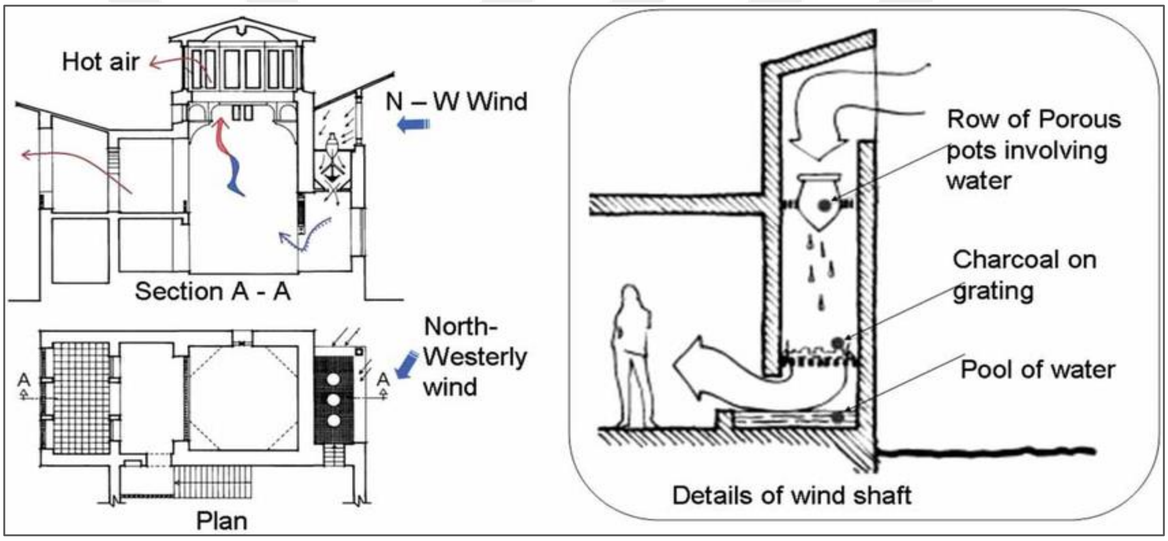


Figure 2.4. Section of renowned architect Hassan Fathy’s design at Maziara, Egypt. Pottery jars used to cool air along with malqaf (Schiano, 2007)

<u>Screens or Jali</u>

Jali (in Urdu vocabulary) refers a fine web or net. In architecture of the Indian subcontinent, a *jali* refers to an ornamental screen that is perforated in different geometrical shapes used as a buffer or a permanent curtain. As privacy was is a major concern in this part of the world, it proved to be very efficient along with its passive cooling characteristics.

As a shading device it is an egg crate, a combination of horizontal and vertical shading device at a minuscule scale. It appears to be 2-dimensional, but the thickness along with the interlinked balusters forms many small devices equivalent to a large overhang. (Kamath and Daketi, 2016).

Jalis or screens have been a significant architectural feature of many decades. In earlier times these structures did not only play aesthetic role in a building design but also played major role in tackling the natural conditions in buildings ventilation and lighting. (Figure 2.5) These passive cooling and lighting screens have been part of many different regions design and architectural techniques which results in different use of materials and designs. Most of the regions with hot climatic conditions have been using the screens efficiently and has been a part of their building practices for years (Kamath and Daketi, 2016).

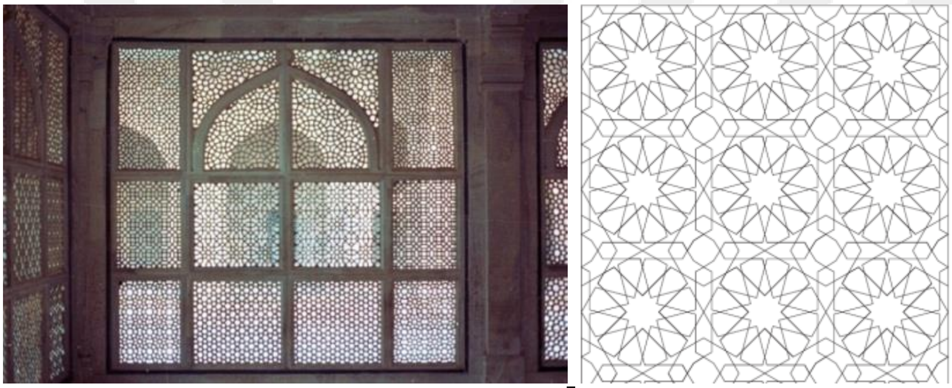


Figure 2.5. Jali at Tomb of Salim Chishti, Fatehpur Sikri (Godel, 2011) Patterns tessellation, similar example from Syria (Broug, 2006: 88-98)

Characteristics of a jali can be mentioned as repetition, infinity and symmetry. Furthermore, Kamath and Daketi (2016) lists the main properties of a jali as follows;

- The jalis are mostly in geometric form which means the module is repeated. Complex patterns are usually made on grids. The composition of the modules usually consists of squares, triangles or hexagons.
- Since the patterns are constantly repeating itself they create the illusion of continuity beyond the frames physical boundary, thus making it challenging to identify the overall patterns starting and ending points.
- This intentional repetition is symbolic of infinite nature of God. It is so because Muslims believe that human cannot imagine a stable palace for God. (Kamath and Daketi, 2016)

- The jalis are usually in symmetrical form made by mirroring of the pattern or unit on the selected stone.

2.2. Kinetic Façades for Sustainability

2.2.1. A brief history on kinetic façade

The skin of the buildings or the façades, today are not only building envelopes or an interface between inside and outside. It not only claims for responsiveness to the place specific character and a unique identity; privacy, transparency and energy efficiency; maximum views and minimum glare; materiality *etc*. but asks to resolve a greatly expanded field of parameters as performance. With the advancement in science and technology the idea of kinetic façade has also evolved. The recent advances in material, chemical science and parametric modeling tools act as major catalysts in the understanding and designing of the kinetic and responsive façades.

The concept of kinetics in architectural design approach isn't a new phenomenon as it seems. In the early 1970's, William Zuk and Roger H. Clark, introduced the idea of kinetic architecture to encounter spatial design problems using mechanical systems. Though in mechanical engineering, understanding of the mechanisms and kinetics had started long time ago. It was the works by the early scholars which provided a basic understanding of kinetics and laid the foundation for a number of ideas for the implementation in kinetic façades. However, these researches have been fruitful for the understanding and in the development of the complex mechanisms design; there is no further work on the use or implementation of these kinetic compositions and mechanism on building façade, for creating responsive kinetic façade. Table 2.4 represents a historical background on the development of the kinetics on the theories of mechanisms used in the mechanical engineering.

It is noteworthy that not only mechanical engineers helped in the development of the understanding of the kinetics and the sense of motion but also artists played a major role aswell. The kinetic sculptors completely changed the idea of art being static. Majorly intrigued and inspired by the natural environment, they explored materials and designed dynamic kinetic sculptures, that later became a source for inspiration in the development of the kinetic façades. Table 2.5 represents a brief description of the artists and their work, followed by Table 2.6, representing the use of kinetic patterns in installations.

Table 2.4. Mechanical engineering to kinetic architecture (prepared by the author)

History of the mechanisms used in the mechanical engineering, leading to the use of Kinetics in architecture	
• 1724 -1739, Jacob Leupold (engineer)	• published a book called *Theatrum Machinarum,* explaining about this basic mechanism. – reviewed and discussed number of significant basic mechanisms – suggested a machine consists of number of basic mechanism in which it has its own function.
• 1772-1779, Kristofer Polhem (engineer).	• Created Letters from a Mechanical Alphabet, – It consisted of a series of small wooden objects that describe the mechanical elements.
• 18th century end	• More scientific study of mechanism – The *Ecole Polytechnique* introduced the subject in their syllabus as “analytical geometry”. It categorised mechanism by the type of transformation of motion their demonstrated.
• 1875, Franz Reuleaux	• Theoretische Kinematik, (extensive scientific analysis of mechanism) – An attempt to analyse and invent new mechanism which lead to the old-established solutions, which is still better and significantly practical
• 1970, William Zuk and Roger H. Clark	• Introduced Kinetic Architecture

Table 2.5. Kinetic Sculptors and their major contributions in kinetic compositions (prepared by the author)

Artists who played a significant role in the understanding of the kinetic movement, patterns and composition.	
• Ruben Hyden Margolin	• Kinetic Sculptor, – nature inspired kinetic compositions inspired – demonstrate the ingenuity of kinetic composition that focuses on geometry and mechanical movements.
• Theo Jansen	• Kinetic sculptor, – His massive sculptures demonstrate the manipulation of kinetic movement through simple adaptation from wind energy and lightweight structures and mechanisms – His works demonstrates the significant role of artists in composing kinetic forms that influence kinetic facades
• George Rickey	• Kinetic Sculptor, – successful kinetic works is the slow and graceful movements of Rickey’s Counterweight – Based on the observation and experience from nature he wrote a theoretical text called ‘*Morphology of Movement’*.
• Len Lye	• Kinetic Sculptor, – His approach was slightly different as he believed film and kinetic sculpture as aspects of the same “art of motion”,

Table 2.6. Responsive kinetic patterns used in installations (prepared by the author)

The installations focusing on kinetic patterns and responses in architecture.	
• Chuck Hoberman (Engineer/ Artist)	• The creation of kinetic components that are expandable for adaptable design. (prototype and full scale building component). – Hoberman sphere, well-known for illustrating different scales of kinetics. – Hoberman Arch (2002)
• Ned Khan (environmental artist/ sculptor)	• The wind walls demonstrates the kinetic composition that has the potential to be applied as a kinetic façade responsive to the environment. – *wind veil (2011)* – *Wind arbour (2011)*
• Asif Khan (Architect)	• MeganFon Pavillion (2014) – the building's facade transforms into a 3D portrait of a visitor.

Today, the application of responsive elements in a building, such as kinetic facades plays an important part in a building's operation. However, the architectural design principles and construction methods of kinetic facades have been under explored (Park, 2011). (Sharaidin, 2014: 29).

Kinetic façades are envelops designed for high performance buildings in response to environmental conditions and for aesthetics. These facades are designed with actual motion, through geometric transformation, affecting the physical structure or material properties of the façade only, retaining the structural integrity. In parametric design, as there are no conventional hard and fast rules or set of standards, the most crucial and challenging aspect is the character selection of the parameters. This stage of the designing process in parametric design is highly dependent on architect's creativity and vision. The selection of the basis of parameters can be completely based on random numbers or on the other hand existing factors related to the site and user requirements can be taken into consideration.

The kinetic design has a major role in responsive façade designs (façade that respond to the environment). Despite the fact it looks simply, these designs are complex and not to create as they are not just design elements they are created to respond in a certain manner to their changing environmental conditions. Table 2.7 shows the kinetic façades that changed the use of kinetic patterns just for the kinetics itself but in response to their environment. The architectural examples, to name a few that have revolutionized the façade design from being static curtain to a living/ breathing skin, are stated below in Table 2.7.

Table 2.7. Kinetic façades, responsive to surrounding environment (prepared by the author)

Kinetic façades Responsive to environment	
Richard Neutra	1962 - LA County Hall of Records (responsive brise-soleil)
Buckminster Fuller	1967 - American Pavilion 67
Jean Nouvel	1987 - Institut du Monde Arabe, Paris
AEDAS	2012 - Abu Dhabi Investment Council

Institut du Monde Arabe, is a remarkable work of Jean Nouvel in collaboration with Architecture-Studio, completed in 1987. Figure 2.6 shows an example of a kinetic façade that is designed based on geometry, aesthetics and responsive towards the environment. The façade demonstrates kinetic geometric patterns and compositions which are made of 25,000 photoelectric cells which work similar as a camera lens aperture. This façade design was ahead of its time, which opened the doors of further research and ideas. Though over the period of time, it went through a lot of critique, as it didn't perform in a way it was designed and expected to, due to mechanical failures, many of the shutters failed to respond to the environmental conditions. However, Institute Monde Arabe's facade demonstrates a surface designed to respond to the environment and this lead to the use of kinetics in architecture for further exploration, for more efficient and responsive façade designs.

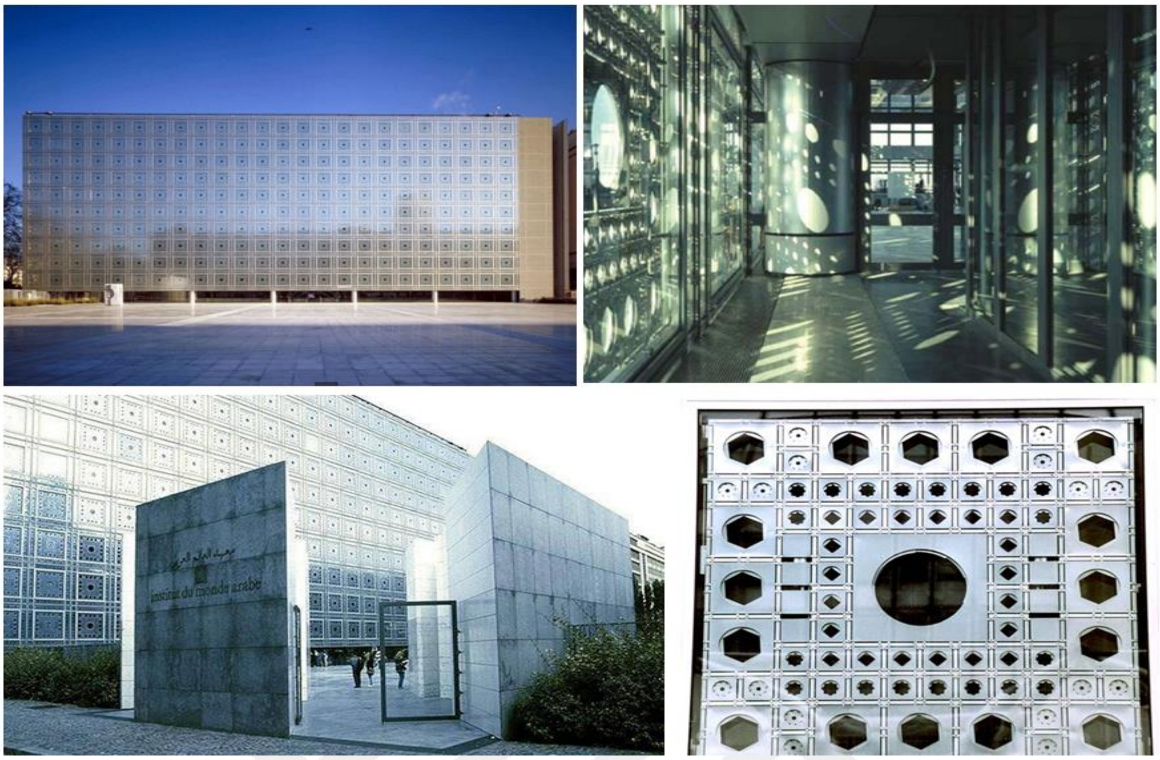


Figure 2.6. Institut du Monde Arabe, Jean Nouvel. The facade's mechanical apertures respond to the daylight, controlling the buildings thermal exposure and with the interior lighting (Michler, 2010)

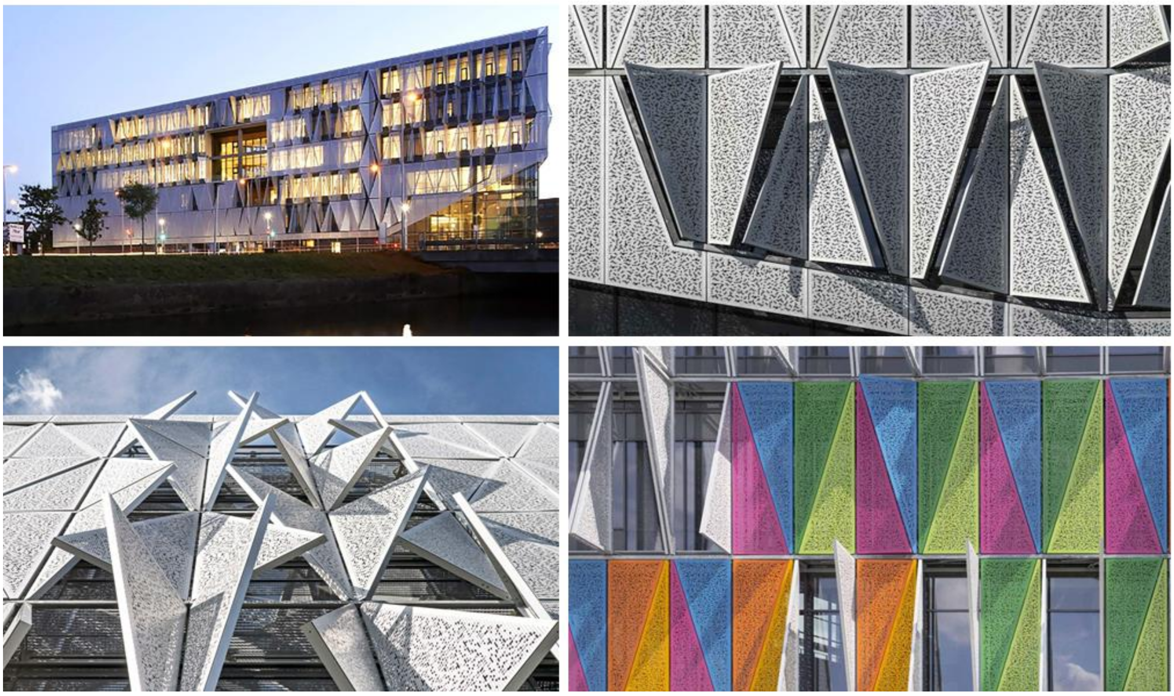


Figure 2.7. University_of Southern Denmark Kolding Campus Henning Larsen Architects (Grozdanic, 2015)

The Syddansk Universitet communications and design building in Kolding, Denmark, as shown in Figure 2.7, is considered as a fine example of a climate-responsive kinetic facade that regulates interior temperatures and it is believed that the energy consumption is reduced up to 50 percent compared to the other buildings or similar nature of use. The facade comprises of around 1600 perforated metal screens that are designed and placed with the sensitivity of the site and these screens control the natural lights intensity reaching the interior. (URL-6).

With the advancing interest in kinetic façade designs, it is observed that can be used to control a lot of factors which initially was impossible, for instance with these smart facades the designer can control some of the aspects, naming; light, air, energy, and even information. As shown in Figure 2.8, the facade reduces solar gain as well as allows the fresh air into the building.

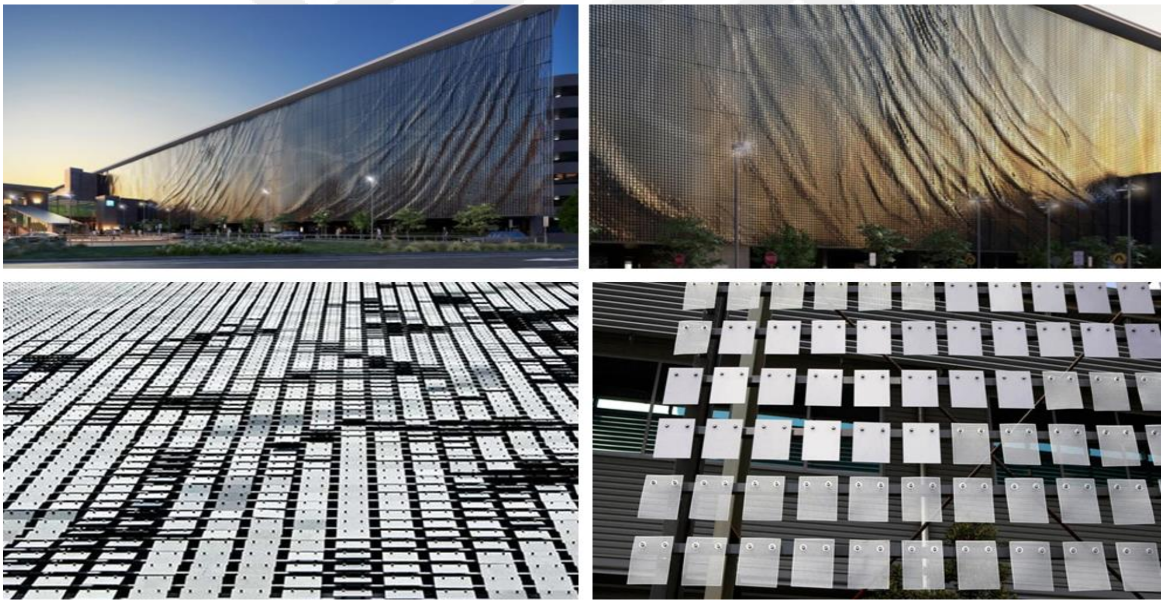


Figure 2.8. Turbulent line, Brisbane Airport, Australia (Kahn 2012)

In Figure 2.8, the Turbulent Line (Brisbane Airport), 250,000 aluminum panels are hinged on the 5000 square-meter facade of a new parking structure at the airport. As the wind blows, these aluminum panels appear to be motion, making the entire wall appears to be kinetic. The movement creates the impression of waves. Inside the building due to the kinetic facade and the sunlight a natural tree shadow like ambiance is experienced, the light and shadow creates interesting intricate patterns, making it more experiential for the visitors. (URL-13).

The kinetic pattern plays an important role in the design process and the movement of the individual of combined components of the façade or skin of the building. The visualization of the interaction between parameters over time provides a strong idea for conceiving the variables, which determine the kinetic pattern (x and y axes, with the time represented as the vertical axis) (Moloney, 2011, Sharaidin 2014: 65). Variables as described by Moloney (2011) are in form of geometric transformation; expanding, contracting, folding, transforming, retracting and sliding. In architecture design, the literature for the kinetic design commonly use these variables, though not enough literature is found on the efficiency of these variables, leaving the patterns to be explored for the best possible façade design solution.

In Figure 2.9, the Penumbra system has a series of vertical and horizontal shading elements work both as kinetic and mechanical solution to the shading and lighting problem of the building. To maximize the solar protection the vertical shading louvers pivot independently and to counter the sun’s rays when it reaches an altitude these vertical louvers rotate upward acting as horizontal shading device. As the designer explains it: *“All of the mechanical components and gear ratios were fully resolved, and the result is a hand or computer-operated system that creates a beautiful undulating form across the facade.” Tyler Short.* (URL-15).

Figure 2.9. Penumbra system by Tyler Short (Kurt, 2014)

To sum up, in today's growing technological advancement in every aspect of life, architectural design practice and its execution has also advanced. Possibilities in creating new and dynamic structural forms are achievable in today's design concepts due to the technological advancement, computer aided design tools and contemporary materials.

In kinetic architectural designs, the approach of the architect and requirements of every project varies, as its dependent on the user, surrounding and the building type. These projects are initially designed keeping the user and the surrounding in focus but with the passage of time the surroundings evolve so does the buildings. The weather and user's effects on buildings are inevitable. Only with the passage of time it can be concluded if the design lived to its designated purpose or it resulted as a lesson for further development and improvements, opening doors for further research.

The parametric design and kinetic façades has brought a drastic change in the mindset of architects and designers, as there is a shift from the conventional problem solving in a defined formal solution to an entire new dimension where there are countless possible outcomes. Due to these advanced computational techniques, where their role is confined to drawing shapes only but has progressed to creating formal possibilities. It's the transition of using computer aided design tool software just for the representation sake to the point that it has become a design tool itself. The use of algorithms and various software is undoubtedly a new paradigm. (URL-10).

In the world of architectural design, the kinetic façade is the new present and the coming future of the façades. It is constantly progressing and putting forward new challenges, addressing new problems and finding new solutions.

2.2.2. Passive Cooling Systems through Kinetic Façades

<u>Responsive façades</u>

As technology is advancing and better tools are used, to evaluate available data such as climate, surroundings of the building, temperature, air quality, sunlight, *etc*. more options and ideas are generating to solve the sustainability and energy issues. Technology has undoubtedly transformed our abilities, to manage the competing claims of façade and to discover new creative, more expressive possibilities.

From energy producing algae façade as shown in Figure 2.10, to a thermal metal screen (Figure 2.11) that curls up when it's hot, to a titanium dioxide-covered wall that scrubs the air of pollutants, as shown in Figure 2.12. The lattice designed tiles acts as a protection layer which slows the speed of the wind to react with the titanium dioxide paint. The paint reacts with the sun's ultraviolet rays, breaking the smog's hazardous chemicals into safer ones. (Wolfson, 2013).

These ideas are inspired by the core source of inspiration, our mother nature. So as a resultant all the disciplines of science and nature work together in this process of designing a responsive façade.

Figure 2.10. BIQ, algae façade (Bernadette Grimmenstein / IBA Hamburg GmbH, 2014)

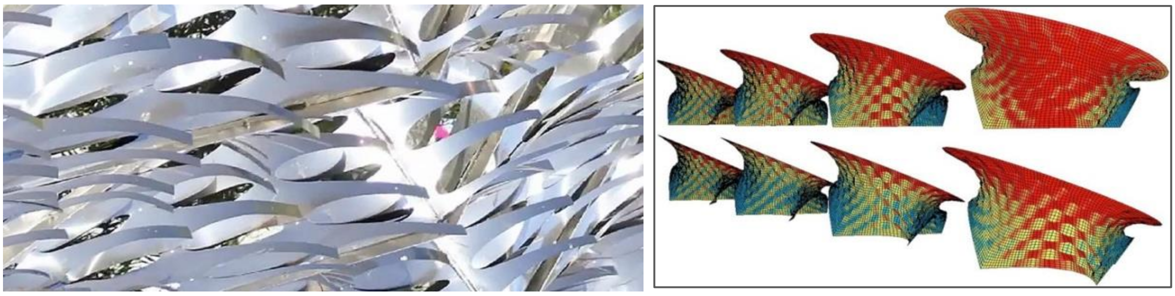


Figure 2.11. Thermo-bimetals. Bloom pavilion, Los Angeles (Sung, 2012)

Figure 2.12. The Torre de Especialidades The smog fighting façade (Wolfson, 2013)

In high performance smart buildings, one of the main features is kinetic façades which are responsive to surroundings. The responsive façade has kinetic climate-adaptive elements including sensors and automation, along with the user or designers ability to dominate and control the settings. The computational algorithms can be controlled by the users in response to their requirement and environmental conditions at the same time these algorithms allow the self-adjustment of the system of the building and to learn over time. Learning takes place in accordance with changing environmental conditions and inhabitant preferences, such that the algorithm anticipates desirable configurations (Velikov and Thon, 2012).

