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DESIGN AND COMPUTATIONAL OPTIMIZATION OF A KINETIC FACADE

MÜMİN BAYAR

THESIS ADVISOR: ASSIST. PROF. DR. FERAY MADEN

DEPARTMENT OF ARCHITECTURE

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We certify that, as the jury, we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Jury Members:	**Signature:**
Assist. Prof. Dr. Feray MADEN Yaşar University	....
Prof. Dr. Koray KORKMAZ Izmir Institute of Technology	....
Assoc. Prof. Dr. Yenal AKGÜN Yaşar University	....

Assoc. Prof. Dr. Cüneyt GÜZELİŞ

Director of the Graduate School

ABSTRACT

DESIGN AND COMPUTATIONAL OPTIMIZATION OF A KINETIC FAÇADE

Bayar, Mümin
M.Sc. in Architecture
Advisor: Assist. Prof. Dr. Feray Maden
April 2020

Building facade has a significant impact in energy consumption since it is responsible for heat loss and over-heating. Thus, architects should consider not only the aesthetic criteria but also the comfort of users, environmental conditions, illuminance, glare and solar radiation when designing a facade. Today's architecture seeks for a new approach for designing building facade that can adapt to changing environmental conditions and occupants' needs. Kinetic facade systems can provide functionally efficient solutions since they play a key role to meet the aforementioned requirements. A kinetic facade can be described as a system that allows movement on the building surface in response to user needs and changing environmental conditions. This is a way of adaptation process of the kinetic facade.

The main objective of this study is to develop a new kinetic facade system that can adapt to ever changing conditions. For this purpose, first, a parametric model of the proposed kinetic façade is built. Then, the parametric model is used in simulations applying the "Multi-Objective Evolutionary Optimization" techniques to obtain optimal results for both the illuminance level inside the building and the solar radiation level on the facade. By this means, more efficient kinetic façade system is developed using the computational optimization which is another focus of the study. In this thesis, the kinetic façade is designed based on regular tessellation technique which has hexagonal shape. The proposed kinetic façade can be applied to all building facades facing any directions. Therefore, its flexibility and mobility provide functional, effective and efficient solutions for user comfort.

Key Words: Kinetic façade design, Tessellation, Simulation and modelling, Computational optimization, Performance optimization, Parametric design.

ÖZ

KİNETİK BİR CEPHENİN TASARIMI VE HESAPLAMALI OPTİMİZASYONU

Bayar, Mümin
Yüksek Lisans, Mimarlık
Danışman: Dr. Öğr. Üyesi Feray MADEN
Nisan 2020

Bina cephesi, ısı kaybından ve aşırı ısınmadan sorumlu olduğu için enerji tüketimi üzerinde önemli bir etkiye sahiptir. Bu nedenle, mimarlar cephe tasarlarken sadece estetik kriterleri değil aynı zamanda kullanıcıların konforunu, çevre koşullarını, aydınlığı, parlamayı ve güneş ışınımını da göz önünde bulundurmalıdır. Günümüz mimarisi, bina cephe tasarımı için değişen çevresel koşullara ve kullanıcı ihtiyaçlarına cevap verebilecek yeni bir yaklaşım aramaktadır. Kinetik cephe sistemleri, yukarıda belirtilen gereklilikleri karşılamada önemli bir rol oynadığından işlevsel olarak etkin çözümler sunabilir. Kinetik cephe, kullanıcı ihtiyaçlarına ve değişen çevre koşullarına cevap olarak bina yüzeyinde harekete izin veren bir sistem olarak tanımlanabilir. Bu, kinetik cephenin adaptasyon sürecinin bir yoludur.

Bu tezin temel amacı, sürekli değişen koşullara uyum sağlayabilecek yeni bir kinetik cephe sistemi geliştirmektir. Bu amaçla, ilk olarak önerilen kinetik cephenin parametrik bir modeli oluşturulmuştur. Daha sonra parametrik model, hem bina içindeki aydınlık seviyesi hem de cephedeki güneş ışınım seviyesi için optimum sonuçları elde etmek amacıyla "Çok Amaçlı Evrimsel Optimizasyon" tekniklerinin uygulandığı simülasyonlarda kullanılmıştır. Bu sayede, çalışmanın bir diğer odağı olan hesaplamalı optimizasyon kullanılarak daha verimli kinetik cephe sistemi geliştirilmiştir. Bu tezde, kinetik cephe altıgen şekle sahip düzenli tesselasyon tekniğine göre tasarlanmıştır. Önerilen kinetik cephe, herhangi bir yöne bakan tüm bina cephelerinde uygulanabilmektedir. Cephenin esnekliği ve hareketliliği sayesinde kullanıcı konforu için işlevsel, etkili ve verimli çözümler sunmaktadır.