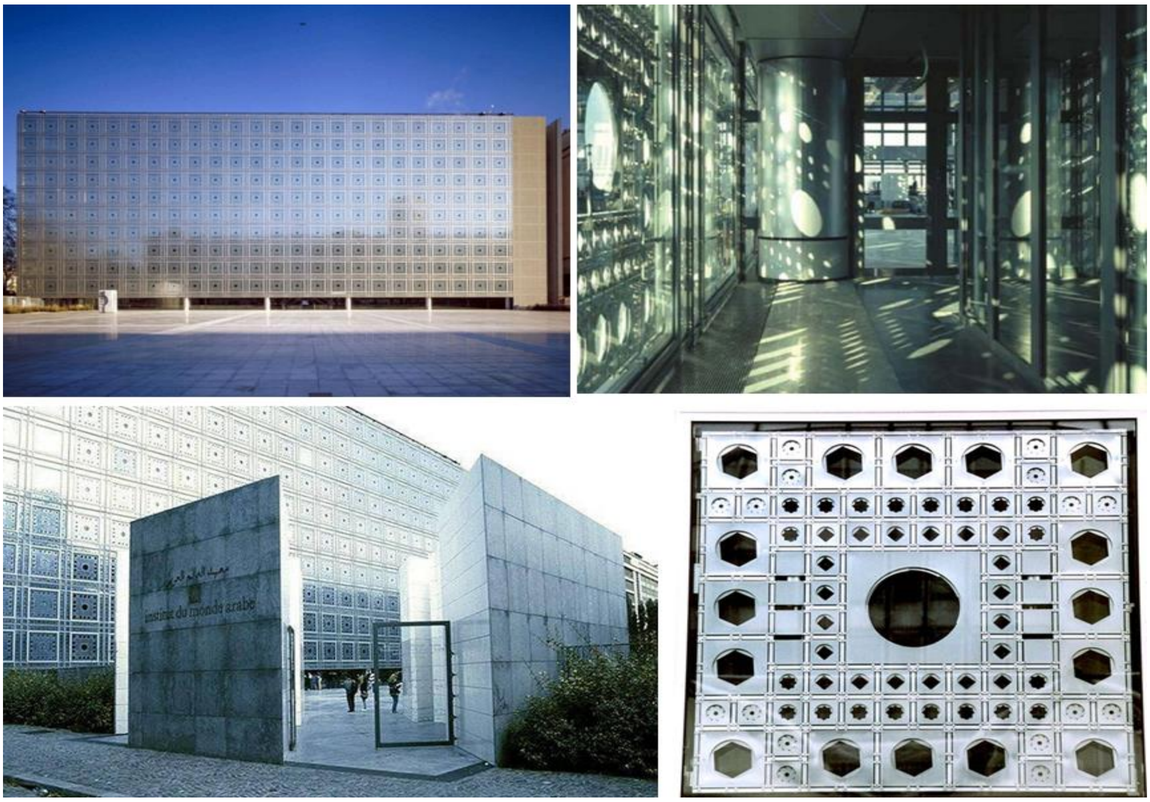


Figure 2.13. Institut du Monde Arabe, Jean Nouvel (Michler, 2010)

Responsive facades examples vary from the location to location as the main objective is to achieve an environmentally responsive facade for maximum efficiency and energy conservation. Every region has its own challenges when it comes to design problems, but the most challenging ones are the designs for hot arid climate regions. The buildings in hot arid regions require more energy especially if it's a high-rise building as the demand for cooling and thermal comfort are the main focus, making the facades the most vital part of the design not only for its aesthetic appeal but also its practical aspects as a membrane covering the building and accommodating efficient thermal performance. Al-Bahar Towers in Abu Dhabi, Institut du Monde Arabe in Paris (Figure 2.13) and Simons Centre at Stony Brook University in New York (Figure 2.14) are pioneering examples of responsive facades, designed for specific site conditions and situated in different contexts.

Figure 2.14. Simons Centre, Stony Brook University in New York (Hoberman, 2010)

Case Study: Al-Bahar Towers, Abu Dhabi

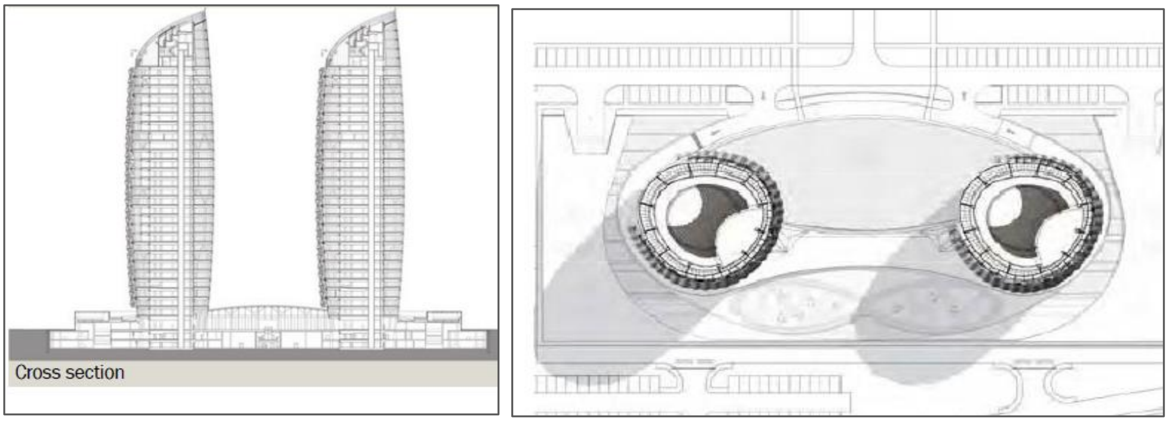


Figure 2.15. Al-Bahar Towers, Abu Dhabi, cross section and site plan (URL-2)

Al-Bahar Towers is an extraordinary example of the kinetic façades and state of the art technology. This case study is considered very significant in terms of this research as it is an example of kinetic façade inspired by the traditional Arabic mashrabiya and its function. The mashrabiya's cooling and light diffusing concept is used in amalgamation with the inspiration taken from nature. On the other hand, this case study also uses triangular modules that open and closes in response to the sunlight which seemed very relevant for this research and the understanding of the design process performed in this thesis in Chapter 4. The main focus of this study is to understand and analyze how the kinetic screen responds and how energy efficiency is achieved in a hot climate of Abu Dhabi.

Al-Bahar Towers also known as Abu Dhabi Investment Council (ADIC) Headquarters Tower 2, are located in Abu Dhabi, United Arab Emirates. The main purpose of these towers is as office buildings which was proposed in 2008 and within four years in 2012, it was completed. It is considered amongst aesthetically and functionally successful projects by the architects team involved in the project, design by Aedas, UK and Architect of Record, Diar Consult. But, since this project is not only an architectural marvel it is engineered to perfection for which the credit for structural engineering goes to Arup.

Design concept of the building

The Al-Bahar Towers design concept, as per Aedas is based on the principles of Islamic geometric compositions in Islamic art and architecture. The form was generated using the principles of these geometric compositions. The concept fuses the inspiration taken from the Islamic geometry and biomimicry, taking the circle as the main element, as Aedas put it “the circle and rotation reflecting the concept of unification and unity evident in nature; an important concept in Islam and in the emerging science of biomimicry” (URL-2). Using this concept along with the parametric design approach the defining geometry was generated for the towers. (URL-2) Figure 2.16 and Table 2.8, briefly explain the design inspiration and the aspects taken into consideration.

Table 2.8. The three major factors taken into consideration while designing the towers

Islamic Architecture	Nature as an inspiration	Sustainability
Subtractive Geometry	Development of form	Shading system
Pattern Composition	Supporting structure	Multi layered skin/façade
Solar Treatment	Energy efficiency	Renewable energy
Ambience Treatment	Skin adaptation	Air circulation

Figure 2.16. The inspirations for designing the towers skin (Karanouh and Kerber, 2015)

Architectural properties of the building

In the Al-Bahar Towers, the towers floor plates are made of six tangential arcs, linked to the building profile to form an additional arc and includes a circular core in the middle (Figure 2.17).

- Flexibility of zoning and orientation due to the form.
- The towers have simple cylinders, a circular plan providing the most economical wall to floor ratio, providing maximum volume with minimum surface area.
- Preliminary solar analysis showed that most solar exposure on east and west elevations and that north elevation requires minimum protection. (URL-2).
- The geometric composition of the towers is designed by the intersection of the infinite arrangements of the circles and spheres which generate infinite arrangements of nodes.
- Various relationships generate as a result of these nodes interpretation and links, as shown in Figure 2.17 and 2.18.
- Plant floor at level 17 contains ventilation plant for tower accommodation, additional water storage, intermediate chilled water pumps and associated electrical switching and life safety equipment.

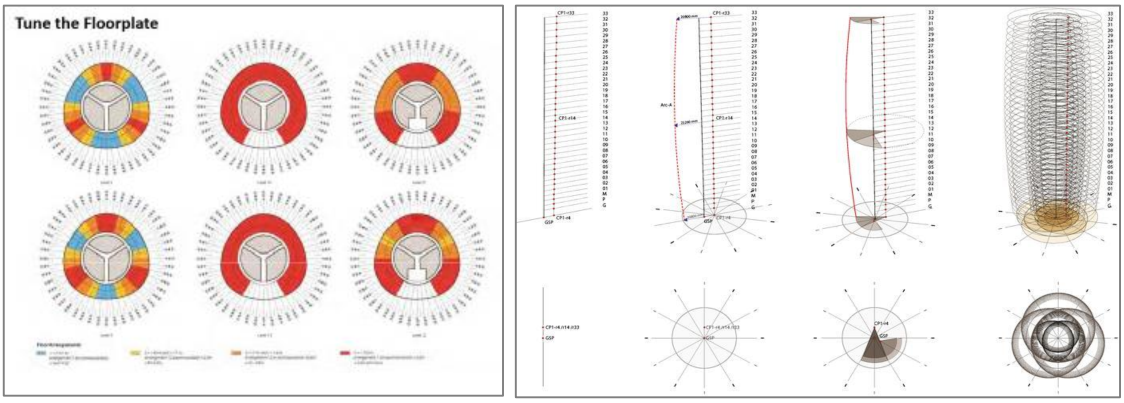


Figure 2.17. The Al-Bahar Towers form and floor plates were generated from arrangements of tangential circles dictated by an underlying radial grid (Aedas 2012)

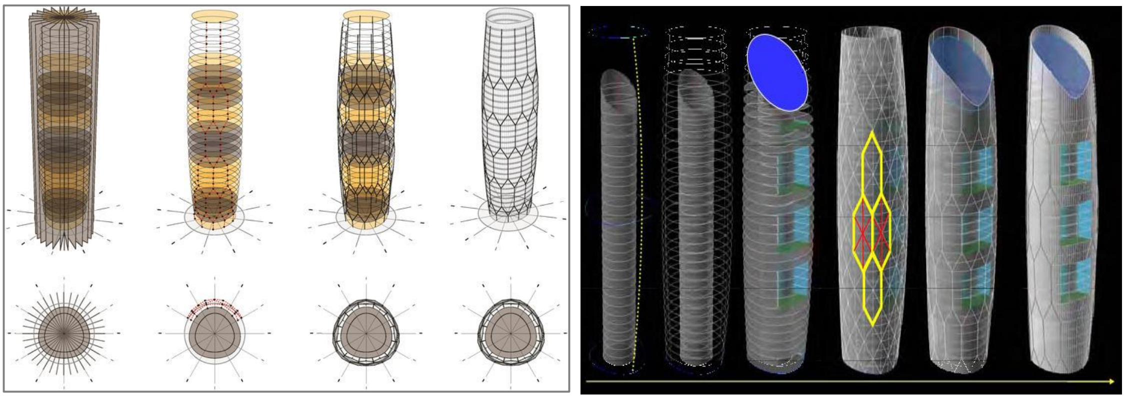


Figure 2.18. The Towers curtain-wall and honeycomb structure were defined by the linking of nodes generated from the intersection of tangential circles (Karanouh and Kerber, 2015; Aedas, 2013)

The importance of façade design

While the towers were being designed and the form development was in process the designers and engineers were focused on protecting the towers from the solar heat gain. Taking inspiration from the vernacular architecture of the region to combat the heat gain from the facades, the mashrabiya became the focus of the main design. Mashrabiya is an architectural term used for a wooden lattice screen for privacy, diffused light and cooling of air. This vernacular architectural element is reinterpreted by the designers at the Al-Bahar towers in form of a screen with numerous of translucent lotus inspired components as shown in Figure 2.19, which are scripted to open and close in response to the sun's movement and light as represented in Figure 2.20.

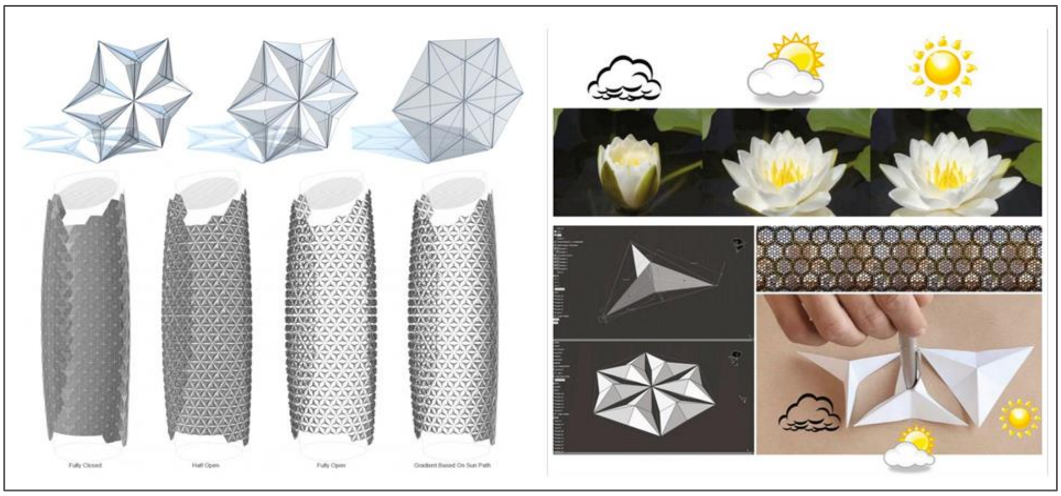


Figure 2.19. Inspiration from lotus flower and its response nature, used to develop the kinetic skin of the towers (Aedas, 2013; Richters, 2013)

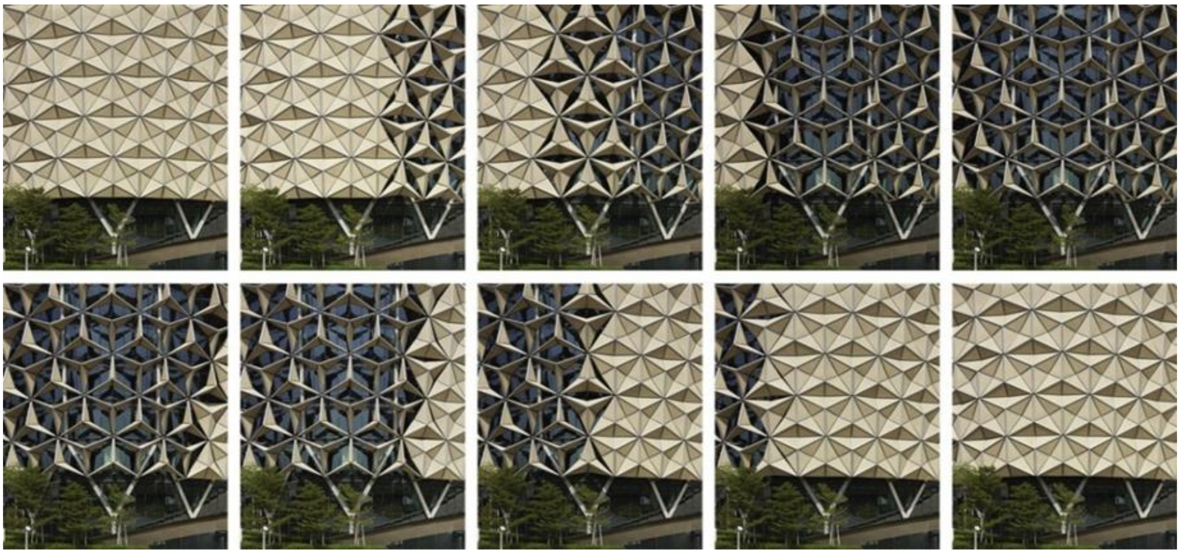


Figure 2.20. Inspiration from nature and integration of processes form development: Supporting Structure, Skin Adaptation, Energy Efficiency (Aedas, 2013; Richters, 2013)

By pre-rationalizing the underlying buildings geometric principles, starting from developing the form, the structure and the envelope along with the designed skin as an adaptive solution a total integration system was achieved, as shown in Figure 2.21 (URL-2) An experiment was performed on different parts of the buildings, in order to explore and find out the impact of mashrabiya's performance with different configurations. This study was based on shading as initially the studies were performed without mashrabiya's and later with the mashrabiya's with different configurations and various faces of the buildings (Figure 2.22).

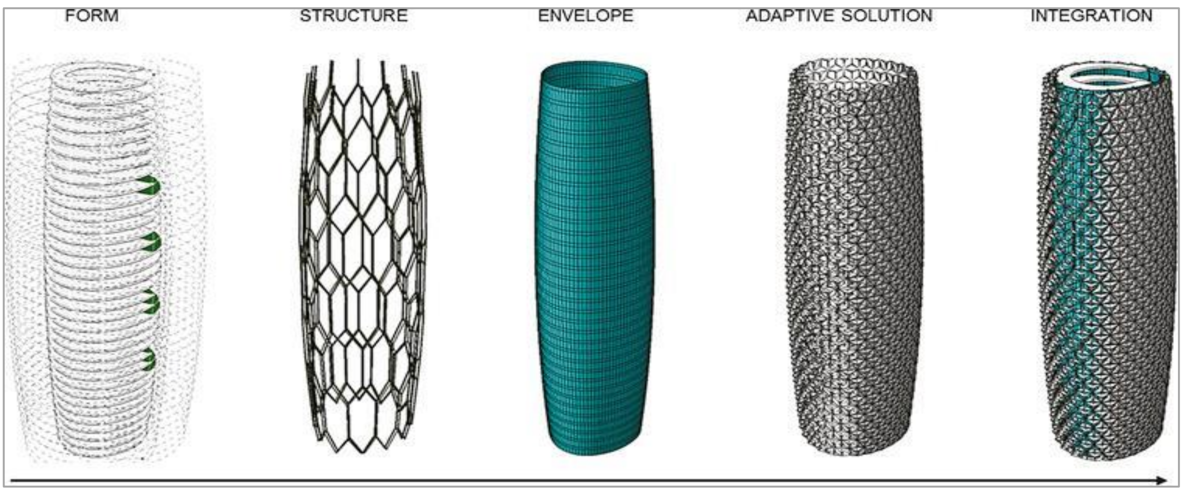


Figure 2.21. A total integration system (Aedas, 2012)

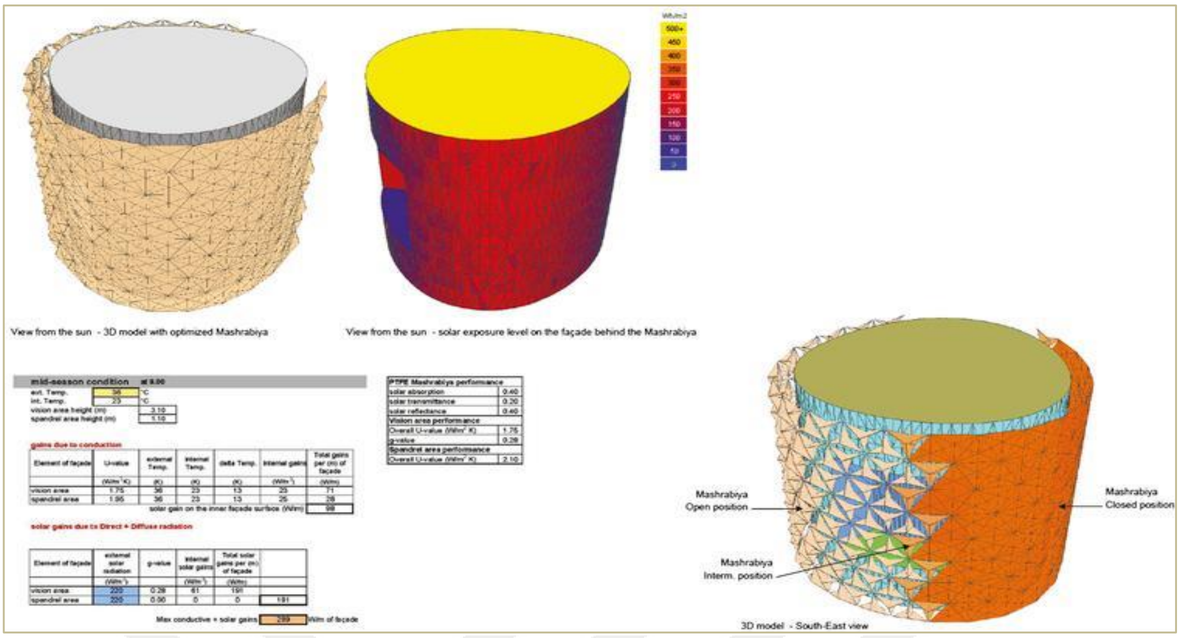


Figure 2.22. The facade opening and resulting improvement in energy performance during mid-season at 9:00 am (Karanouh and Kerber, 2015)

The following automation conditions are extracted from Opening Configurations Principles: If solar rays land on the curtain-wall:

- between 00 and 79 degrees → Un-folded configuration
- between 80 and 83 degrees → Mix-folded configuration
- greater than 83 degrees → Fully-folded configuration

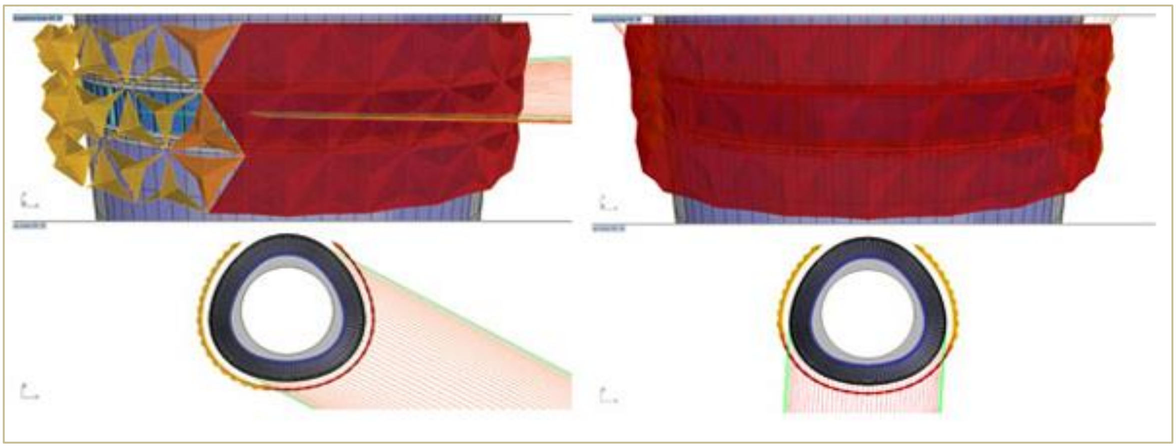


Figure 2.23. The mashrabiya dynamically reacting according to these principles during solar simulation (Karanouh and Kerber, 2015; Aedas 2012)

Custom designed computer application was used to stimulate the operation of the automated screen as it responds to the sun’s movement. (Karanouh 2015) In high rise buildings (designed in hot arid climate) use of heavy tinted glass is commonly observed to reflect direct solar radiation, resulting in poor daylight inside the building, poor views and excessive use of curtains or blinds.

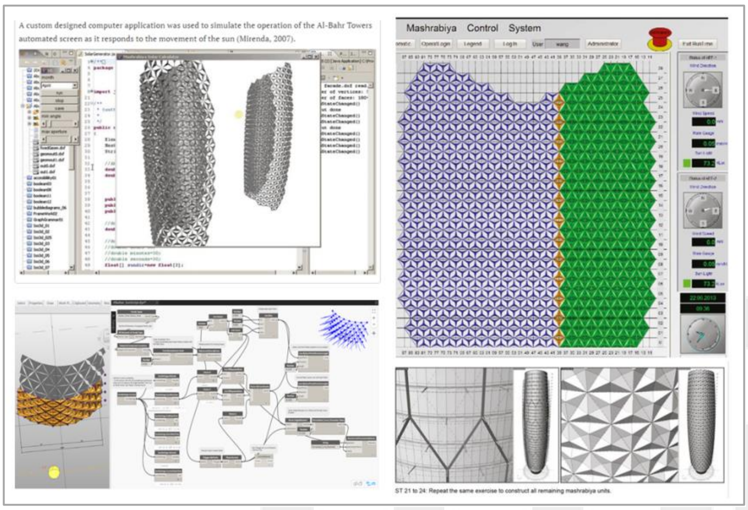


Figure 2.24. The software for the dynamic facade offers clear information and control (Mirenda, 2007; Aedas, 2012)

The dynamic skin has linear actuators that drive the shading devices to respond and reduce the solar gain, eliminating the use of tinted glass as a result there is a reduction in the use of artificial lighting as well, as shown in Figure 2.25. This is the first time such a moveable façade has been used at this scale, enabling a reduction in solar gain of over 50%, as the graph represents in Figure 2.26. (URL-2)

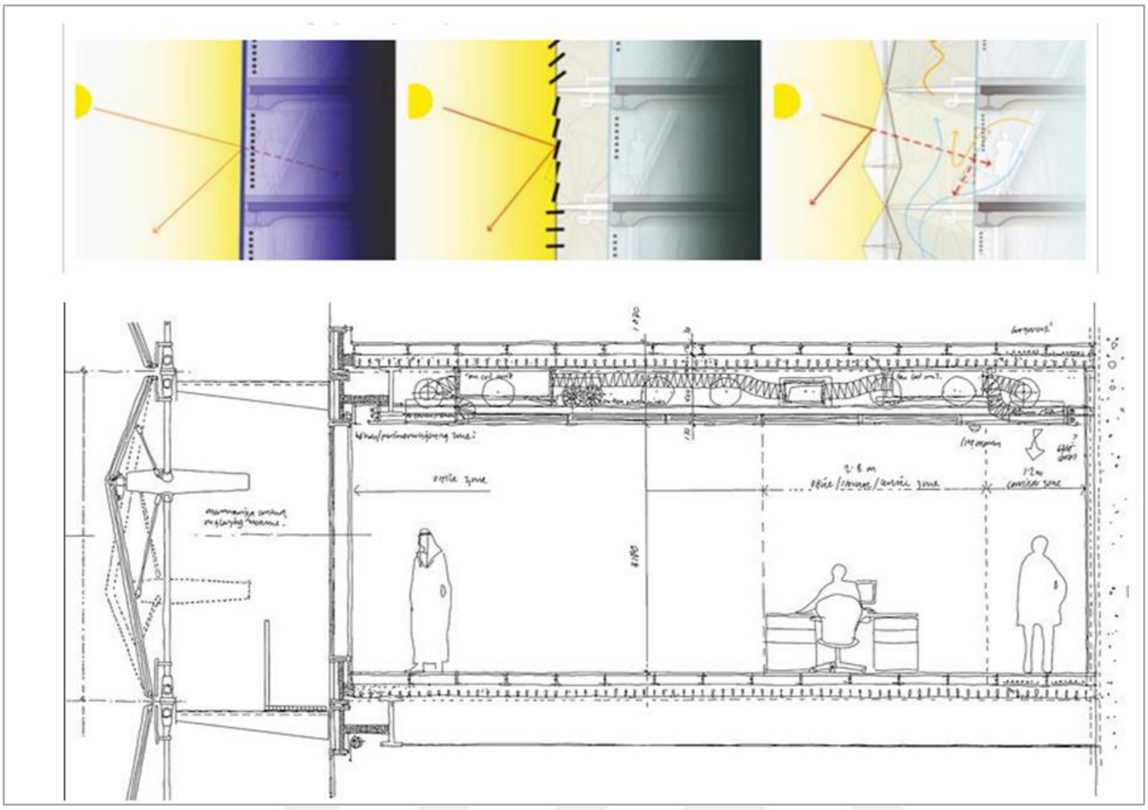


Figure 2.25. The section of the Al-Bahar tower showing the double layers of the facade (Karanouh and Kerber, 2015)

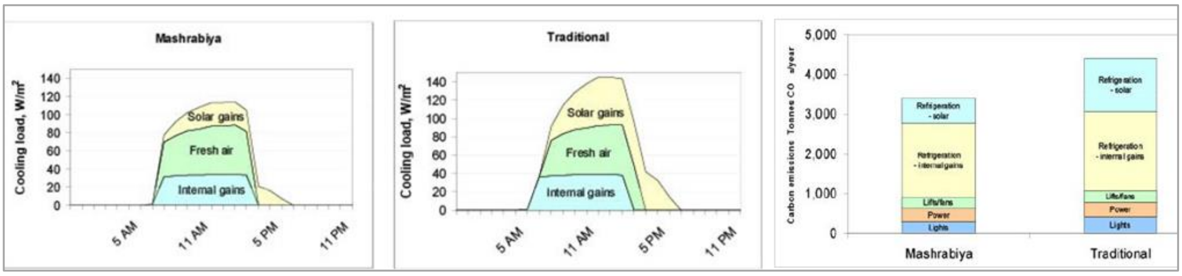


Figure 2.26. The comparison of cooling load and the the carbon emission on mashrabiya and the traditional facade (Karanouh and Kerber, 2015)

To sum up, the Al-Bahar Towers represent a successful example of a kinetic façade and a benchmark in the architecture and technology evolution. It has set a new record for the architects and engineers in terms of design and functionality, signifying qualitative and quantitative gains in both design phase and final built product. In present day design practice, where energy efficiency and consumption are major factors, constant innovative tools and ideas are explored and Al-Bahar is a resultant of this approach.

It can be concluded that with inspiration taken from mashrabiya's and the lotus flowers response in nature, along with a hexagon module with the use of a design tool helped them to formulate and bring the vernacular architectural element back to life in their architectural practice, gaining benefit in terms of energy efficiency and aesthetically pleasing designs. The amalgamation of the mashrabiya with the kinetic screen has resulted in a finest example of the use of geometry in kinetic façades, where the function and form are present in complete harmony and perfection.

2.3. Significance of Geometry in Kinetic Façades

Geometric patterns have been a major part of all art and architecture practices since decades and with the passage of time these patterns have evolved and became more complex. The two-dimensional shape evolved with time and wasn't restricted for ornamentation purposes only but also as three-dimensional form in architectural design. With the advancing technology and computer aided design we see these forms play a major role as building skins in modern day architecture designs, kinetic forms and parametric tools.

Since geometry and geometric patterns play an important role in design architectural practice, therefore it is essential for us to understand the significance and the evolution of these geometrical patterns in the Islamic architectural world.

2.3.1. Evolution of geometric patterns in Islamic world

Geometry in Islam was turned to an art form and ornamentation purposes due to constraints of using human or natural figures. For centuries these geometric patterns have been used and have evolved according to the time and the region. These patterns not only show the aesthetics of the craftsmen, but also the extraordinary skills and understanding of geometry in Islam as well. They provide the evidence of no matter how elaborate and complex these patterns are they are based on simple grids. Created by using only a pair of compasses and a ruler, these mathematical complex frameworks are examples of the scientific advances and inventions of the Islamic Golden Age. This chapter investigates the evolution of Islamic geometrical patterns from the surviving buildings of the different regions. The study examines how these patterns evolved over the time and how the great Mughals, who were originally from Central Asia, descended from the ethnic Turks of Mongol, adopted and adapted these patterns in the Indian subcontinents art and architecture. It also attempts to document the historical significance of the patterns, focusing on the patterns used by the artists and craftsmen in making of jali in Mughal art and architecture.

Jalis (meaning fine net/web) or screens have been a significant architectural feature of many decades. These ornamental perforated screens, in earlier times did not only play aesthetic role in a building design but also played major role in tackling the natural conditions in buildings ventilation and lighting. These passive cooling and lighting screens have been part of many different regions design and architectural techniques which results in different use of materials and designs. The major focus of the study is on the importance of the jalis (screens), as decorative architectural elements along with their functional significance.

Geometry in Islamic world

In Islamic geometric figures, circle is the ultimate base of all creation and represents the symbol of unity. The expansion and natural division of this important figure into regular divisions is the starting point for many patterns and it also originates three most essential figures, the triangle, the square and the hexagon. When the circle is expanded from one circle into three circles the first and the simplest figure originates a triangle. As per Critchlow's (1976) cosmological analysis of geometrical patterns in Islamic art and architecture, a triangle represents "human consciousness and the three basic biological functions: ingestion, digestion, and excretion" (Oweis 2002). Expanding the circle further gives us a square, symbolizing earth and materiality, also representing the universe's four main elements: water, earth, fire and air, where as a hexagon symbolizes the heaven.

In Islamic geometrical patterns, most of them are based on polygons and when the vertexes of these constructive polygons are connected, they give birth to the fundamental Islamic patterns, the star-polygons. This fact forms the base for the classification of the patterns, for example all patterns which are generated from an octagon, transforms to an octagon star and are classified under 8-point geometrical patterns and the pattern will be called as an 8-point star and where the two adjacent rays of the star are parallel, resulting in a shape representing rosette leaves, is classified under 8-fold rosette (Abdullah and Embi, 2012).

As shown in Figure 2.27, the illustration shows how to generate 6-8- and 10 fold complex shapes deriving from single polygons.

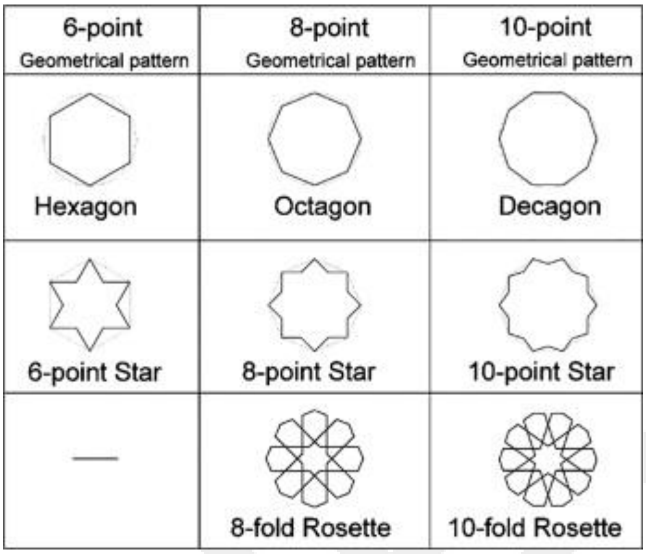


Figure 2.27. Geometrical patterns classification (Abdullah and Embi, 2012)

The geometric patterns in the Islamic World have been used and have evolved with the time, the empire and the region. These patterns don’t just show the aesthetics of the craftsmen, but the extraordinary skills and understanding of geometry in Islam as well. They provide the evidence of no matter how elaborate and complex these patterns are they are based on simple grids. Created using only a pair of compasses and a ruler, these mathematical elegant frameworks are an amazing example of the scientific advances and inventions of the Islamic Golden Age. From the rise of Islam in the 7^{th} century till the 9^{th} century not many original contributions have been made by the Muslims in the field of geometry.

But it wasn’t as if they weren’t progressing, it was during the 8^{th} and 9^{th} century that the Muslims significantly progressed in scientific innovations by translating ancient texts into Arabic and learning different philosophies which undoubtedly increased their knowledge and broadened their visions. By the 8^{th} and 9^{th} century Muslims scientific and technological knowledge had grown in Middle East, Central Asia and Iran and on the basis of that the expansion of geometry in Islamic art and architecture is also observed (Abdullah and Embi, 2012). It was during the 10^{th} century that Muslims original contributions in the field of sciences became significant which was also observed in the complex field of geometry.

The natural division of the circle into regular divisions is the ritual starting point for many traditional Islamic patterns, as demonstrated in the drawings by Henry (2009), shown in Figure 2.28 and Reeves drawings that are presented in Table 2.9.

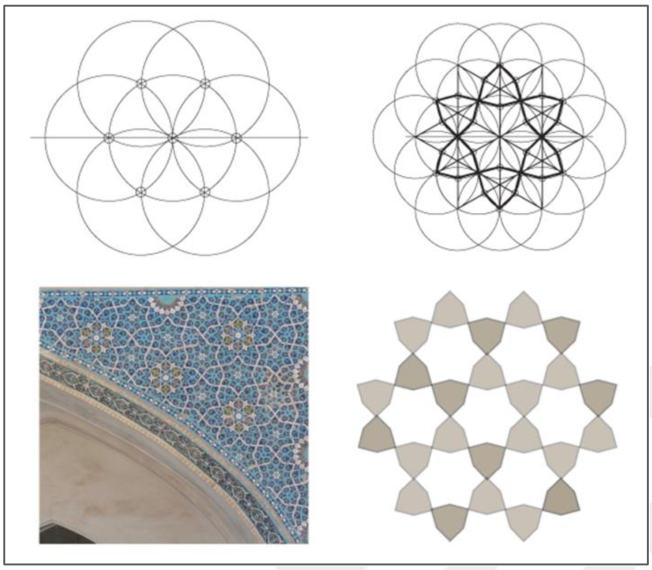
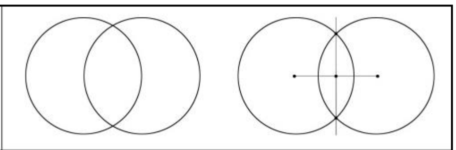
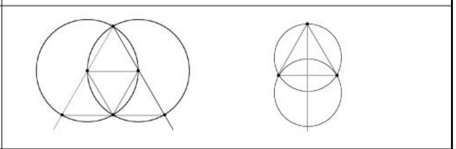
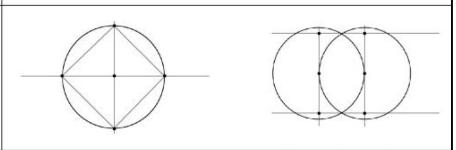
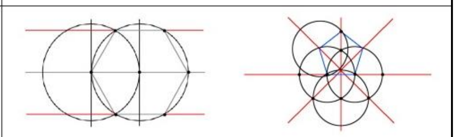


Figure 2.28. Geometrical patterns designed from division of circle (Henry, 2009)

Table 2.9. Significance of Circle (URL-17)

Vesica piscis	
The in-triangle	
The in-square and rectangle	
The hexagon and pentagon	

In Figure 2.28 (URL-9) explains a pattern from Yazd (15th century), Iran. The pattern is derived using the basic shape of that is, a circle. Its six regular divisions form a regular grid of triangles, which acts the base of the design that is elaborated on top of it. It is worth noticing how the complex tracery of pattern interweaves with the basic design which appears in white outline. (URL-9).

2.3.2. Evolution of geometric patterns through the Islamic dynasties

The evolution of the Islamic geometric patterns has been studied and understood by the surviving architectural buildings of the Muslim dynasties. The dynasties that made a major contribution in the development and shaping of Islamic art and architecture can be as follows:

- Umayyad Dynasty (661 to 750 CE)
- Abbasid Dynasty (750 to 1258 CE)
- Seljuk Dynasty (1038 to 1194 CE)
- Fatimid Dynasty (909 - 1171 CE)
- Mamluk Dynasty (1250 to 1517 CE)
- Ottoman Empire (1290 to 1923 CE)
- Safavid Empire (1501 to 1736 CE)
- Mughal Empire (1526 to 1858 CE)

The first Arab monarchy based in present day Syria was established by the Umayyad Caliphs. The Umayyad architecture was based on the mosques and palaces, which reflects the influences and inspirations drawn from the Byzantines and Sassanian empires construction techniques and ornamentation. By the end of 7^{th} century the floral patterns from and ornamentation was common in the Islamic architecture (URL-24). One of the first and iconic surviving buildings of their empire can be mentioned as The Dome of the Rock, Jerusalem (late 600s CE). The façade and the exterior are ornamented with mosaics, the interior surfaces gives the hint of swirling designs with vegetal motifs with gold tesserae (small blocks used for the construction of mosaics) (Botchkavera, 2012). Another example can be mentioned as The Great Mosque of Damascus in which floral ornamentation inspired by the landscape of Damascus (Labatt, 2012).

After the Umayyad Empire, the Abbasid Empire took forward. The works of ornamentation in architecture gained popularity and new techniques and more abstract styles were adopted. Frescos, wood and stone carvings, brick works, stucco and terracotta were extensively used (URL-3). The Great Mosque of Kairouan in Tunisia (built in 670 CE, rebuilt in 836 CE) has elementary geometrical patterns with the floral and vegetal motifs on the building, making it one of the earliest examples of use of geometrical patterns in Islamic architecture (Apelian, 2014). (Figure 2.29). Abbasid Palace of Baghdad (1179-1230 CE) is also a building belonging to this period (Figure 2.30).

Figure 2.29. The Great Mosque of Kairouan. The geometric patterns on the wall around the dome of the mihrab (Mortel, 2012) The pattern drawn by author

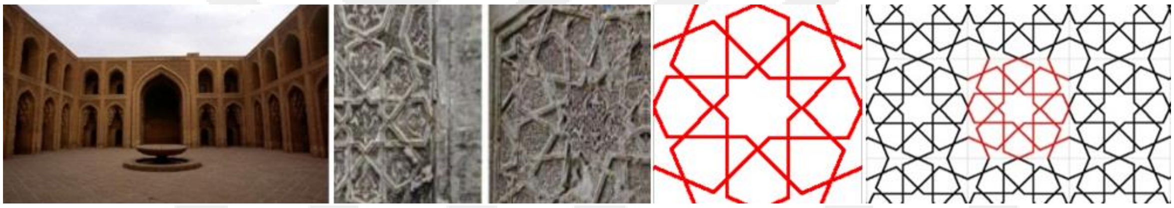


Figure 2.30. Abbasid Palace, the original decorations before restoration. The basic 8-fold rosette pattern (Paolino 2012, Abdullah and Embi 2012) The pattern drawn by author

The Madrasa of Mustansiriyeh (1233 CE) has highly ornamented and detailed muqarnas. The entrances exhibit arabesque-sculpted terracotta and geometric patterned brickwork (URL-13). The earliest examples of six-point geometry, eight and twelve-point geometrical patterns, rosette pattern and eight-point star were observed (Abdullah and Embi, 2012) (Figure 2.31).

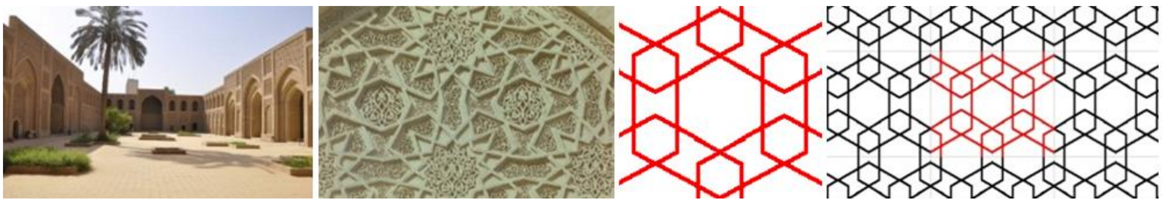


Figure 2.31. The Madrassa of Mustansiriyeh's courtyard (Ministry of Culture-Iraq, 2013) The pattern tessellation drawn by author

It was by the late 8th century that the geometrical shapes were introduced on surfaces but only as individual elements for ornamentation. During the Seljuk Empire, the focus of the Islamic world was more on tombs and madrasas The Seljuk's artistic movement brought transformation in geometric motifs and introduced complex patterns. The use of 10-point geometrical patterns, abstract 6- point and 8-point patterns and unusual patterns made of non-constructible polygons such as 7, 9, 11 and 13-point geometrical patterns was all observed during the Seljuk's era. Among the Early Seljuk architectural examples of tombs Iran's province, Qazvin, tomb towers of Kharaqan (1067-93) can be mentioned. It has an octagonal plan, with double crusted domes and brick walls along highly ornamented panels with different abstract and star geometrical patterns on the façade (Dehkordi 2016: 389-390) (Figure 2.32).

Figure 2.32. The tomb towers of Kharaqan (right) and the brick wall and arch detail (Zereshk, 2008) The pattern tessellation drawn by author

Additionally, the Friday Mosque of Isfahan is the absolute example of Seljuk style, highly detailed and decorated geometrical motifs, made of brickworks, over a plan of four-Iwan style, with earliest examples of heptagon and geometrical patterns used in the decoration of the walls (URL-4) incorporating geometrical patterns (mostly 5 and 8-point star patterns) with the structural elements (URL-8).

The Fatimid Dynasty (like the Seljuk's) six-point stars have also been very popular in their works of architecture, but it was more isolated or sculptural as they didn't cover entire form or surface and always directed towards a focal point (URL-18). One of the Fatimid's remarkable works known till date is The Al-Azhar Mosque (Figure 2.33) and madrasa (970-2 CE and later), decorated with stuccowork floral and geometrical patterns. Ornamentation is on panels and windows along with Arabic inscriptions in six-point star designed in the interior apex of the dome. Later addition of a new façade and mihrab with detailed ornamentation has been made by the Ottomons restoration (URL-1). Also, The Al-Aqmar Mosque (1125 CE), can be mentioned as one of the finest examples with fluted domes, arches, Muqarnas and highly carved facades with Arabic calligraphic, geometric and floral ornamentation (URL-18).

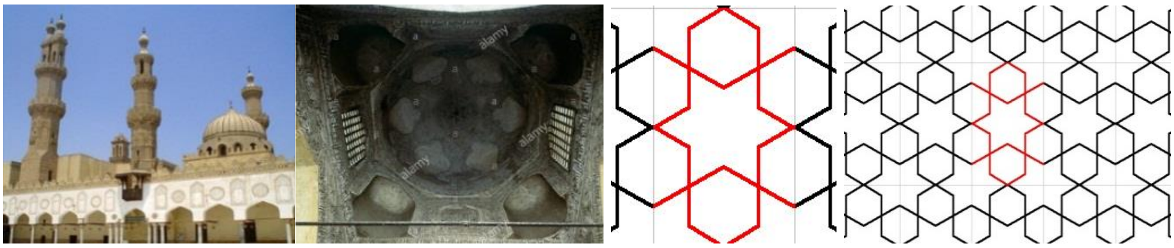


Figure 2.33. Al-Azhar Mosque and the detail of the dorm showing a six-point geometrical pattern (Tentoila, 2006) The pattern tessellation drawn by author

Following, Mosque of Al-Salih-Tala'i (1160 CE) in Cairo like the Al-Aqmar Mosque, the use of six and eight-point star is used in the bas-relief sculptural ornamentation on the walls. (Figure 2.34). During the Mamluks a 12-point geometrical pattern was carved over the Minbar adding to the significance of the mosque and a decorated carved wooden door is also added which shows a fine example of 8 and 12-fold rosette pattern. (Jarrar, Riedlmayer and Spurr, 1994; Abdullah and Embi, 2012).

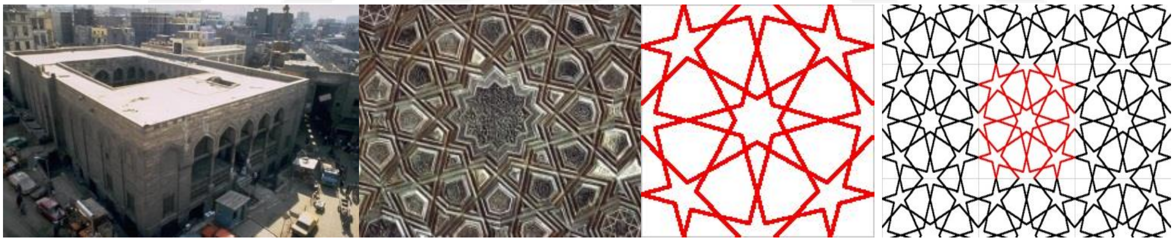


Figure 2.34. Mosque of Al-Salih Tala'i the fold rosette pattern detail in the mosques interior Rabbat, n.d; Wade, 2017) The pattern tessellation drawn by author

After the Seljuk's, the Mamluks period is considered as the second artistic movement. Their architectural ornamentation geometrical motifs were designed more as main focal motifs and less interwoven (Bloom, 1999). 16-point geometrical patterns were an extraordinary feature of the ornamentation of their time. One of the most remarkable works of the Mamluks can be considered as Mosque of Baybar's (1260 CE). Its interior ornamentation has scripts carved in stucco and it has geometrical ornamentation on windows (similar to the 12-point pattern in Kharaqan tombs, Qazvin, Iran). (Abdullah and Embi, 2012) The facade of the mosque has Ablaq (ornamentation using dark and light-colored stones).

Secondly, in the Qalawun Complex of Cairo (1283-5 CE) the surfaces have remarkable geometrical motifs in different techniques such as stucco and marble carvings, wooden inlays and paintings (Madrasa Wa Qubbat wa Bimaristan al- Sulatan Qalawun, n.d). The patterns used majorly in the interior, for the ornamentation over the ceiling, doors, windows and walls are the 6, 8 and 12-point geometrical motifs. (Figure 2.35) The most extraordinary element of the mausoleum is the Mihrab with the 10-point geometrical motif which is considered as the earliest of its type (Abdullah and Embi, 2012).

Figure 2.35. Qalawun Complex (Badaway, 2010; O'Kane, 1995) The pattern tessellation drawn by author

Sultan Qaybtay Mosque and Mausoleum (1472-75 CE) is the ultimate achievement of architectural development in Cairo (Fletcher and Cruickshank, 1996). The remarkable carved geometrical motifs on the dome's exterior (with 10 and 9 and 16-point geometric patterns) and the wooden Mimbar with 10 and 16-point geometrical pattern are the most important achievement of that period (Abdullah and Embi, 2012), (Figure 2.36).