Anahtar Kelimeler: Kinetik cephe tasarımı, Tesselasyon, Simülasyon ve modelleme, Hesaplamalı optimizasyon, Performans optimizasyonu, Parametrik tasarım.

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Finally, my special appreciation and great gratitude are devoted to my family for their endless love, patience, moral support and encouragement in every moment of my life.

Mümin Bayar
İzmir, 2020

TEXT OF OATH

I declare and honestly confirm that my study, titled “DESIGN AND COMPUTATIONAL OPTIMIZATION OF A KINETIC FACADE” and presented as a Master’s Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Mümin Bayar

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April, 27 2020

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CHAPTER 1
INTRODUCTION

1.1. Motivation

Building facade is always considered as only a physical separator between the interior and the exterior environment (Sharaidin, 2014). However, it is not just a physical separator but also an effective building component that is multi-functional (Tzempelikos et al., 2007). Because the building façade has an active role in maintaining optimum living indoor conditions (Sharaidin, 2014), designers should consider reducing the energy consumption of the building in the design process.

Building construction and usage play a significant role in overall energy consumption; because, %36 of the energy consumption is caused by the building sector which is higher than transportation and industrial sectors (Abergel et al., 2017). Since the building façade is responsible for heat loss and over-heating, it becomes a vital element in the design process. Thus, it may be a part of the solution to the energy problem (Loonen et al., 2013).

The focus of this thesis is the building façades that have multi-functionality. In a conventional way of building design, the facade contains fixed elements that cannot respond to the changing environmental conditions and occupant needs (Sharaidin, 2014). Even though classical blinds and louvers have a strong influence on mainstream facade development as they are seen in many landmark projects, they cannot meet the changing requirements very well. Thus, a new design solution is required which provides adaptation not only to the environmental conditions but also to the user preferences. This solution can be found in kinetic architecture.

Over the last few decades, the interest on dynamic, kinetic, adaptive and responsive building facade systems have been increased (Sharaidin, 2014). These façade systems have the ability to facilitate adaptation and responsive process to the changing environmental conditions. This ability gives designers an opportunity to provide better energy performance of the building and user comfort (Sharaidin et al., 2012).

In this thesis, first, the kinetic façades which have been applied till the present day have been examined. Based on the results of the investigation, a kinetic façade is designed by considering the future problems of the existing kinetic facades. Although this kinetic façade design is made in a digital environment, the construction of the physical model and the testing of its mobility on the model does reveal a strong side of the design.

1.2. Problem Definition

The interest on kinetic façade designs has increased but the applications of such designs are still limited to certain solutions. One of the main reasons is the mechanical and structural complexity of their systems. This complexity stands out in many existing examples.

Although the main aim of the kinetic façade design is to adapt to ever changing conditions, the developed kinetic façades may not achieve the intended goals when the kinetic design is applied on another building façade or in another country.

Even though the use of digital tools in today's kinetic façade designs has great importance in developing the façade elements, the issue remains insufficient when it comes to the energy use. Because, the design proposals analyzed in computer environment cannot reach the levels obtained from the analyzes when they are constructed.

1.3. Aim of the Study

Due to the aforementioned deficiencies in the existing kinetic facade designs, the necessity of designing a new kinetic façade is revealed. The aim of this thesis is to design a kinetic façade based on tessellation technique which not only adapts to changing conditions but also eliminates the aforementioned fundamental design problems. The proposed kinetic façade is created as a secondary layer on the building surface. A much more efficient solution is developed to adapt to the changing environmental conditions.

The proposed kinetic façade, which is integrated into a façade formed in the simulation and whose mobility is determined, is optimized by using computational optimization tools as measuring the level of illuminance in a closed space and the solar radiation level on the façade. In this way, it is provided to work more efficiently within the kinetic façade.

Many kinetic façades implemented till now have either complex mechanical systems or require high technology computer system to control the movement of the façade elements. One of the aims of this thesis is to reduce the complexity of the facade system by offering a simple system that does not include high technology to create the required movement on the façade. Another aim of the thesis is to develop such a kinetic façade system that can be applied on each facade of the building to reach the intended goals.

1.4. Method of the Thesis

In the first stage, the literature about the kinetic facades are reviewed to examine the existing examples of the kinetic facades in detail. By this means, main design principles of the kinetic facades, their strengths or weaknesses and movement principles are revealed. In addition, a new classification table is created for the examined façade systems since there is no systematic review in the literature based on the motion.