Figure 2.36. Sultan Qaybtay complex (Right above) The interior of the dome showing the geometric pattern using eight-point start, the exterior of the dome showing the use of 9, 10 and 16-point pattern (Torky 2017)

Later, the Ottoman Empire, considered as the master builders. Their work was influenced by the Seljuk's style, with some inspirations from Mamluks (URL-24). The Ottoman artisans used various materials for ornamentation but majorly wood, marble and glass (colored). The use of polychromic tiles with floral and geometrical patterns known as Iznik has been the most distinctive element that has been widely used in their buildings. In the Ottomans works more floral and vegetal patterns are observed and the geometrical ornamentation was limited to doors and Minbar panels only. 8 and 16 point geometrical patterns, 5, 6, 10 and 12-point geometrical patterns were more popular amongst the artisans and architects of the Ottoman Empire (Abdullah and Embi, 2012). The most remarkable architectural works of the Ottoman's is in the present day cultural capital of Turkey, Istanbul, which was then the capital of the Ottoman Empire.

Sehzade Complex (1544-8 CE) has 6 and 10-point geometric motifs over the doors, portals and on the stone minbar 9, 10 and 12-point geometric motifs are carved. It is one of the most significant architectural masterpiece of the era designed by the Master Architect of the Ottoman Empire, Mimar Sinan (URL-24), (Figure 2.37). Süleymaniye Complex (1551-8 CE), Haseki-Hurrem Baths (1556 CE) and Selimiye Complex (1568-75) in Edirne. All these buildings main ornamentation focus has been on floral motifs designed on Iznik tiles with few geometric patterns on doors, window crowns and carved marble mimbars (URL-23, URL-11).

Figure 2.37. Sehzade Complex, Istanbul (Millett, 2008; Kocaman, 2013; Kose, 2012)

It was during the Safavid period when there was a significant growth in art and science. They got the rich architectural traditions and techniques in the legacy (URL-24). They used geometrical (fusion of floral) ornamentation on all building types. In Isfahan there are two important examples; Ali-Qapu Palace (1598 CE) and Chehel Sutun Palace (1645-47), both the buildings are secular and show extensive use of geometrical ornamentation (8 and 10-point geometrical patterns) on balconies and ceilings along with decorated muqarnas, carved stuccos and paintings with floral and figural motifs. Figural paintings narrating historical events were also common in palaces of Safavid era. (Abdullah and Embi, 2012). In religious building these geometrical patterns were fused with calligraphic inscriptions. In the Safavid architecture the use of combined patterns was less.

Then came the Great Mughals contribution to geometric patterns, they ruled as a multi-cultural empire and drew inspirations from all great works of art and architecture (early Islamic, Hindu and Persian style) expressing their multi- cultural perspective. This enriched their aesthetics, teaching them the significance of geometry in architecture as a universal language of unity and symmetry (Anwar, 2015).

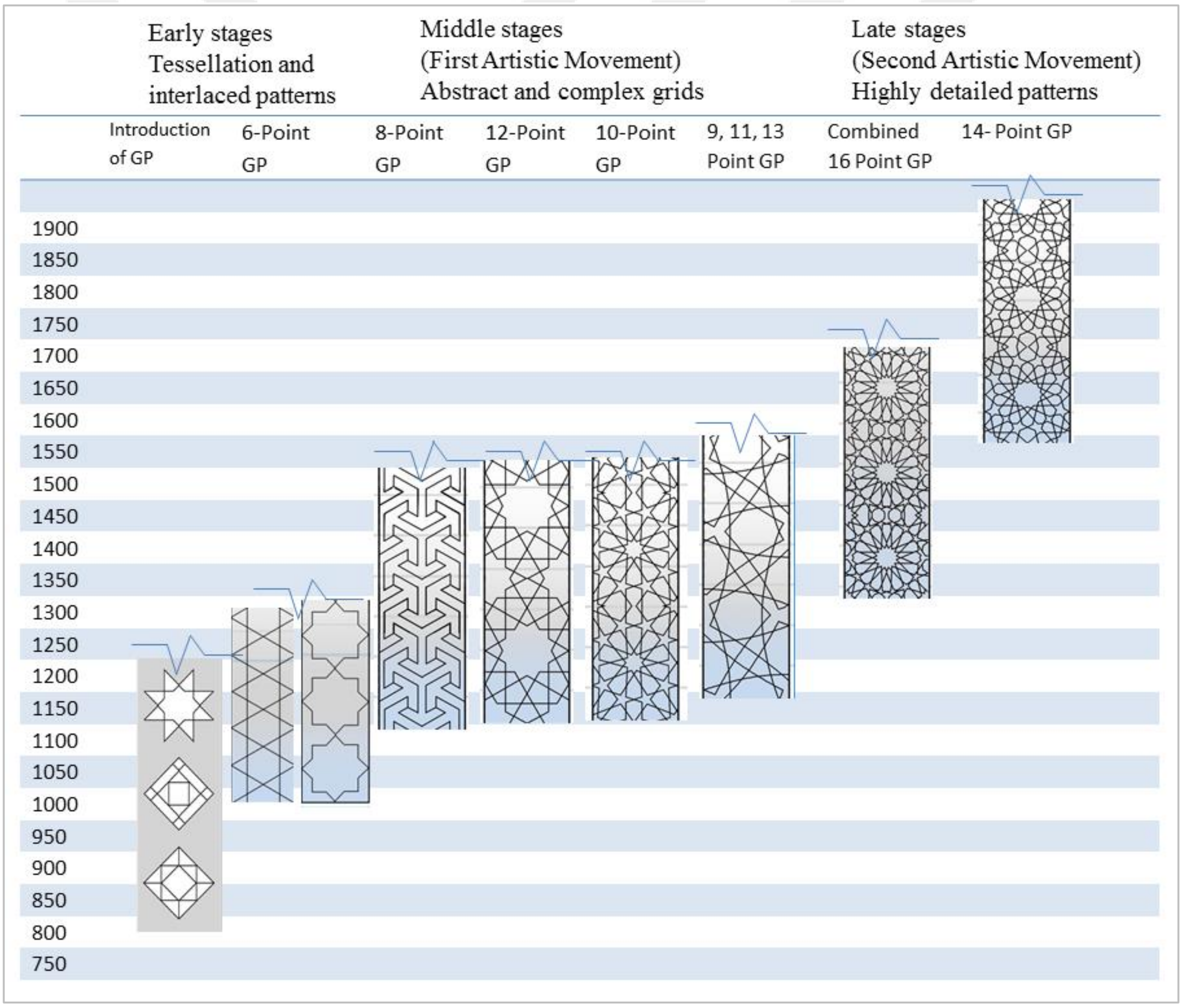
Their early architectural example with floral ornamentation (tiles and paintings) is found in Sher- Shah Mausoleum (1540 CE). Later, in Delhi, the Mausoleum of Humayun displays the use of different materials and techniques, the use of white marble frames over a contrasting red sandstone structure makes this building one of its kinds. The use of 6-point and 8-point geometrical motifs are used in floor patterns and are gracefully designed and carved in the window grills (screens or jali) and balcony railings. (Figure 2.38) The same use of materials and patterns are also found in Agra's Red Fort (1564-80 CE), along with few 10 and 12-point geometrical patterns. By the end of this era more examples of 10-point geometric motifs are observed, such as in Fatehpur Sikri's Friday Mosque (1571-96 CE), where one of the earliest examples of 14-point pattern over the main dome's piers is also found (Abdullah and Embi, 2012).

Figure 2.38. Humayun's tomb, Lahore Fort, Taj Mahal, (Remsberg 2017, Nawaz 2013, Asitjain 2009) The pattern tessellation drawn by author

They avoided complex geometrical patterns in their designs and focused more on proportions and angles while designing the patterns. Finest examples of this period which display the designs with 6, 8, 10 and 12-point patterns over sandstone and marble inlay work are, Akbar The-Great's Tomb (1602-12 CE) and the Tomb of Etimad-ud-Daulah, in Agra. The most extraordinary Mughal Complex that represents geometric patterns and ornamentation at its best are found in the Great Taj Mahal and Lahore Fort. (Figure 2.37) Remarkable work of craftsmanship is seen in the screens, windows, floor finishing, courtyard's fountains, mosaics and railings.

To sum up, tracing back the formation of the geometric patterns and its evolution over the time shows the strong impact all the empires had over the following one. The artisans and craftsmen of each era tried to make the pattern one of its own kind, more symbolic and more complex. The use of materials and experimentation of different techniques shows that with the passage of time they mastered this art of composing and repeating in any possible area. The dome, walls, floors, minarets, mihrabs, windows and balconies, all elements were used as the artisans' canvas for ornamentation.

Table 2.10. The era when a geometric pattern was introduced and how they co-existed in certain eras. The influence and the development of the patterns are visible in this table (Table drawn by the author)



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2.3.3. Mughal screens as a medium to analyze geometric patterns

The screens or jalis have been a major architectural element in the Mughal architecture and the use of geometrical patterns and different layouts have been observed in most of their works. The most extraordinary Mughal Complex that represents geometric patterns and ornamentation at its best are found in the Great Taj Mahal and Lahore Fort. Remarkable work of craftsmanship is seen in the screens, windows, floor finishing, courtyard's fountains, mosaics and railings. Geometry has been important in planning as well as designing. The Mughal artisans and architects focused more on proportions and angles while designing the patterns. Finest examples of this period which display the designs with 6, 8, 10 and 12-point patterns over sandstone and marble inlay work.

<u>Case study: The Jalis of the Naulakha Pavilion in the Lahore Fort</u>

The case study focuses on a pavilion located in the northern section of Lahore Fort, the Naulakha Pavilion. This pavilion and the compound holds a great significance in the entire fort due to the uniqueness of the structure and highly ornamented walls, floors and ceilings. Naulakha is derived from nau meaning nine and lakha meaning lakhs, it is believed that the pavilion which is a summer house, was constructed expensive, costing 9 lakh rupees, which is a great amount at that time, due to its unique curvilinear roof and semi-precious stones inlay work, making it an icon. Not only the structure is extraordinary but its placement with its west facing façade giving the view of the entire old city (walled city) made it more special.

Lahore, the city that was once the historic capital of Punjab and it was the Great Mughal Empir's thriving cultural hub, due to which it holds a very important historical and cultural significance for Pakistan. The Walled City Lahore is amongst the most remarkable example of planning and architecture during the era of the Great Mughals. The Lahore Fort situated in the Walled City Lahore is one of the great architectural legacy left by the

Mughals. It not only tells us tales of how the common people and the royals lived there but also about the highly skilled artisans who ornamented every space with detail and finesse.

The Lahore Fort has numerous fine examples of jalis which is not only used for ornamentation purposes but also plays significant role in the different spaces architectural requirements. When the fort was designed and built, the river Ravi flowed along the north of the fortification wall. The cusped arched openings with marble geometric jalis, integrating viewing windows not only provided a delightful scene from the fort but also made the pavilions more comfortable during the hot summer days, by allowing more air movement and diffused light only. The fort complex is humongous therefore only few parts of the widely spread complex are discussed regarding the main aspect that is the jali work.

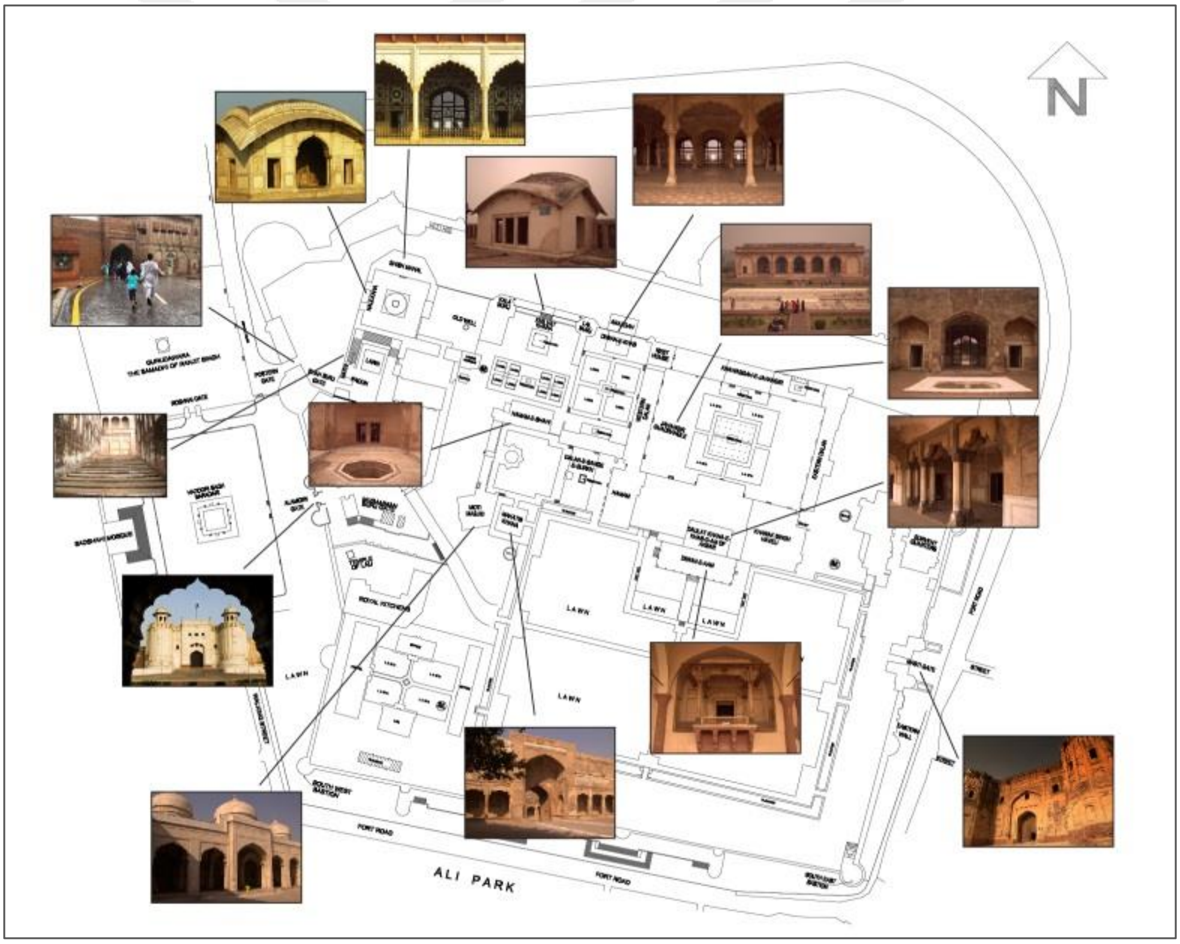

Figure 2.39. The Lahore Fort Complex plan showing the buildings place (Saqib, n.d)

The Naulakha Pavillion

Located in the northern section of the complex this pavilion is a personal chamber built im 1633 by the Mughal ruler Shahjehan as a summer pavilion. It is constructed in white marble and is considered remarkable due to the thinness of its curvilinear roof and the jali inside. It’s considered as a masterpiece due to the fact that no joints exist and is perfectly balanced to equalise the strains and stresses of each piece of pure white marble used. To hide from view from the ground, the joints had ‘merlons’ capped at the edges (URL-21). The center of the pavilion has intricately carved marble jali, which was descirbied to be ornamented in delicate ‘parchin kari’ (pietra dura) covered with a silver lining, which is considered amongst the finest in the world evn today. The rest of the walls are ornamented with semi-precious stones inlay work in floral patterns and geometric ornamentation on floor and roof of the pavilion. (Figure 2.40)

Figure 2.40. The Naulakha Pavilion (Mir, 2011) The pavilion drawn by author

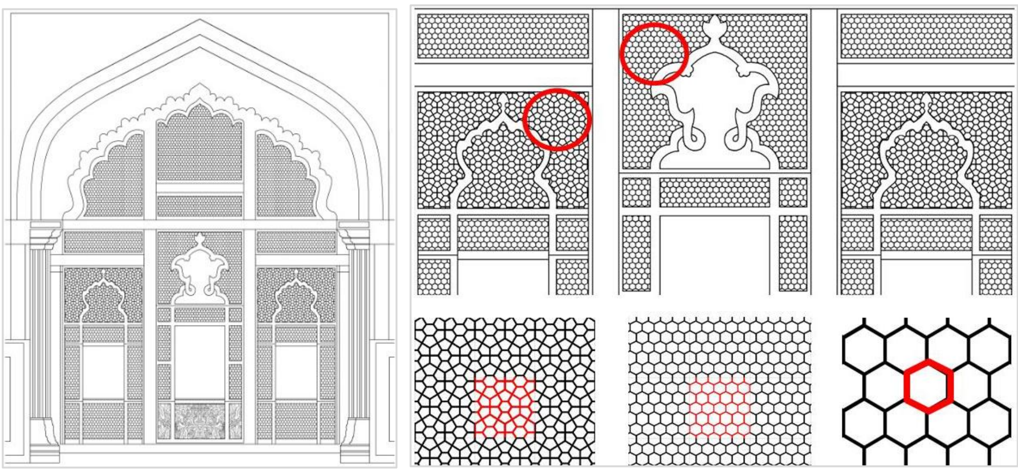

Figure 2.41. Drawings of the pavilion and the central arch of Naulakha Pavilion, with intricate patterns carved out from marble. The pattern tessellation drawn by author

The interior of the pavilion, stone inlay on the floor and glass work on the roof show the intricate use of pattern by the artisans. The 8-pointed star pattern and 8-fold rosettes is observed on the floor and the roof but the layout. The jali of the pavilion is not very complex, it’s a honeycomb pattern carved out from the while marble. The central panel is a classic example of the use of hexagon in jalis, as shown in Figure 2.41, whereas the two side panels of the pavilions screen wall show a different layout using the same basic hexagonal pattern. (Figure 2.41).

Figure 2.42. The interior of Naulakha Pavilion, The Sheesh Mahal (Malik 2015, Shah 2011)

These exquisite jali windows allow cool breeze and a view of the city streets. The same jali design is observed in the Sheesh Mahal (The Palace of Mirrors), which is also in the same compound as represented in Figure 2.42. The finely carved jali isn’t only a part of these marvelous pavilions but also repeated throughout in the surrounding walls of this complex. (Figure 2.43) Again, as observed in the earlier jalis, it is a honeycomb pattern using the hexagons (six-point geometrical patterns) and on few of the panels, octagons (eight-point geometrical patterns) are used in a fairly complex pattern.

Figure 2.43. The walls and balcony railings are also carved jalis, with six and 8-point geometrical patterns (URL-16)

To sum up, throughout the history of the Muslim Art and Architecture one can observe that all the empires focused on the architecture and its ornamentation. Art and architecture are always considered as major elements in each empire, as it reflects the strength, wealth and success of that era. It not only marks their rule in that region but also leaves an everlasting impression, telling the tales of their golden era to the generations to come.

This study is an attempt to map the styles of ornamentation in different Islamic empires and the evolution of the Islamic geometric patterns. This chapter focuses on few major empires and their contribution in the development of the patterns, in the light of the examples found in the existing architectural examples of that dynasty. One thing that remains constant in all these empires is their passion and focus on the ornamentation and glorification of religious and important buildings, to mark their eras own significant style.

The timeline shows how the Muslims took inspiration from the existing cultures and with the passage of time they successfully developed their own artistic style and language. Experimentation with different materials, the complexity of the geometric patterns is observed. Concluding example from the Mughal architectural marvel shows how these various patterns are used differently, along with the significance of jali, as intricate finely designed and crafted screens for ornamentation purposes along with its major role in the passive cooling and tackling the natural conditions in buildings ventilation and lighting.

After years of evolution and complexity of the Islamic geometric patterns, the Naulakha Pavilion shows us how the geometric pattern used in the screens and flooring, retains its basic form, as seen in the earlier example of the Abbasid Dynasty's, Ibn Tulun Mosque in Cairo, where the six point geometrical pattern, hexagons and eight point geometrical patterns were introduced. The basic elements of the pattern and its formation remained intact and in between new compositions and tessellations took birth, giving each tessellation an identity of its own and each pattern a new life, on a different material with a different technique.

2.3.4. Geometry in Kinetic façade

The ground of parametric design is the generation of geometry from the definition of a family of initial parameters and the design of the formal relations they keep with each other

(URL-10). The parametric design uses algorithms, which generates geometrical and mathematical relationship hierarchy that allows us to create and explore a design along with the countless possible solutions (by initial parameters variability).

Parametric geometry modeling is a field studying algorithms that compute geometry (Kelly 2013). A major barrier concerns the level of effort necessary to implement the algorithms: "the task is foremost; the tool need only be adequate to it" (Woodbury 2010). Since 2003 and the release of a new parametric software like Generative Components or Grasshopper, the conceptual representation containing the algorithms can be achieved through visual dataflow programming language (VDPL) dedicated to 3D modeling (Gallas, Jacqout and Jancart, n.d).

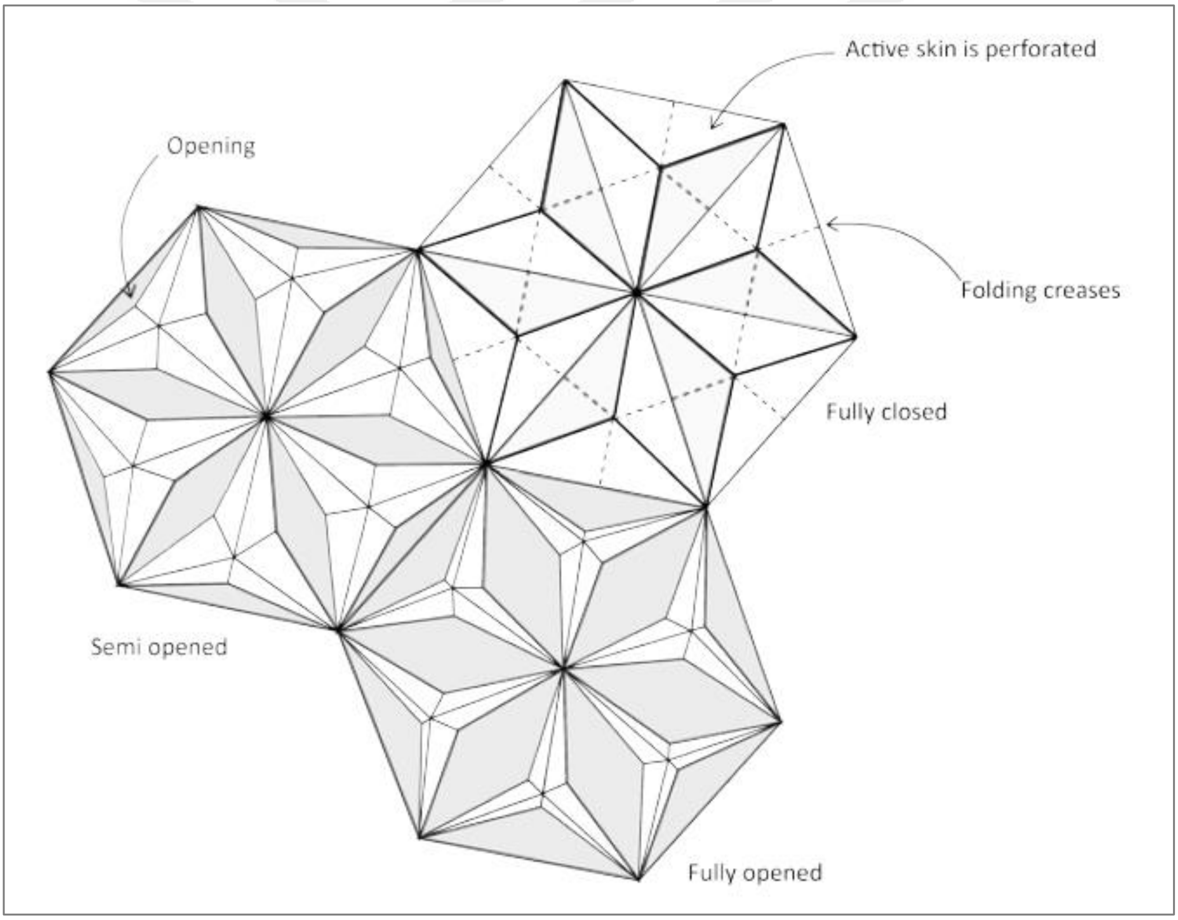

Figure 2.44. Al-Bahar Towers kinetic façade panel designed by Aedas (Sharaidin, 2014)

Geometry has always played a significant role in architectural design, be it the plan or the elevation. In present day advancing methodologies and design techniques, the geometry and algorithms have opened more doors to explore more possibilities and dynamic forms, when it comes to designing. The façade design isn't limited to aesthetics only, more focus is on its design, as it's the outermost shell of the building, which is explored through different computational possibilities and softwares, where geometric patterns play a vital role. For instance, the design of the Al-Bahar Towers, which has a kinetic responsive façade, we observe the importance of geometric shapes and its understanding, as shown in Figure 2.44. It is evident that the folding of the patterns and its tessellation is entirely based on the comprehensive understanding of the shape, its components and its tessellation.

Another finest example of the significance of geometry in kinetic façade is observed in Institute de Monde Arabe. It is believed to have been similar to the US pavilion design by Fuller (1976) in context of the kinetic patterns and composition, though the scale is different. The geometry pattern of the shutters is composed of different parts and demonstrates kinetic composition and response similar to the camera lens, as shown in Figure 2.45 (Sharaidin, 2014).

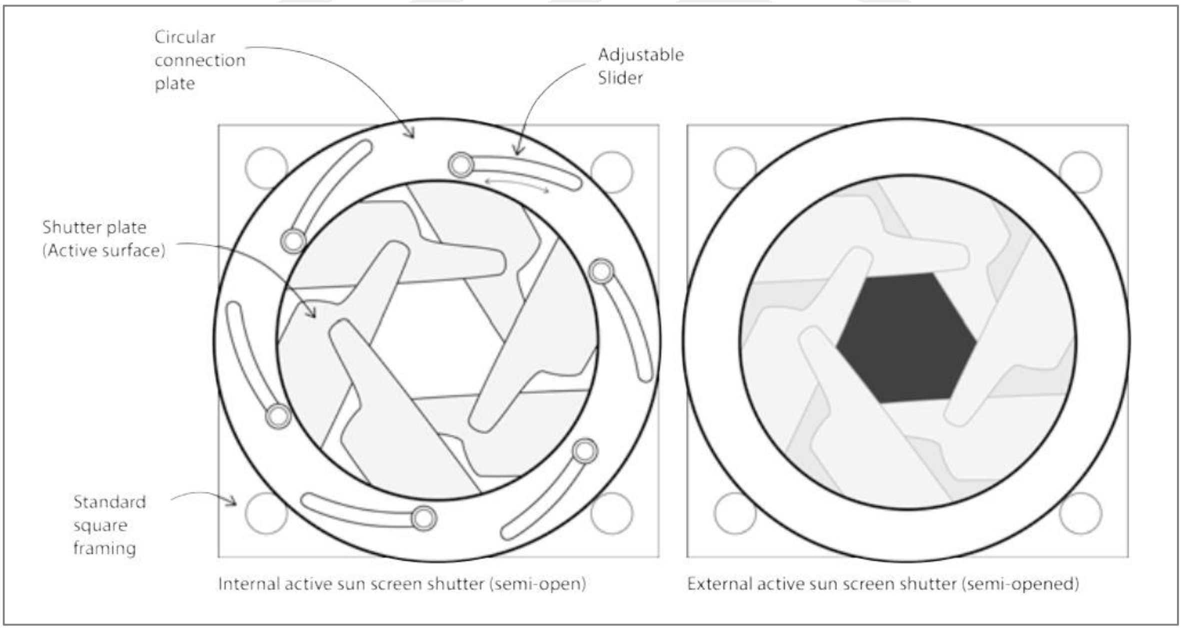

Figure 2.45. Kinetic shutter panel of Institue de Monde Arabe (Sharaidin, 2014)

Without the understanding of the geometry, achieving a façade of a kinetic nature, as explained in the examples provided above wouldn't have been possible. The geometric composition and its different elements make either basic patterns or complex patterns, along with the kinetic mechanism it works in complete harmony and synchronization, as we observe in the nature and our surroundings.

3. MATERIAL AND METHODOLOGY

3.1. Design Methodology/ Software

Grasshopper as a parametric design tool is used, where a hexagon is taken as a basic pattern and it is used to develop the screen tessellation. In this research exercise only two different options are explored using the same basic geometric pattern. As we know, with digital tools the possibilities are infinite, and the designer has to set their boundaries and restrictions themselves, as a result only two pattern tessellations are explored using the basic pattern for a better understanding and comparison. Keeping the process simple and to the point in order to explore the idea and hope to open further possible doors for future exploration and design development.

3.1.1. About the software

Grasshopper, developed by David Rutten at Robert McNeel & Associates, is a visual programming language which is operated within another design software which offers parametric modeling and the visual algorithms, named as Rhinocerous 3D modeler. Grasshopper is a plug-in software and gives the user the space and flexibility of exploring and creating custom designed programs that can extend the functionality. Various type of analysis ranges from sound, structural, design optimisation and controlling Arduino are just a few tasks that can be operated within the Grasshopper software (Sharaidin, 2014).

Rhinoceros 3d is a software developed by Robert McNeel & Associates. It is a commercial 3D computer graphic and computer-aided design application, majorly used when it comes to parametric modeling, as it is based on NURBS mathematical modeling, which focuses on generating mathematically precise representation of curve and freeform surfaces within computer graphics as different to polygon mesh-based application(Sharaidin, 2014).

3.2. Abstraction versus Realism

It is a clear fact that there are a large number of permutations possible when it comes to designing using parametric modeling tools and geometry. If a range of geometric configurations is also considered, such as the proportion shape and scale of the kinetic facade, the number of permutations increases exponentially. All configurations will not be utilized, nor is this required to meet the research objectives (Moloney, 2009).

The screen module consists of hexagon units, which is considered as providing the best example in a basic understanding and feature for this exercise. The computer generated visuals are deliberately abstract when the curves or attracting points are introduced, in order to study the dynamics and the effect of these inputs on the module. The objective of the study and the visuals are to identify and understand the key elements of the morphology of the kinetic screen due to the inputs. Using this approach and these exercises, wide range of possibilities of options can be generated, analyzed and utilized in terms of designing dynamic skins.

3.3. Components/ Scripting

The components that are used in the two design exercises performed in this study are stated in the two tables below, providing basic understanding of their function and description.

Table 3.1. Components used in the design process

HEXAGRID	CLOSED	REMAP
FLIP	CULL	DISCONTINUITY
BREP	PCEN	AMPLITUDE

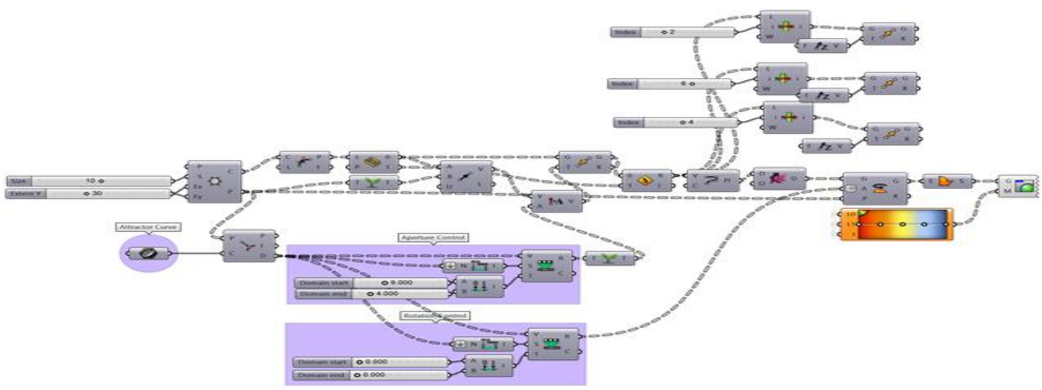

Table 3.2. Components used in the design process of pattern 1

Components	Purpose
HEXAGRID	The hexagon grid is designed.
FLIP	Helps in flipping the curves after flattening the list.
BREP	a boundary to crop any cell that lands outline the grids boundary; this provides the freedom to use the surface in any place fitting as per our requirement.
CLOSED	to check which of the remaining cells are closed and filter the ones that are open.
CULL	to remove the cells that are open.
PCEN	used to calculate polygon centers of the remaining cells.
MD SLIDER	Evaluate surface is used to remap the bounds of the sliders onto the bounds of our cell outline.
PULL	To apply the scale factor to the cells creating an offset, based on the distance from the input point..
BOUNDS	To set the upper and lower limits from the values generated by Domain component.
REMAP	To apply the scale factor to the cells creating an offset, based on the distance from the input point.
UNIT Z	(vector component + REMAP) the offsets are moved in Z direction to provide a pivot for the modules, affected by the distance from the input point.
LOFT	To loft the two version of the cell to create the module, which opens as it gets close to the input curve.

Pattern 1

Table 3.3. The components and their description

Componenet	Purpose/ Description
HEXAGRID	A hexagon grid is achieved
DISCONTINUITY	To extract its vertices
VEC2PT	To generate vectors
REMAP	To remap these values on the scale of the hexagon grid
AMPLITUDE	To feed the remaped values on the scale of the grid in the vectors
POLYLINE	The vertices are now joined, to make the outline of the modules.
ROTATION	To provide rotation to each and every module based on the amplitude calculated earlier
CRV CP (Closest point on Curve)	For calculating the amplitude that will affect the vector's intensity, when used with curve and grid it gives the closest point on each curve cell on the grid and its distance from the input curve
BOUNDS	It calculates the extremities of the data set and the Domain component remaps those distance values onto the provided range.
REMAP + AMPLITUDE	It is used to remap these values on the scale of the hexagon grid and then is fed via AMPLITUDE component in the vectors.

Pattern 2

4. PARAMETRIC DESIGN FOR KINETIC FAÇADE USING HEXAGON AS A BASIC DESIGN UNIT TO DEVELOP A SCREEN OR A SECOND SKIN FOR THE FACADE

4.1. Design concept and methodology

Inspired from the *jali* in Mughal architecture and use of Islamic geometric patterns, the study aims to use the findings from the literature review and use it to develop a skin using parametric design. The main concept of this aspect is to design a kinetic skin for facades or screens that are responsive to the sunlight and movement. The aim is to diffuse and control the direct sun rays entering from open spaces like balconies and windows. The developed screen can also act like the second skin of the façade that acts as a shield between the façade and the environment.

A hexagon is taken as a basic pattern and it is used to develop the screen tessellation. Using Grasshopper as a parametric design tool, only two different options are explored using the same basic geometric pattern. As we know, with digital tools the possibilities are infinite, and the designer has to set their boundaries and restrictions themselves. In this research only two pattern tessellations are explored using the basic pattern for a better understanding and comparison. Keeping the process simple and to the point in order to explore the idea and hope to open further possible doors for future exploration and design development.

4.1.1. Pattern 1

- A hexagon grid is introduced with a spline as the boundary that trims the grid.
- This spline can be taken as the area required for the screen and can be of any size.
- The hexagon grid is then offset itself and a planer surface is created connecting the two grids, creating a tube with a hexagon base.
- A point attractor is then introduced as an input parameter.

The point attracter can be considered as any of the factors, be it physical or social (Figure 5.5). This attractor affects the offset of inner hexagon, hence changing the aperture of the opening as it moves. For instance, if sunlight is considered as the opposing factor and shaded area as the point attractor, the hexagonal cells will respond according to the attractor, the cells that are closer to the point attractor will be wider and will allow more light/view/wind to pass through, while the other cells that are away from the point attractor have narrower openings, to minimize the light from entering the interior spaces and minimize heat gain as shown in Figure 4.5 and 4.6.

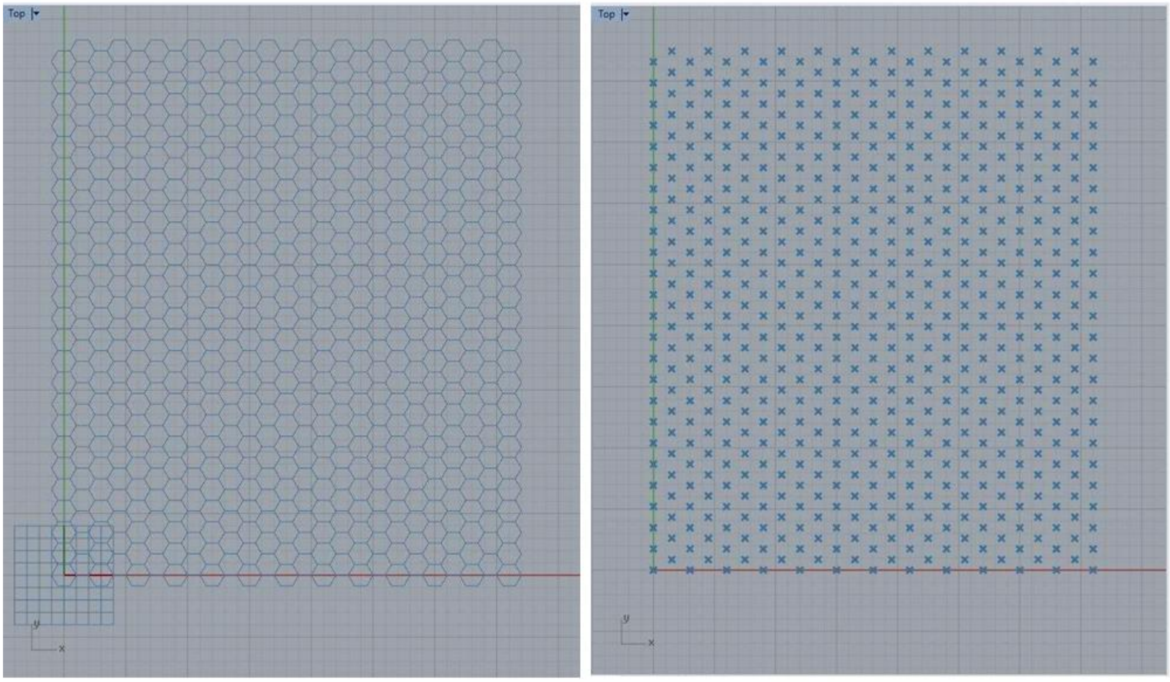

Figure 4.1. The process starts off with a hexagon grid by using hexagrid component

The hexagon grid is designed using a HEXAGRID component. Once the grid is formed, the Flip component is used, which helps in flipping the curves after flattening the list. Then project a BREP as a boundary to crop any cell that lands outline the grids boundary; this provides the freedom to use the surface in any place fitting as per our requirement. (Figure 4.1).

Then CLOSED component is used to check which of the remaining cells are closed and filter the ones that are open and then use a component named CULL to remove the ones that are open, as shown in Figure 4.1(right). After removing the open cells, PCEN component is used to calculate polygon centers of the remaining cells.

An outline of the remaining cells is generated as shown in Figure 4.2, to be used as the bounds for the MD SLIDER component and Evaluate surface is used to remap the bounds of the sliders onto the bounds of our cell outline. Then the PULL component is used to pull the input point within our grid boundary (Figure 4.2).

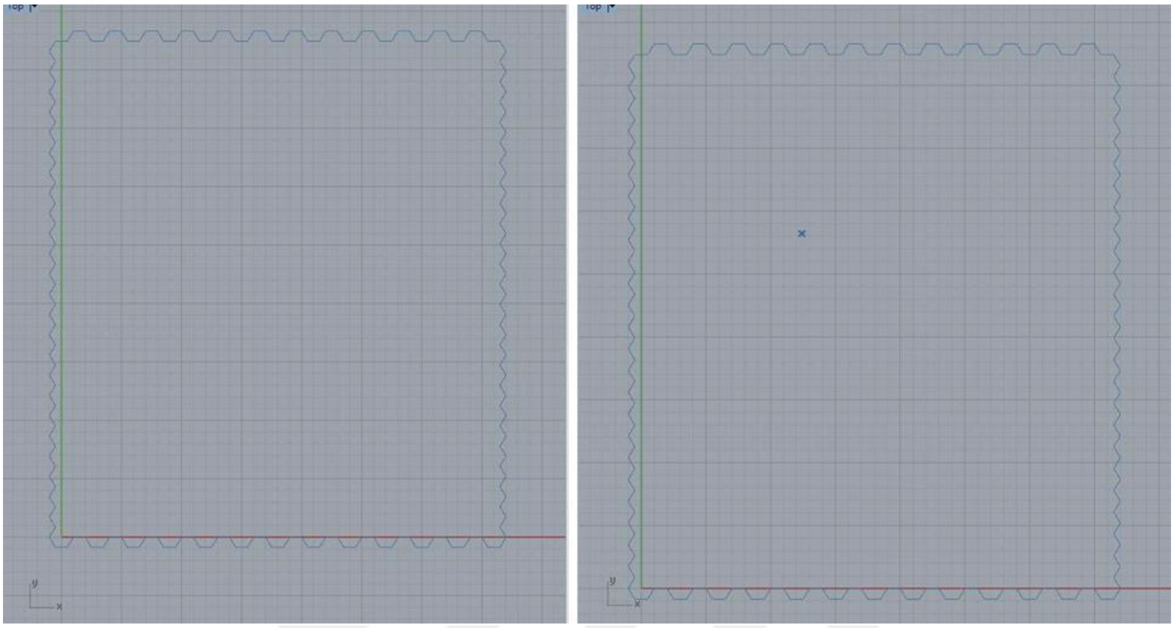

Figure 4.2. (left) Outline of the cells generated. (right) the component pull used to pull the input point

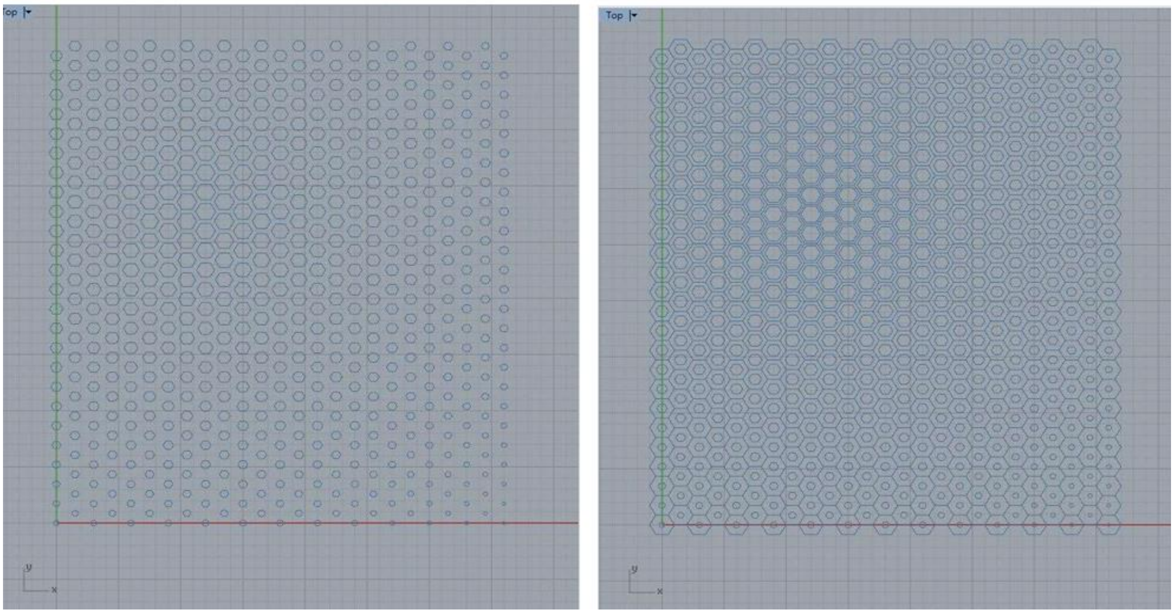

Figure 4.3. The two lists of cells are merged putting corresponding cells in one branch of the tree to be lofted

Then the BOUNDS component is used to set the upper and lower limits from the values generated by Domain component and use REMAP component to apply the scale factor to the cells creating an offset, based on the distance from the input point. Using a UNIT Z vector component along with the remap tool, the offsets are moved in Z direction to provide a pivot for the modules, affected by the distance from the input point, as shown in Figure 4.3.

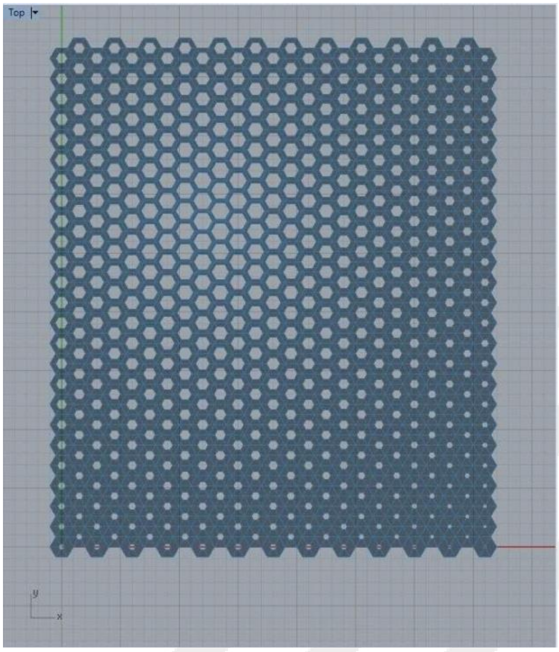

Figure 4.4. Finally LOFT component is used to loft the two version of the cell to create the module, which opens as it gets close to the input curve

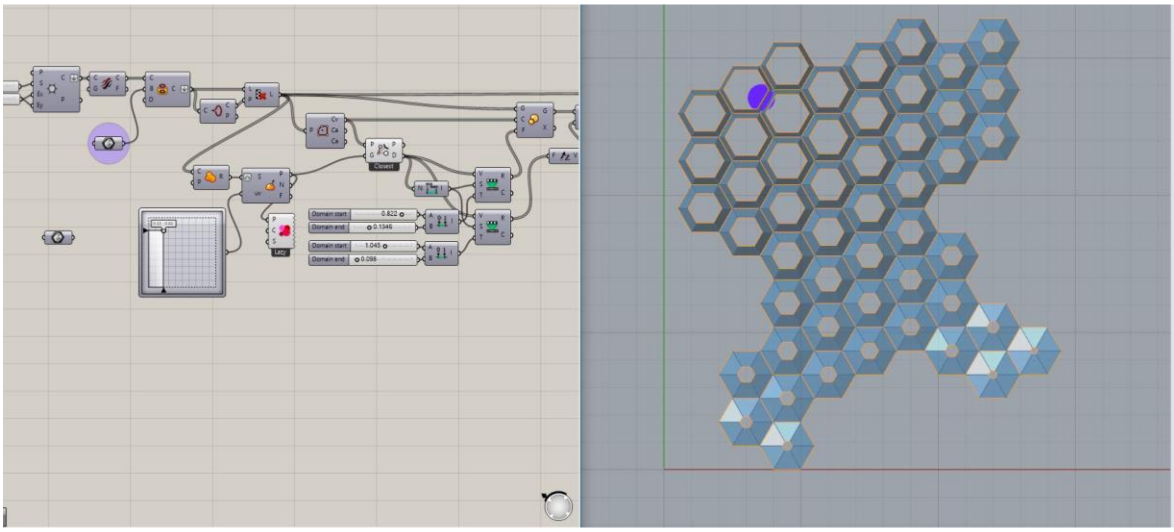

Figure 4.5. The hexagonal grid with a point attractor

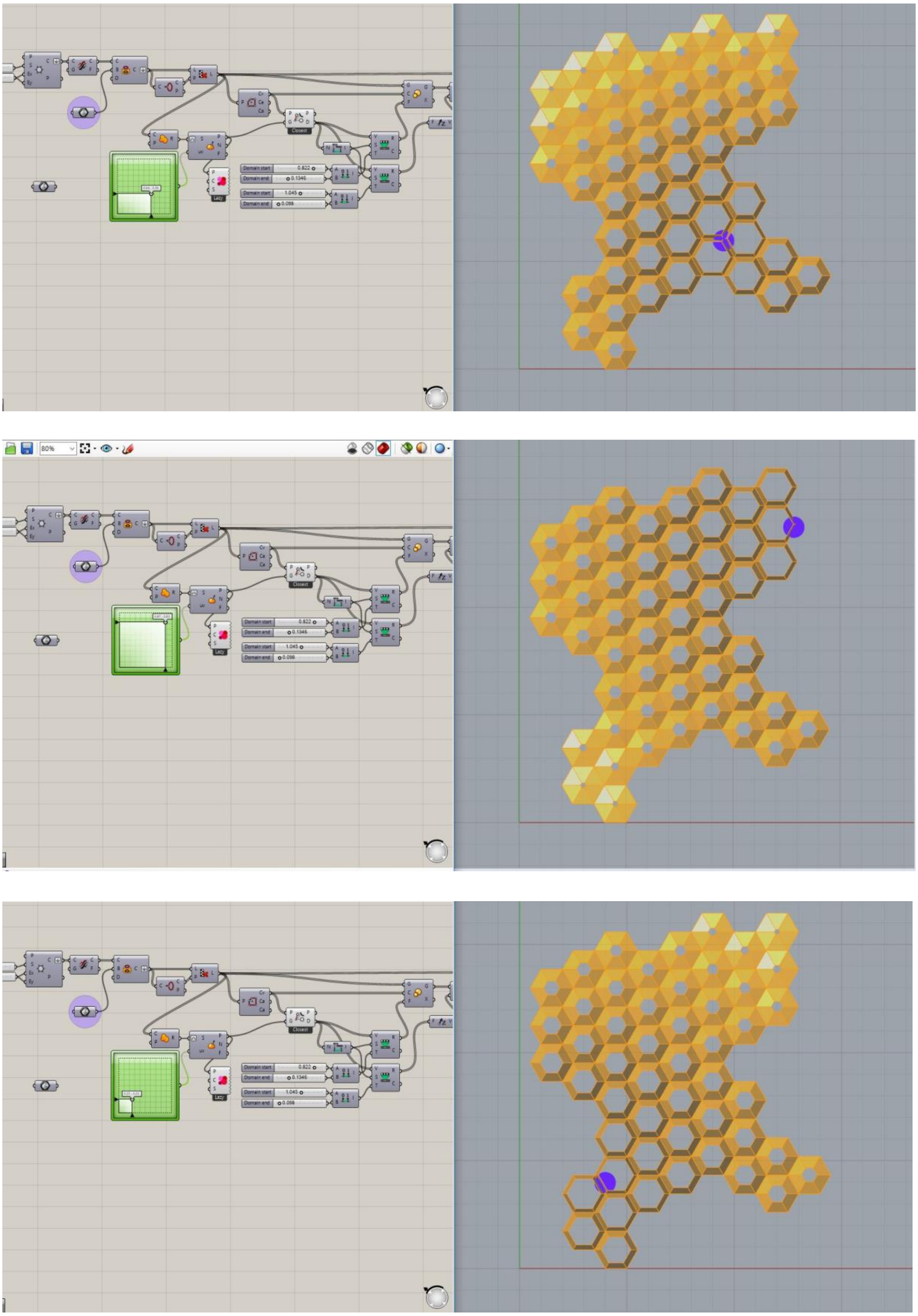

Figure 4.6. The hexagonal grid with a point attractor

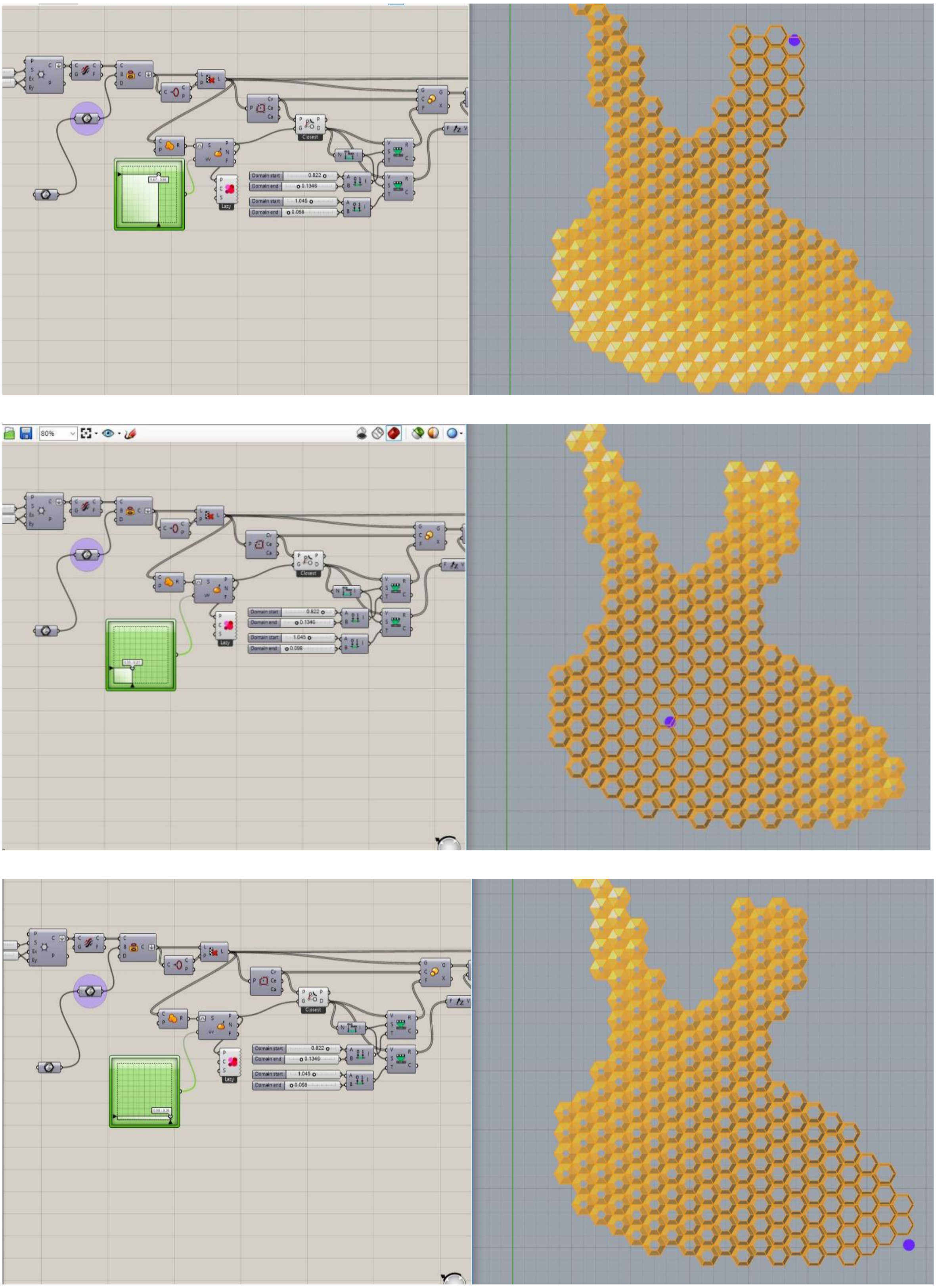

Figure 4.7. The widening and contracting of the apertures as the point attractor moves around

As a result, this grid's base is static, but the design is effective in terms of the controlling the apertures. Material with expanding and contracting properties will be required along with a hydraulic system to control the expansion and contraction of the opening.

4.1.2. Pattern 2

A hexagon grid was introduced which is used to extract edge vertices of its cells. A curve is also introduced in Rhino as an attractor curve which will serve as the source of our input. The input can be based on the basis of the architects' requirements, as to what will be the factor which needs to be looked as the focal point; here the two major factors taken into consideration are solar exposure and privacy. By solar exposure it is suggested that the screen will be responsive to the sunlight, to avoid direct light and heat entering the interior spaces or the façade. On the other hand, the other major factor taken into consideration is privacy. As privacy is one of the major elements of a screen, the inputs for this factor respond to the users' requirements and interaction. The response of the screen in this case is directly responsive to the user, to provide them privacy without obstructing the views.

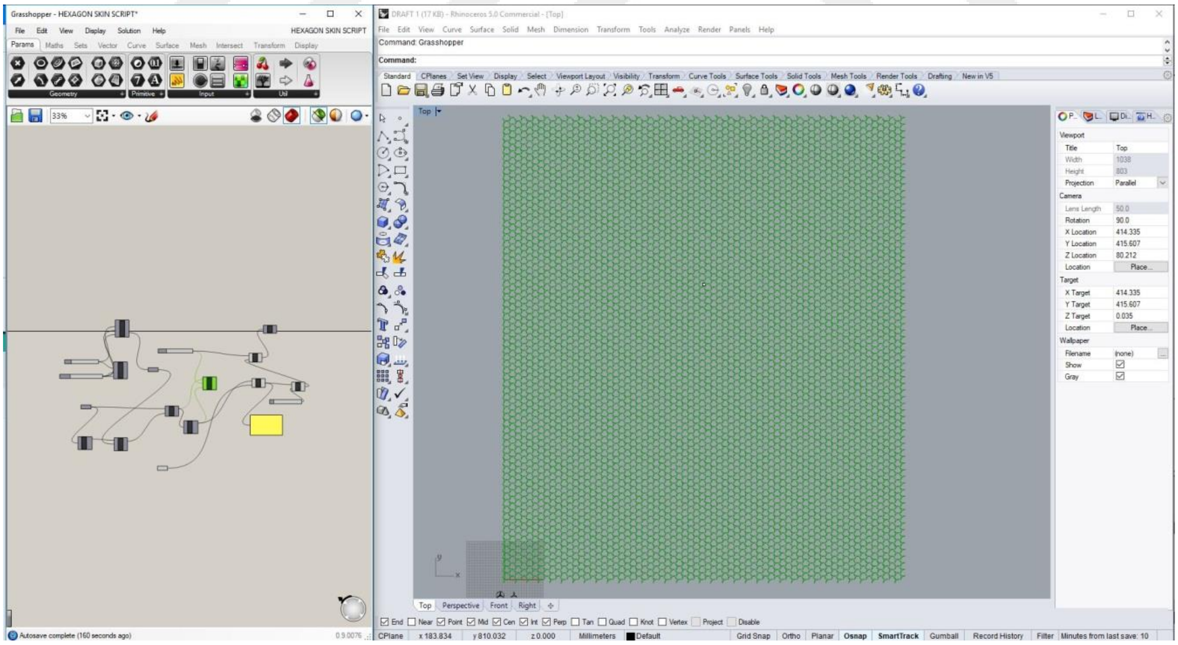

Figure 4.8. The hexagonal grid

Through the interaction of these curves and points, a set of points closest to the curve is generated which will become the bases in calculating distance of module from the attractor curve and calculate its effect on it.

Using a set of points is generated along each cell, to create a basis for the module modified as per its intensity calculated from the distance from attractor curve. For the rotation, same range domains have been made which is affected by the distance of the cell from the closest point in the attractor curve, whose value is then fed into the module.

Once all the forces have been calculated and applied to the module's vertices, a polyline is generated to create outlines of individual module, and then a planar surface is applied to the closed polyline curve to form an opaque object. A color gradient module is then introduced to display the intensity of effect of attractor curve on each module, creating a field. This process then repeated for the next layer of the screen, but here the effect of rotation is kept zero to keep the grid intact and not lose its structural integrity. The script generates a field of module, initially without any rotation at their original state.

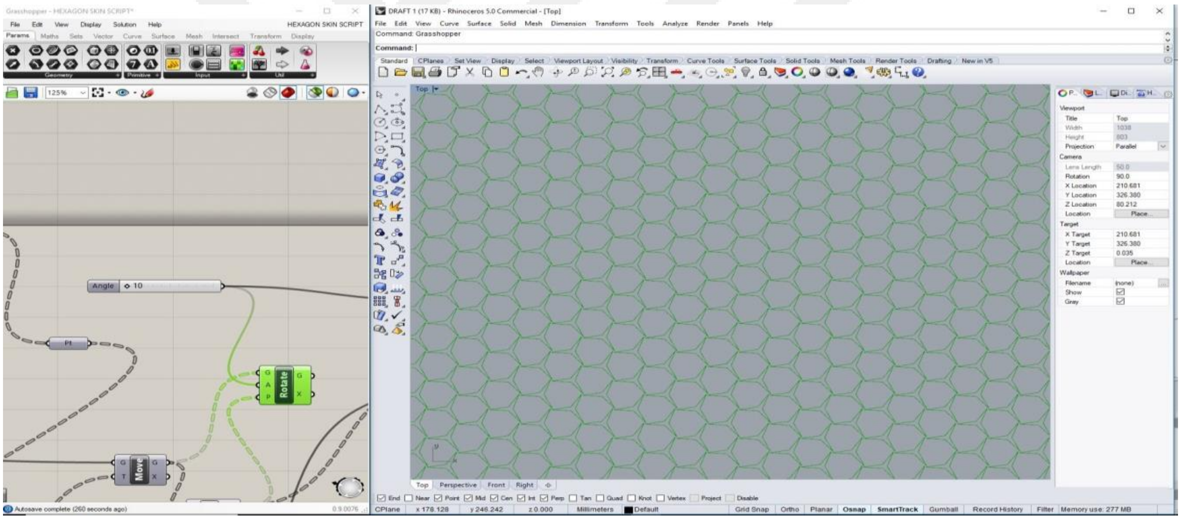

Figure 4.9. The hexagonal grid. The pattern starts evolving as an attractor is introduced

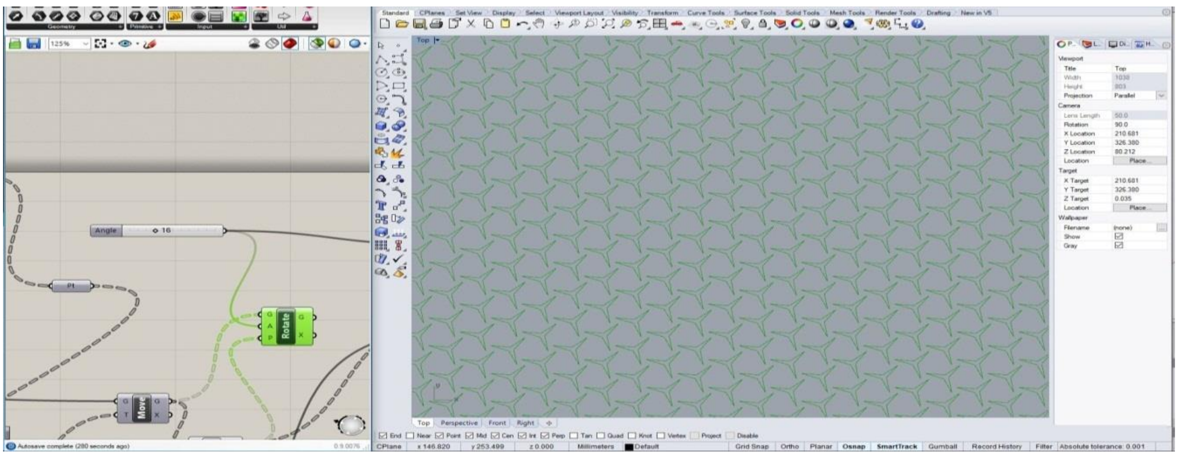

Figure 4.10. The grid breaks as the module breaks and the components rotate

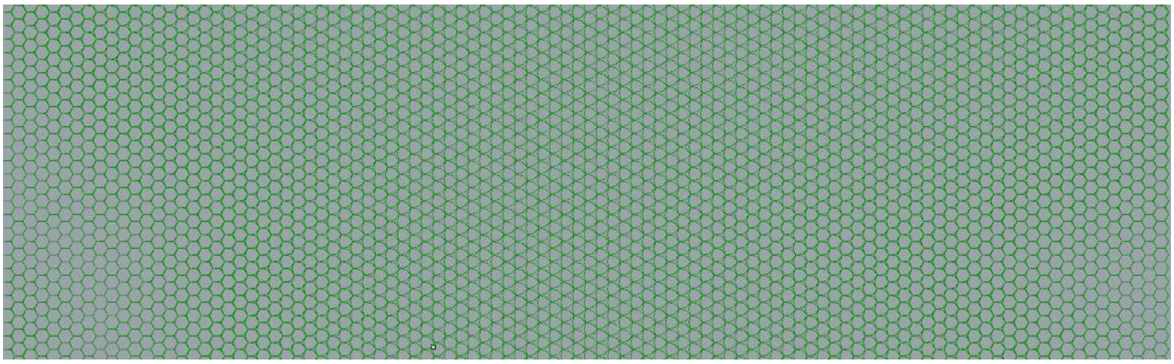

Figure 4.11. All the edges are touching each other at the tangents and the grid appears to be closed cells, almost like a hexagon grid

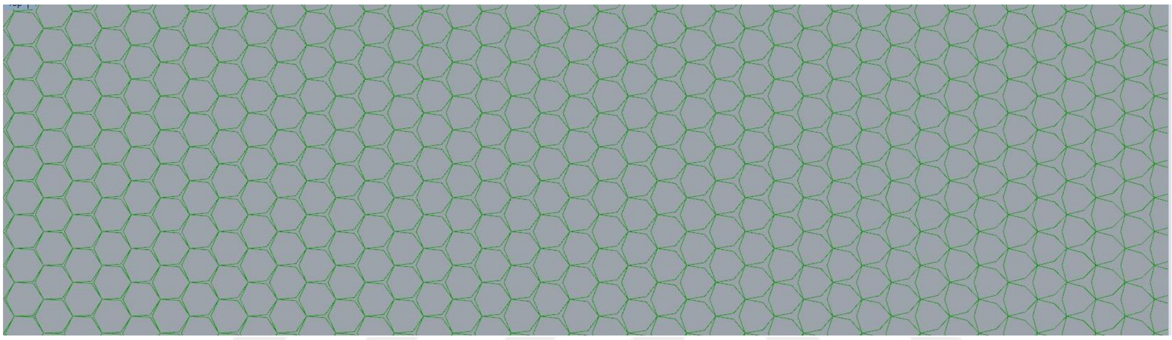

Figure 4.12. The transformation starts appearing from left to right when an attractor or factor is introduced, changing the hexagonal grids formation and making triangular patterns

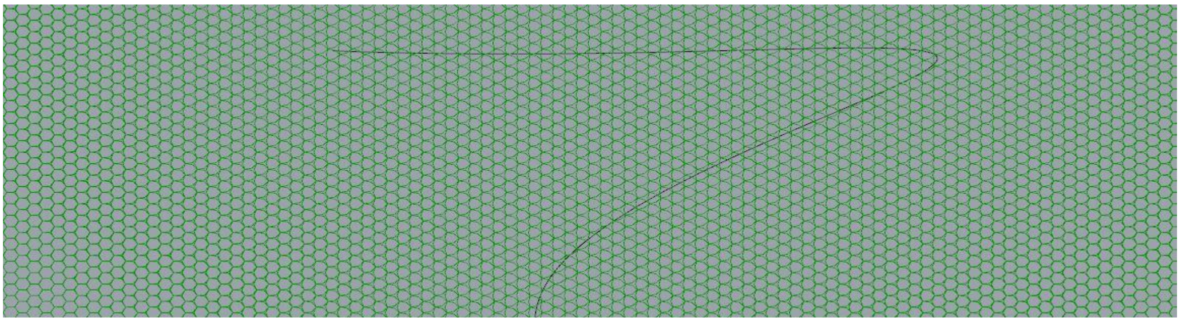

Figure 4.13. A curve is then introduced as a field that will interact with this grid of module and affect their state. This curve can be interpreted as any physical or social parameter, as an input to disrupt the field.

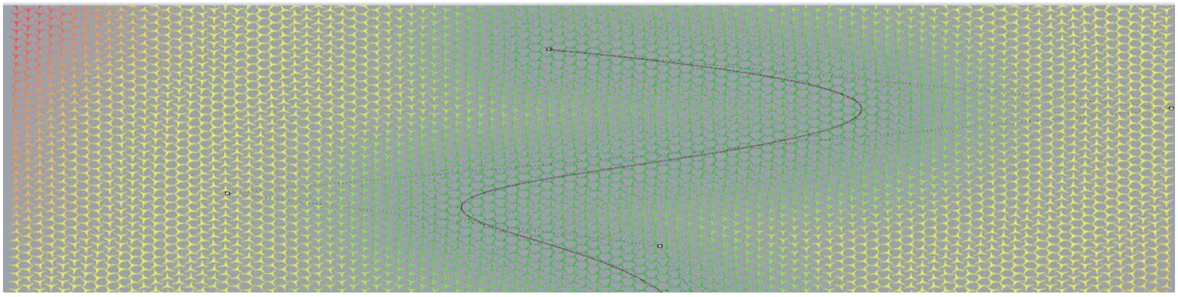

Figure 4.14. As an interaction with the introduced parameter, the grid of modules reacts

As shown in Figure 4.14, an interaction with the introduced parameter, grid of and modules reacts and the modules rotate based on the distance from the curve. The distance from the curve, in this case, is directly proportional to the rotation of module. The gradient in color shows effect of the added parameter curve on the field. Its intensity increases from red to green.

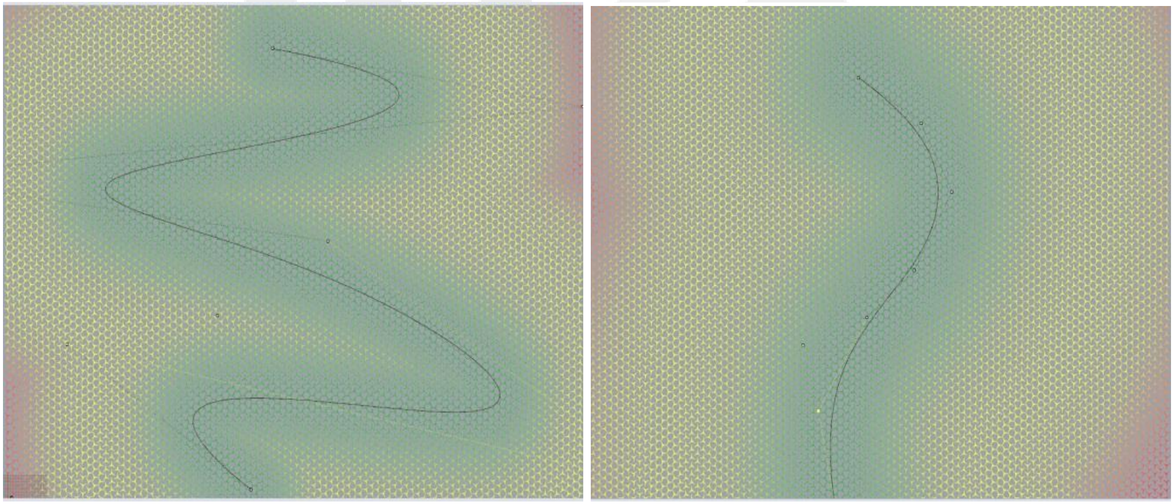

Figure 4.15. As the curves shifts its segments, the field interacts and adapts to its input

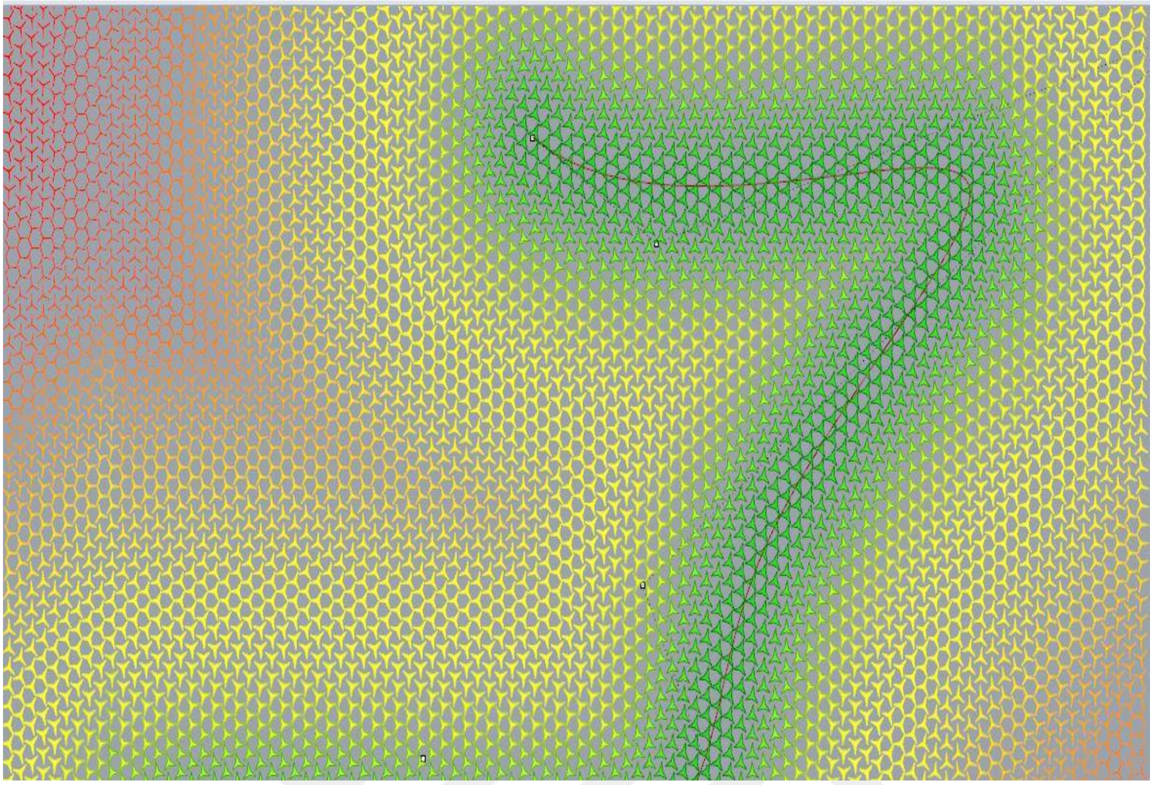

Figure 4.16. As an extension of the adaption, another layer is introduced to the modules, as an interaction with the parameter curve

The amplitude of the joints of the star module is then connected to the distance of the module with the parameter curve. Hence the closer the module is to the curve, the thicker it gets and opens up as it moves away from the curve, as shown in Figures 4.13 and 4.14.

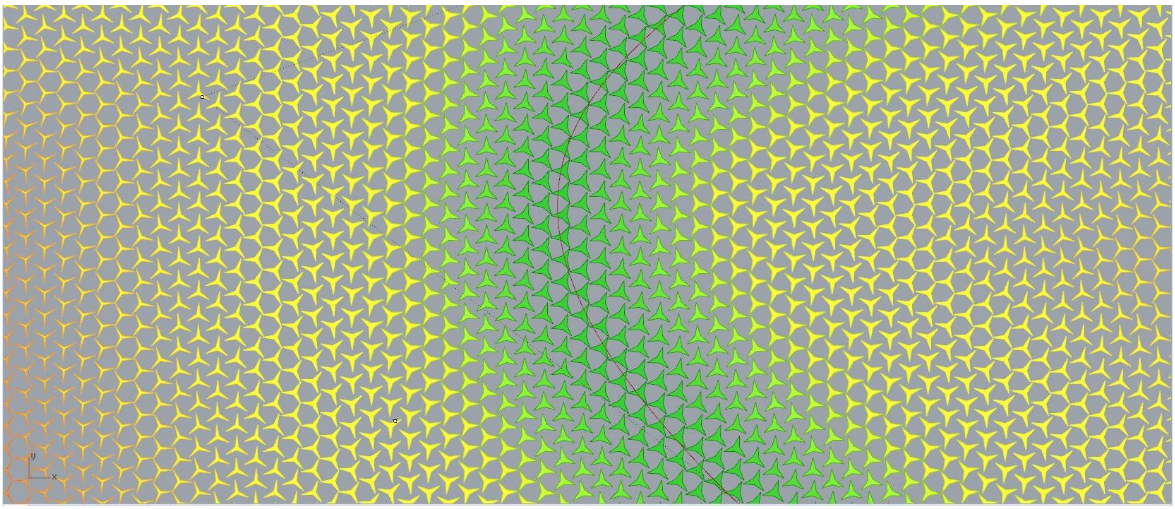

Figure 4.17. The closeup shows the thickness gradually increasing as the modules gets closer to the parameter curve

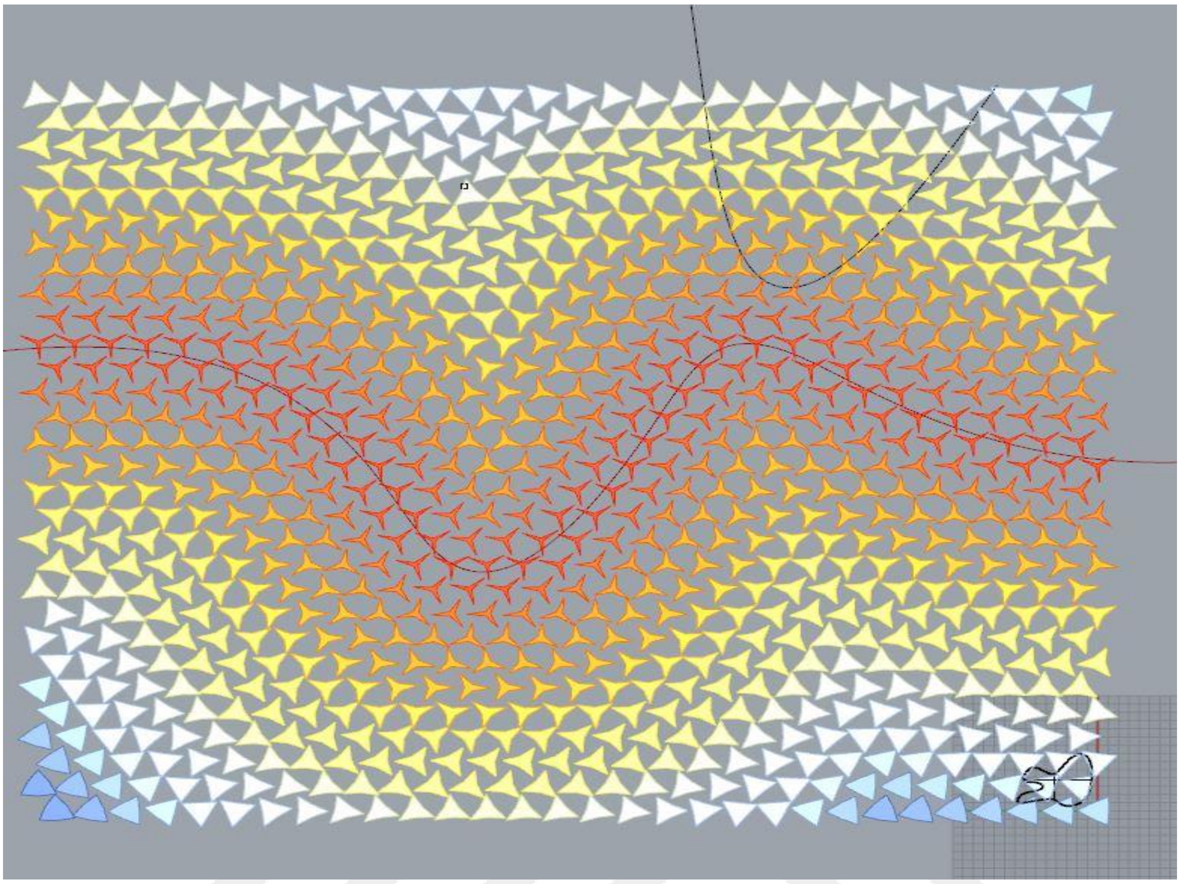

Figure 4.18. The closeup shows the thickness gradually increasing as the modules gets closer to the parameter curve

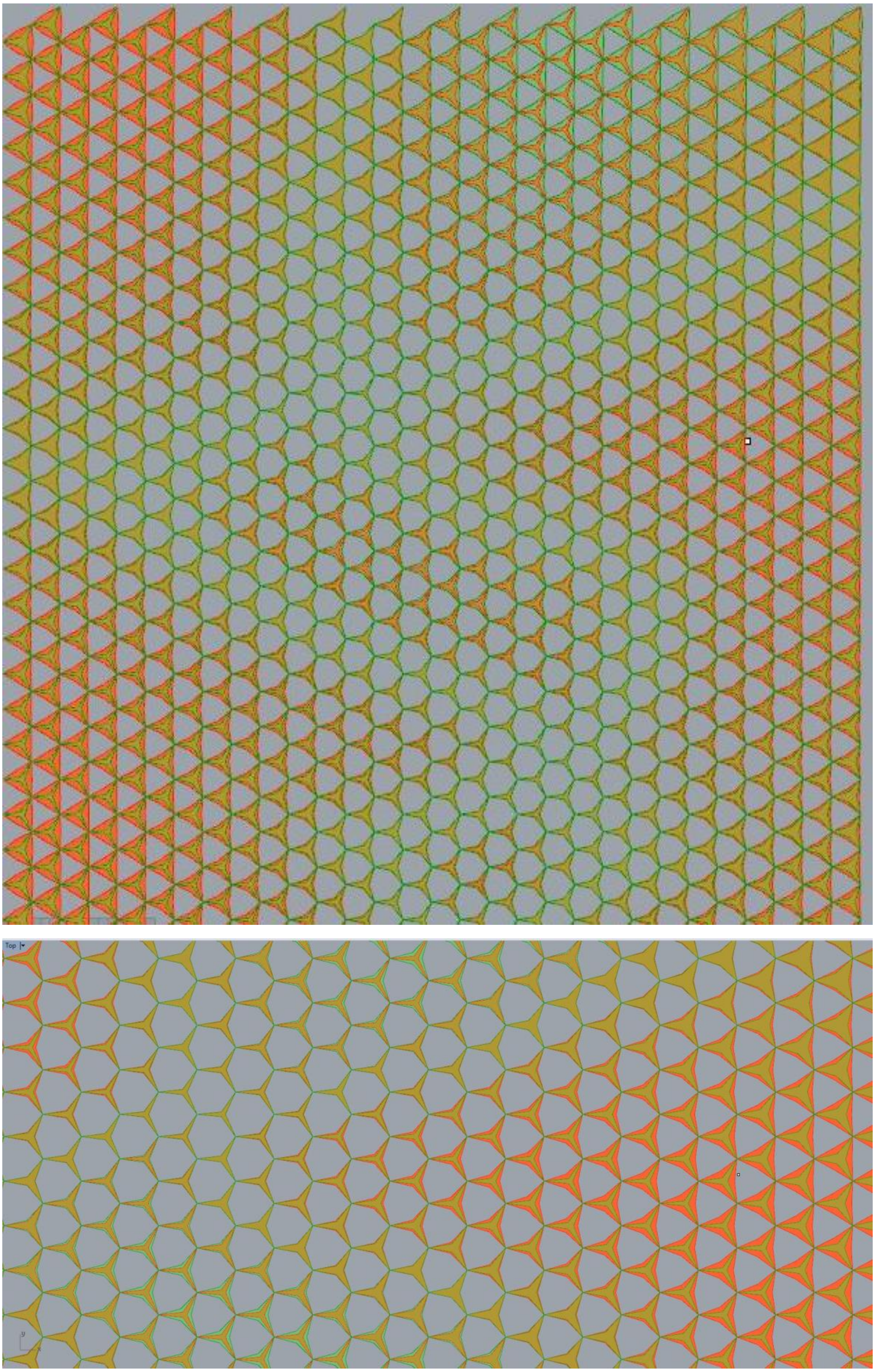

Figure 4.19. The two overlapped grids

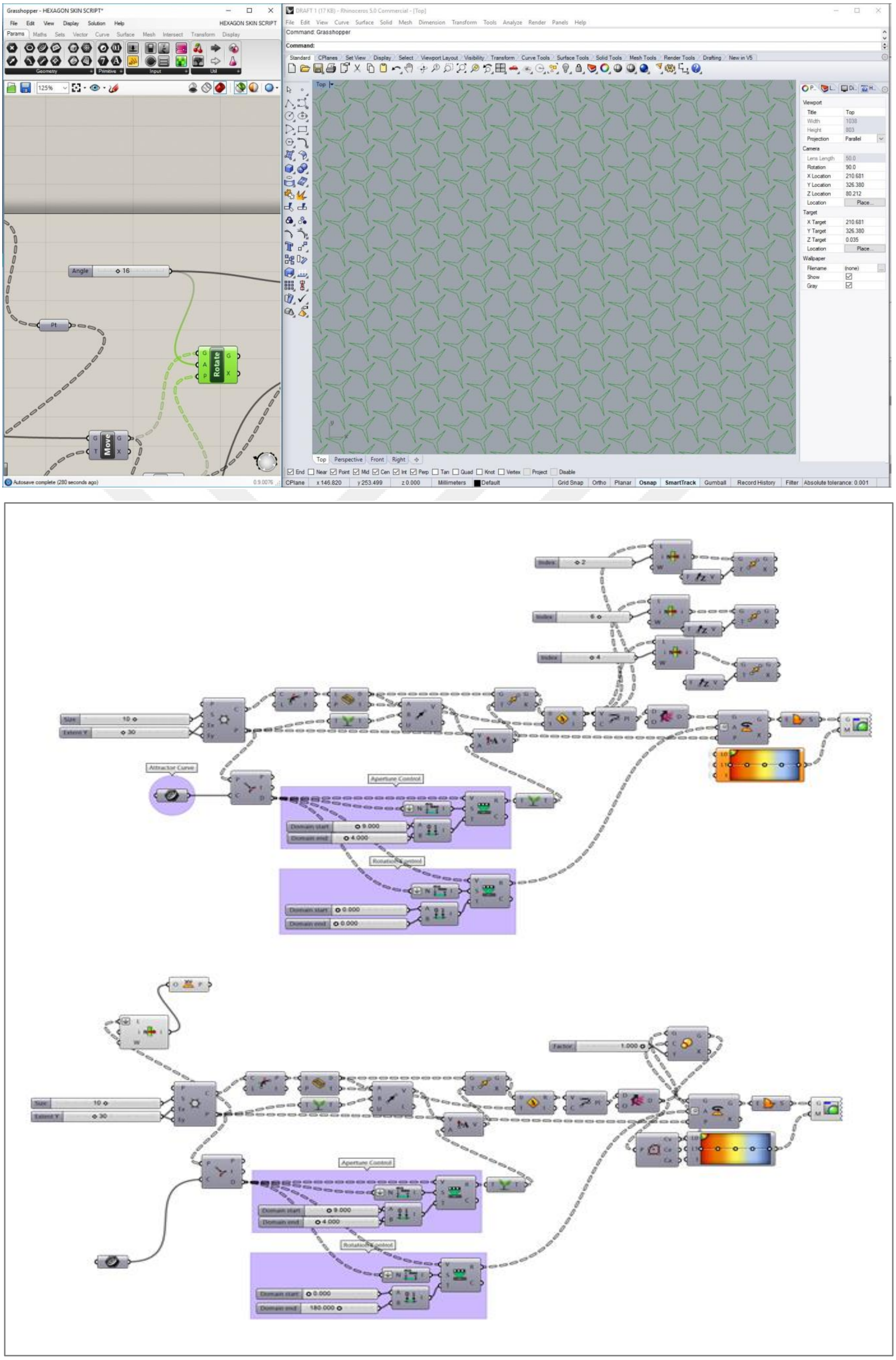

Figure 4.20. The scripting processes

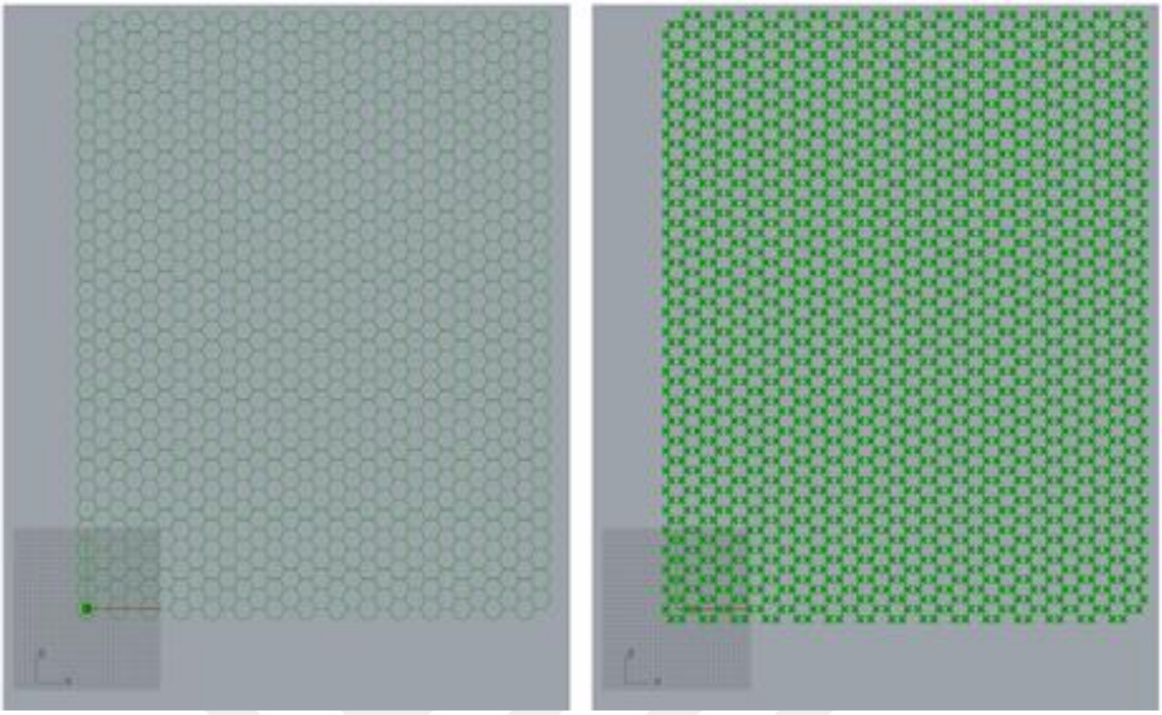

Figure 4.21. The process starts off with a hexagon grid by using hexagrid component (left). Then extract its vertices using discontinuity component (right)

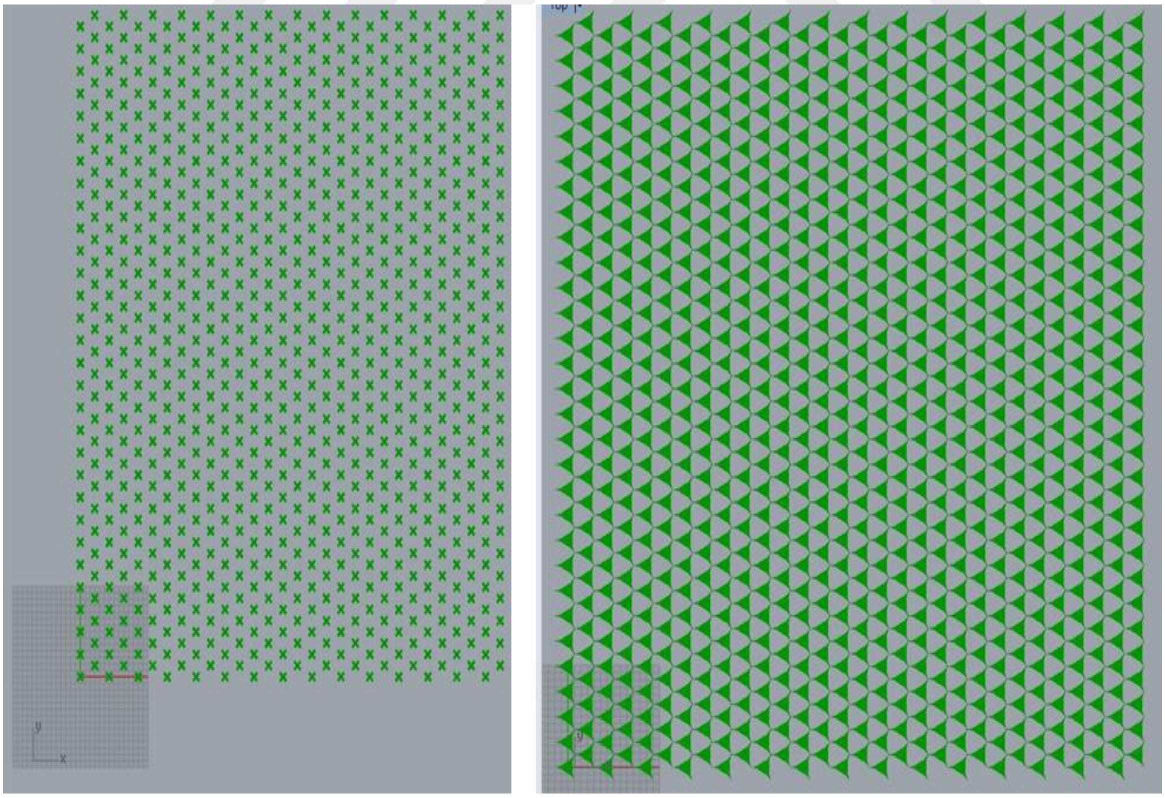

Figure 4.22. Then the polygon centers are extracted using the HEXGRID component (left). use a VEC2PT component to generate vectors (right)

By using a HEXAGRID component, a hexagon grid is achieved. Once the grid is formed its vertices are extracted using a DISCONTINUITY component, the curves are exploded into segments and vertices, as shown in Figure 4.21. Then the polygon centers are extracted using the HEXAGRID component and grafting the list to match the lists created by discontinuity component, as shown in Figure 4.22. Then a VEC2PT component is used to generate vectors that will then be amplified based on the distance from the remapping done by the input curve. (Figure 4.22)

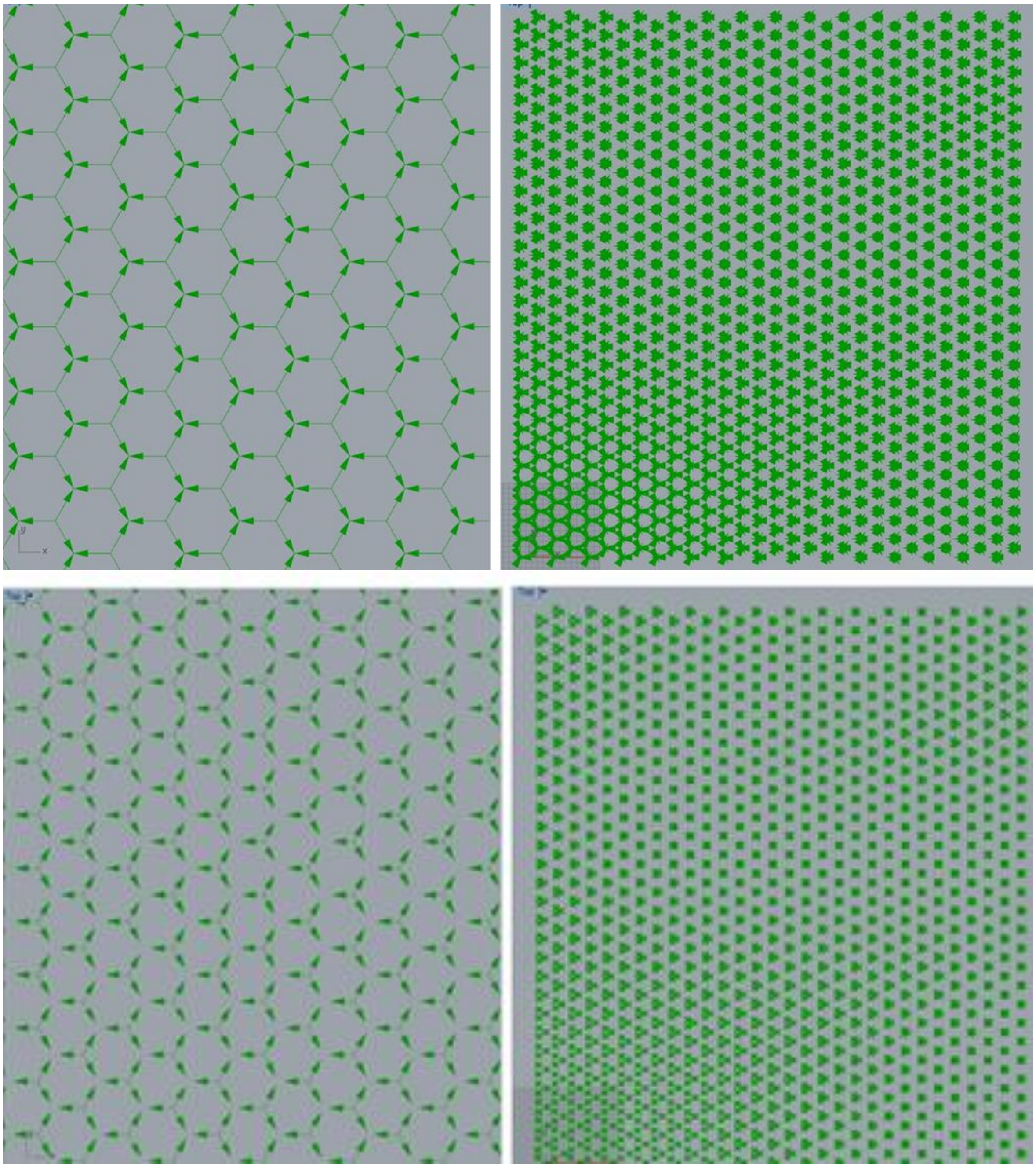

Figure 4.23. REMAP component is used to remap these values on the scale of the hexagon grid and then is fed via AMPLITUDE component in the vectors

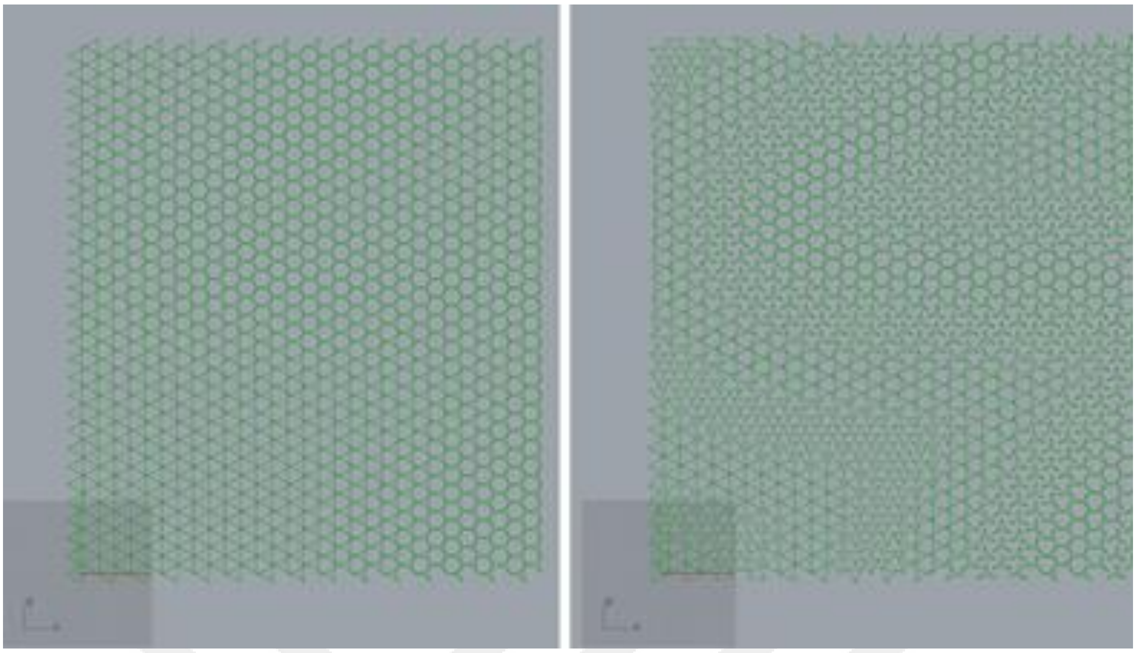

Figure 4.24. These vertices are now joined using POLYLINE component, to make the outline of the modules (left). Now the rotation component is introduced to provide rotation to each and every module based on the amplitude calculated earlier (right)

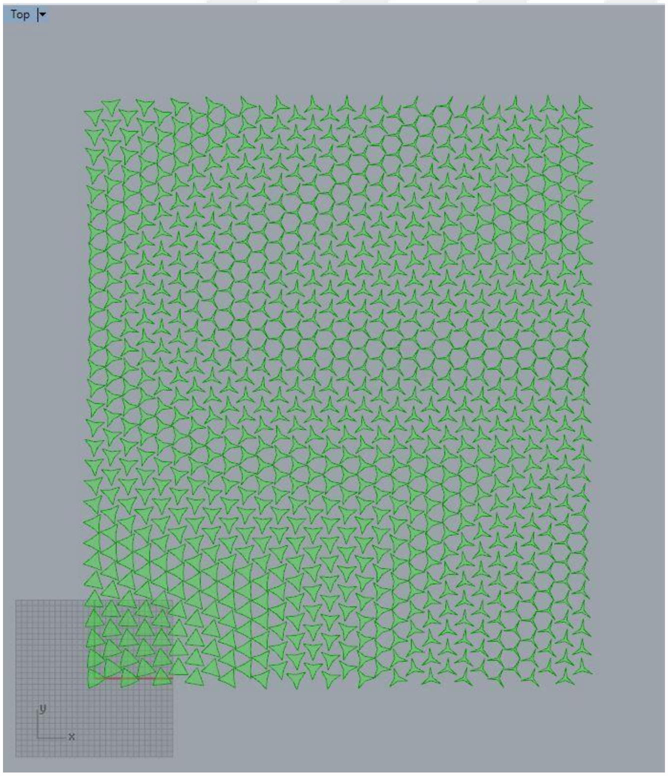

Figure 4.25. Final outcome, a planar surface component is used to add the surface to the outlines

For calculating the amplitude that will affect the vector’s intensity, a component CRV CP (Closest point on Curve) is used with the curve and hexagon grid as inputs, which gives the closest point on each curve cell on the grid and its distance from the input curve, as represented in Figure 4.23. These values are then fed into the BOUNDS components which calculate the extremities of the data set and the Domain component remaps those distance values onto the provided range.

Then a REMAP component is used to remap these values on the scale of the hexagon grid and then is fed via AMPLITUDE component in the vectors. The result is following diagram showing the changed amplitude of vectors as per the distance of input curve. Then these vectors are used to move our points to create an outline of each module, each affected the amplitude calculated from the input curve (Figure 4.23 lower right).

4.2. Design Drawings: The Three Layered Jali

In this design exercise a hexagon is used as a basic unit and it is broken into four parts, each part is a three-cornered star/ fan shaped form which is a single module with its own pivot point. These modules rotate on its pivot point and they expand as well. The two parameters that are responsible for the expansion and contraction of response and the kinetic motion of this form are light/heat and motion.

The screen is designed in three layers. The script controls their movement and can be programmed as required. The first is the lattice structure, a hexagonal grid. This is the static frame that acts as the base of the entire screen. (Figure 4.26)

The second layer, as shown in Figure 4.27, is the kinetic translucent modules parameters, defined by the privacy, which is also user interactive, as its rotation is based on motion sensors. This layer can be sensory based and scripted to respond to movement as a result it is user interactive screen. This layer is for privacy and view control. As the sensors detects the user’s presence/ movements, the units start rotating from its pivot point creating semi permeable screen between the interior and the exterior, keeping the privacy of the user inside and at the same time doesn’t obstruct the view of the outdoors.

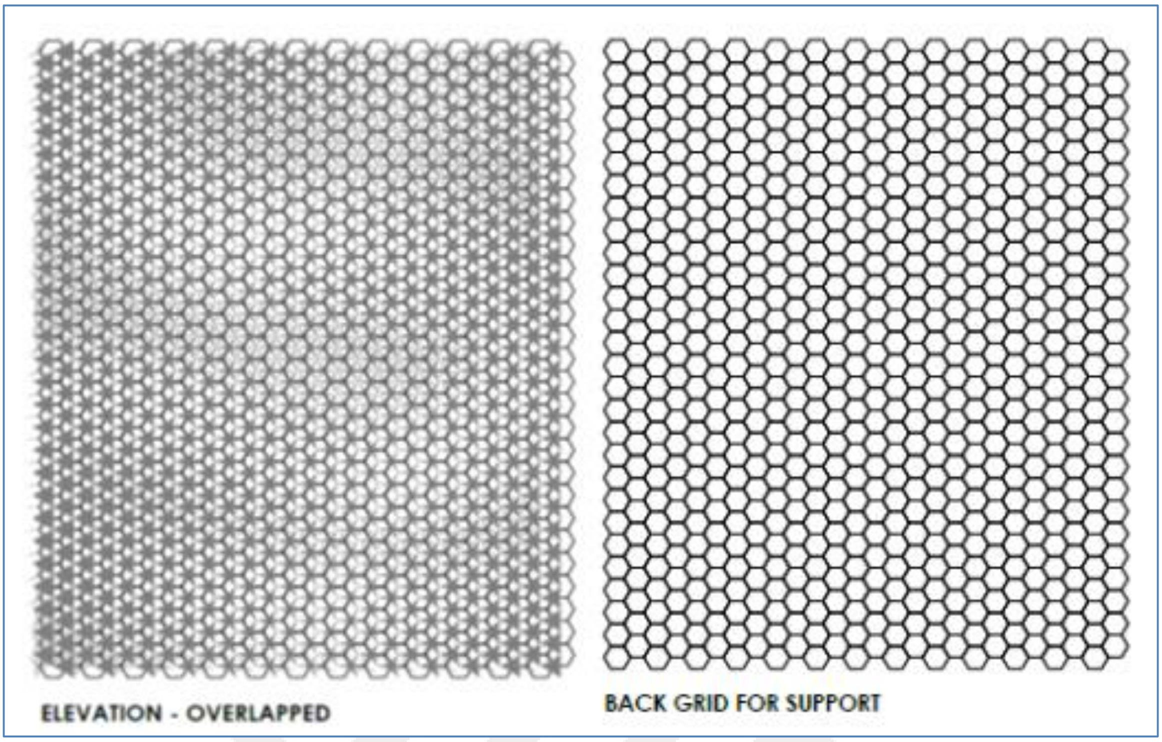

Figure 4.26. The overlapped layered screen (left). The hexagonal grid for the base. The static back grid for structural support (right)

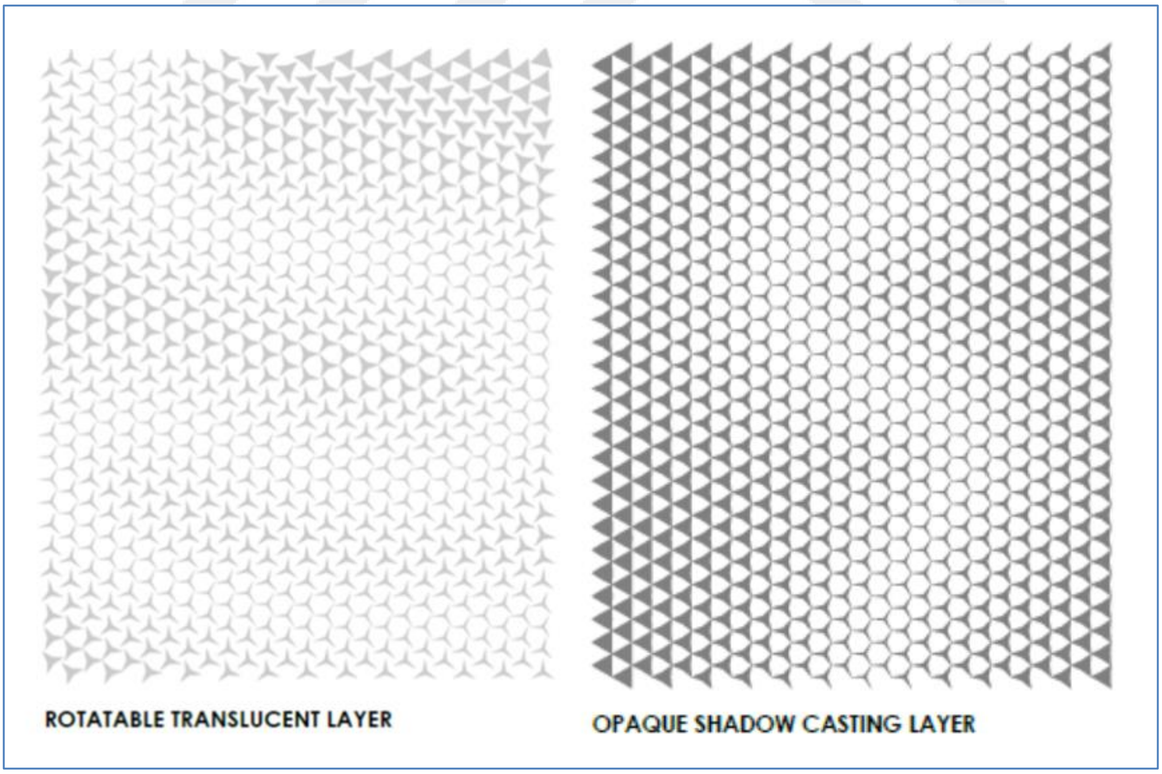

Figure 4.27. The second skin, the rotatable translucent layer that is movement sensor based and user interactive (left). The opaque responsive layer of the screen (right)

The third layer which is also the outermost layer is the opaque skin with the kinetic star modules that contract and expand, shown in Figure 4.27. These are scripted to respond to heat and light from the sun as a result the units expand to minimize the light to enter the interior spaces and control heat as well. The shaded areas remain in their original state. These modules don't close completely, retaining their unique character of a screen, to diffuse light and allow ventilation.

Mechanism: The screen is designed in three layers, first is the hexagonal grid that remains static. The second layer is the translucent skin, which is sensitive to motion and user interactive with sensors and the third is responsive to the sunlight. The two kinetic layers has a pivot point that is connected to the static grid, which acts as a base. The electric motor helps in the movement of the star shaped triangular modules.

The second layer which is the translucent layer just rotates on its pivot point and expands like the opaque third layer. The third layer of the screen remains static on its pivot point and expands and contracts depending on the sun light. Figures 4.28 and 4.29 shows the working of the screens single module.

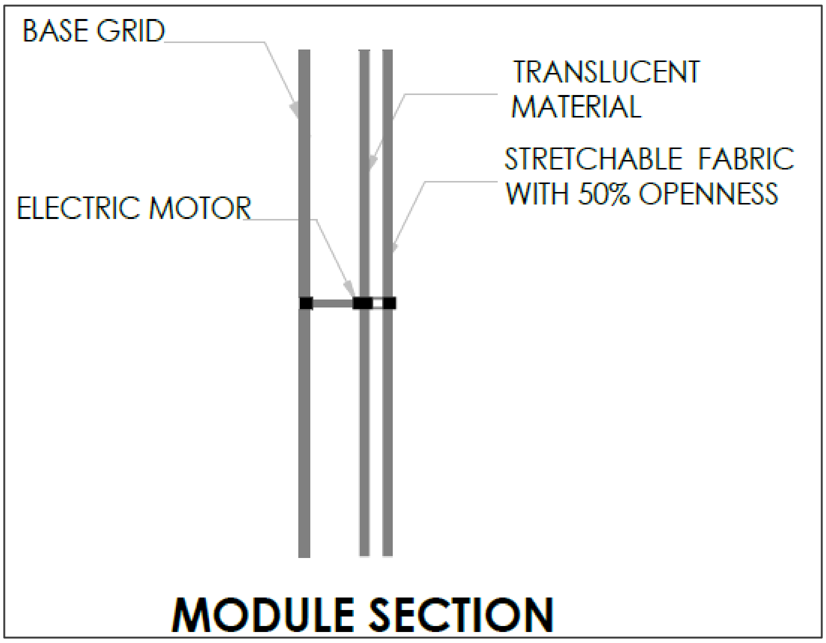

Figure 4.28. The section of the module showing the base grid, the electric motor being the pivot point, the translucent screen and the final layer of the stretchable fabric

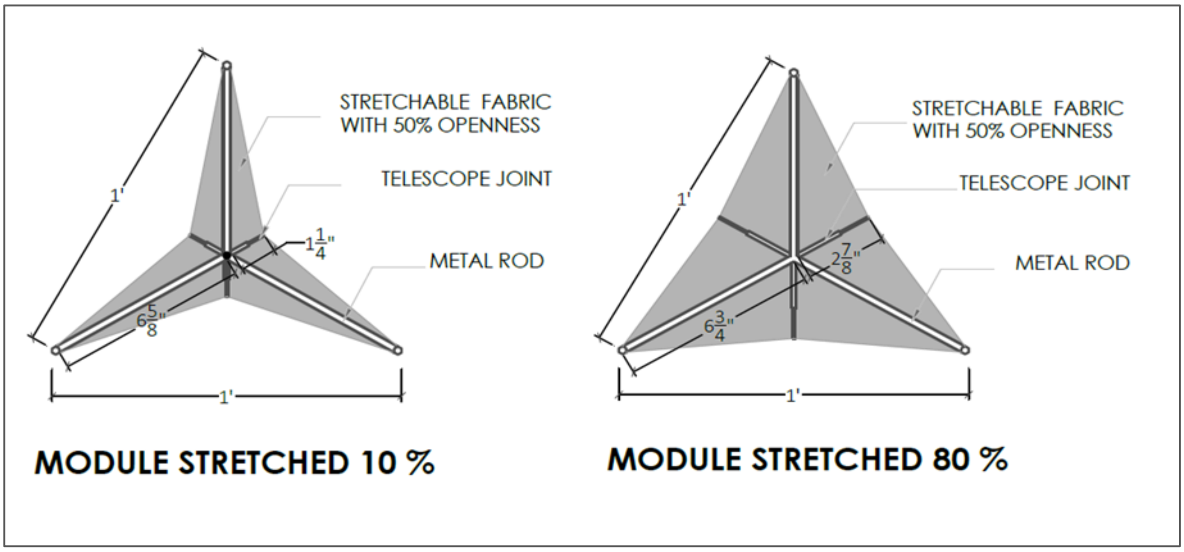

Figure 4.29. The single module details when its stretched 10 % (left) and 80% (right). The metal rod makes the basic structure, along with the telescope joints which helps it to stretch and contract easily

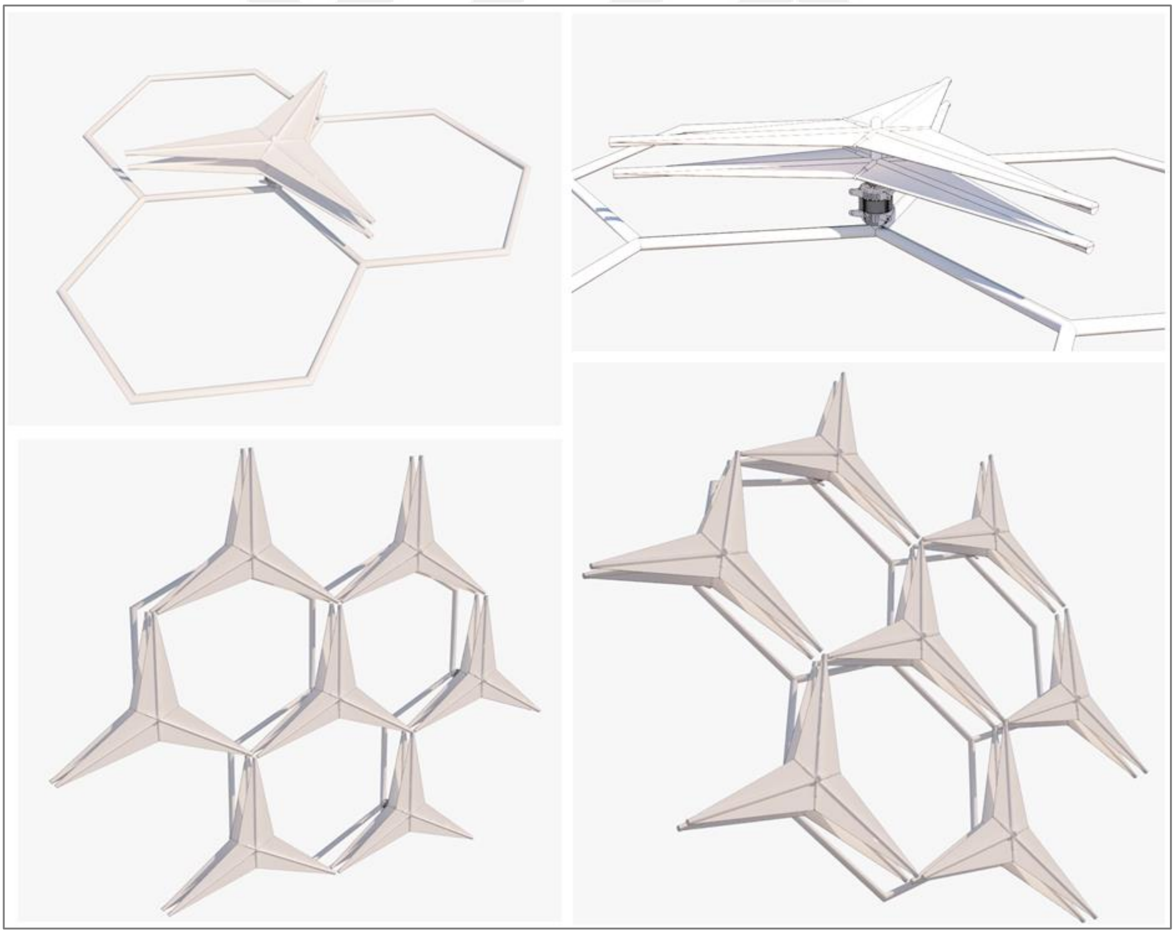

Figure 4.30. The three-dimensional drawing of the three layers of the screen. The first, lower mesh is a hexagonal static grid which acts as a base for the two kinetic triangular modules that are attached to it

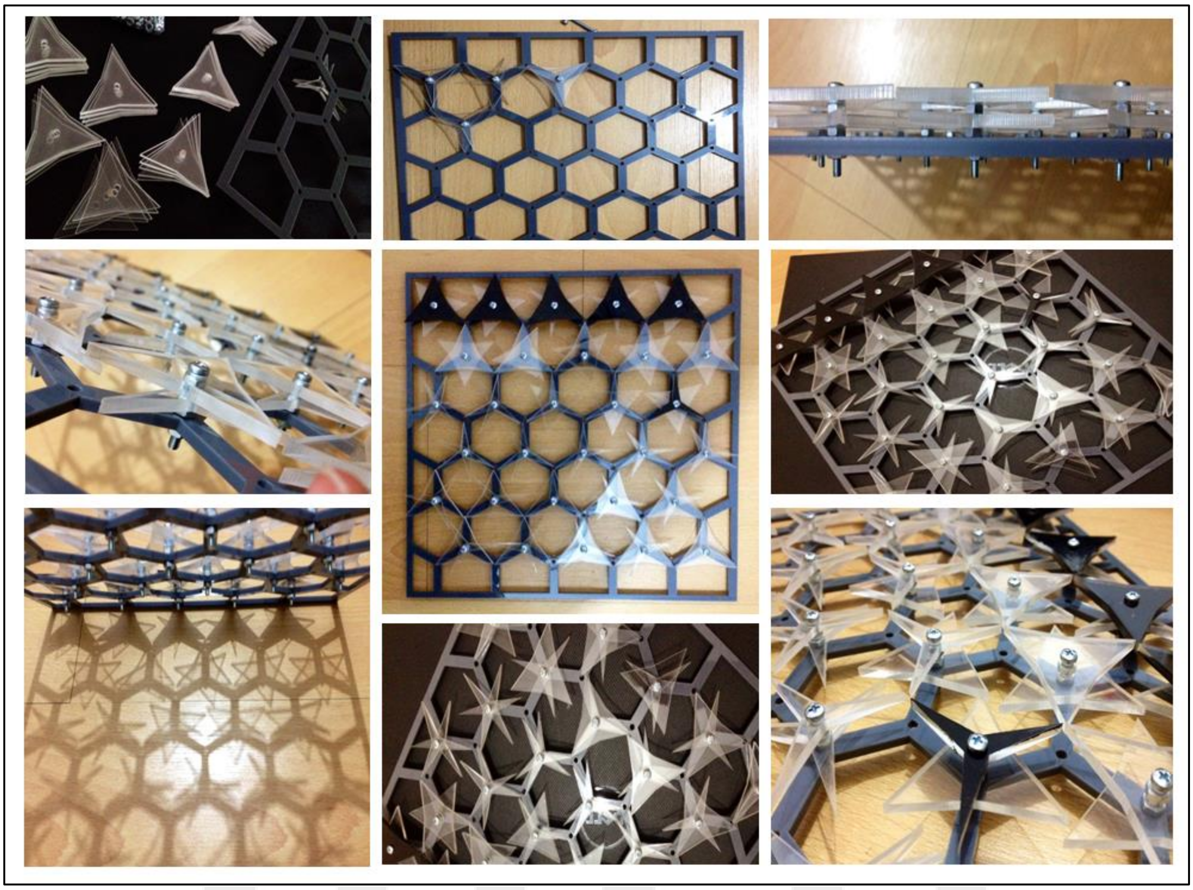

Figure 4.31. Study model

4.2.1. Application

The developed screen is applied on a conceptual building, to understand its application and its overall look.

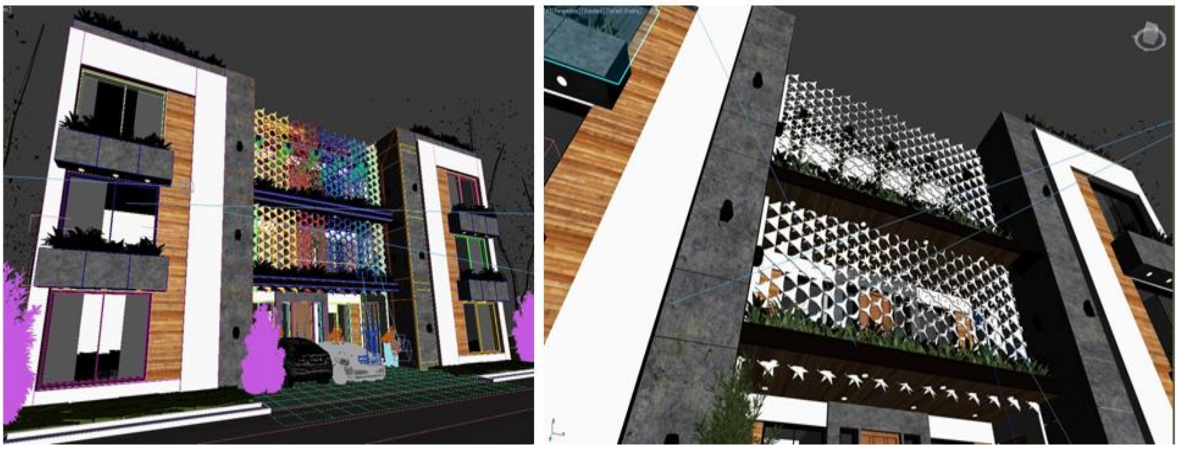

Figure 4.32. The application of the designed three-layered screen on a conceptual building

Figure 4.33. The application of the designed three-layered screen on a conceptual building

As a conclusion, in this design, the module and its adaptation to the curve is easily achievable by using motors as pivots for modules and a light sensor connected via a computer with the script. Even for the application in a live project, the technology required is currently available, as opposed to some other adaptation techniques with requires going into transformable materials. In terms of cost, this application is relatively cheaper and easily applicable.

5. CONCLUSIONS AND FUTURE REMARKS

Façades or the building envelopes have always been the most significant feature of an architectural design, as it's not only the buildings elevation, it is the interface between the building and the environment. With the changing time and evolution of technology, the focus still remains on the façade design, due to the numerous significant roles that a facade plays, as it is responsible for the thermal comfort, aesthetics, acoustics, lighting of the building.

Energy conservation and optimization have been a major concern, since the last few decades. The ideas of sustainability and passive cooling techniques in design have once again gained popularity. The effective facades that are designed to adapt the environmental conditions aren't a new phenomenon, it dates back when windows and ventilators were designed carefully in response to the site conditions and environment. Lately the architects and engineers are aiming at improving the interior spaces and thermal comfort, using innovative ways for efficient systems or designs that eliminate or reduce the need to use mechanical heating or cooling. As the architects and engineers work more on the skin of the building, experimentation has resulted in high performance building facades, which have become one of the main focuses for researchers and designers.

This study focuses on the high-performance buildings that have changed the way we perceive and design the façade; these smart façades are the new phenomenon, where the façade is not just a static elevation but a dynamic building component, a living skin. In high performance smart buildings, one of the main features is kinetic façades. Architects and engineers fascination of kinetic façade has been there for long, but now it has surpassed the aesthetic reasons only and is considered as a vital element in designing for environmental reasons. The kinetic façades are designed to be responsive to surroundings, having kinetic climate-adaptive elements including sensors and automation, along with the user or designers ability to dominate and control the settings.

The parametric designed kinetic façades has brought a drastic change in the field of design and architecture. It has undoubtedly widened the design possibilities in the mindset of architects and designers, as there is a shift from the conventional problem solving in a defined formal solution to an entire new dimension where there are countless possible outcomes. Due to the advanced computational techniques, their role is not confined to drawing shapes only but has progressed to creating formal possibilities and more dynamic forms. As we have seen and analyzed in the case studies of the built architectural marvels like Al-Bahar towers.

This aim to this exercise is, reviving the use of jali in the modern day architectural design practice of façade design or a skin for a building. Jali's have been very essential architectural elements of the Indian subcontinent, due to its architectural significance of passive cooling properties and cultural importance of privacy. In this study the screens and the geometric patterns have been studied and analyzed in order to understand its formation and tessellation, to proceed with the design case study to find new possible outcomes for the façade design in amalgamation of jali.

This research demonstrates the basic understanding of the concept of parametric and use of software in designing a kinetic facade. The design exercise is based on the findings from the research and literature review. The two design exercises that have been carried out are in order to explore kinetic systems, with the potential of a simple geometric design used as a module to generate the skin and its kinetic response.

In both the design exercises, hexagon grid is taken as a basic layout. The design focuses on the kinetics of the screen that is responsive to the light and privacy of the user. The screens are generated using grasshopper, where they are introduced with an attractor curve, as an input, the responding factor. The interactions of these curves and the points of the vertices of the hexagonal grids cells result in the kinetic movement of the screen, making it like a living skin of the façade or an opening.

In the Design 1, the grid remains static and the screens hexagonal cells respond like a cameras aperture, which expands and contracts in response to heat/light. Its effective and controls light entering the interior spaces, using materials with expanding and contracting properties, along with a hydraulic system to control the expansion and contraction of the opening. In this design the screen becomes very opaque and obstructs the view as well, unlike a jali where the screen fulfills its purpose as a viewing curtain along with a light diffuser.

In the Design 2 the base grid is static and the other two layers are kinetic, one that rotates and expands without obstructing the view and one that only contracts/expands to control the sunlight. This screen is also easily applicable as the technology required for this type of kinetic motions is currently available (as opposed to some other adaptation techniques with requires going into transformable materials), it’s achievable by using motors as pivots for modules and a light sensor connected via a computer with the script.

With the present examples of use of kinetics in architectural design, the kinetic façade is the new present and the coming future of the façades. It is constantly progressing and putting forward new challenges, addressing new problems and finding new solutions, to make the best use of resources in order to achieve harmony, with the environment the building is placed in. So far in this era of kinetic façade design and fascination, it cannot be concluded that a perfect solution or formula has been achieved. One cannot simply say which is the best model to use or which design has the best environmentally responsive approach, as all these designs are different in nature and differ in the context they are placed in. As a result we can look at all these existing designs in order to study them and as models to analyze, to find out which approach worked the best for the user comfort along with the environmental context it was placed in and the results that these projects have in terms of optimizing energy efficiency.

It can be concluded from these investigations that if further research and design exercises are performed using various geometrical patterns, unlimited solutions and forms of screens can be achieved. The single module taken from a conventional screen can be the basic pattern generator and transformation in a parametric design for a screen or skin of facade or the facade itself. The numerous solutions and options that these computer-generated designs have opened a gateway for further explorations in the field of design which undoubtedly leaves us more inquisitive. The investigations made in this research are significant in terms of the potential use of screens, in modern architectural practices in responsive facades, using parametric patterns.

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