In the second stage, this study focusses on designing the kinetic façade by investigating the tessellation techniques. As shown in Figure 1.1., the overall design process consists of many parts. The design process firstly starts with choosing a suitable geometric shape for tessellation. Hexagonal shape is selected, because the proposed kinetic façade can be adapted to every facade and the sun rays at different angles can be prevented. The edges of this shape are used as the structural frame. The placement of the moveable louvers on the hexagon is that each louver has equal distance to each other. Then, the motion principles and rules of the designed movable louvers are determined. The applicability of these movements is tested within parametric modelling. Finally, a mechanism is designed in accordance with the designed principles of motion.

In the third stage, a parametric model of one-room building is created digitally. 90% of the southern façade of the one-room building is made of glass material and all other facades are designed with non-transparent walls. The kinetic façade is applied on the south façade of this building. Both the level of illuminance in the building and the solar radiation level on this façade are measured. After this stage, by changing the angles of the louvers of the kinetic façade, computational optimization tools are used for the optimization to keep the illuminance level within the building at 500 lux and the solar radiation level on the façade as low as possible. This optimization is made for predetermined days and times.

Figure 1.1. Design stages of a kinetic façade from start to the end.

In the fourth stage, the positions and angles of the kinetic facade elements are determined according to the day and hour determined by the results of simulations and optimizations. In addition, a comparison table of the results are created.

1.5. Significance of the Study and Contributions

Creating a kinetic façade is a complex design process where many interrelated issues must be considered simultaneously. It requires an interdisciplinary study where architects, mechanical engineers, computer engineers, structural engineers and even electrical engineers should work together. This study presents the following contributions with the kinetic façade system.

- A systematic review on the kinetic facades is presented.
- A simple mechanical system is used.
- A simple solution is proposed for the façade elements.
- The proposal can be used in each direction of the building facades and energy efficiency is preserved.
- Optimization is conducted with Multi-Objective Evolutionary Optimization techniques to increase efficiency.
- Although the entire system is in closed position, the illuminance is at the targeted level.

- Solar radiation on the building facade can be substantially blocked.
- The methods used in this thesis can be considered as an example and guidance to the other researches.

1.6. Outline of the Thesis

This thesis consists of six chapters in total.

Chapter 1 introduces the motivation, problem definition, aims, context of the thesis, method, significance, and contributions of the study.

Chapter 2 where the existing kinetic façades from the past to the present are examined and divided into three categories by considering the factors in the formation of the movement. These three categories are actuator-based systems, smart material-based systems and passive systems. In addition, these categories are divided into three sub-categories based on the type of the motion which are radial motion, translational motion and rotational motion. Also, a new classification system is proposed based on the motion types of kinetic façade systems.

Chapter 3 investigates the tessellation technique that can be used in architectural applications. Tessellation is categorized into three groups as regular tessellation, semiregular tessellation and demi-regular tessellation. Architectural examples of the tessellation are also presented in this chapter.

Chapter 4 focuses on the design of the kinetic façade which includes all the design rules related to the geometry, parametric model and movement. Starting with the geometric design of the hexagonal modules, this chapter introduces the design of the louvers, the movement of the louvers, the parametric design of the hexagonal modules and the mechanism design. After the design of the movable façade elements to be used on the façade, this façade system which is prepared parametrically becomes ready for simulation. Simulation is of great importance in determining the mobility and motion rules of the designed system.

Chapter 5 introduces the simulation and computational optimization process of the kinetic façade. In this chapter, illuminance level measurement of the indoor environment and the sun radiation measurement on the façade of the building are measured. The proposed kinetic façade is applied to the south façade of the building that is created as a generic model. The computational optimization of the kinetic façade is made to increase efficiency of the kinetic façade within the selected date and time. In addition, the measurements and the comparisons of the results of the simulations are presented in this chapter.

Chapter 6 concludes the study by summarizing main achievements of the research and providing suggestions for the future work in this field.

CHAPTER 2
CLASSIFICATION OF KINETIC FAÇADE SYSTEMS

Efficiency of the façade systems depend on the sun angle that changes by the time and the day of the year. Static façade systems cannot adapt efficiently to the changing environment conditions in terms of the indoor quality and the user needs. Compared to the static façade systems, kinetic façade systems can offer alternative solutions by changing their geometric configurations according to the movement of the sun for the optimal solar radiation and daylight (Schittich, 2006; Meagher, 2015).

Kinetic façade systems have gained an increased attention from both the researchers and the building industry with the technological developments in the twenty-first century. This increased attention has led the researchers to develop new façade systems and build various classifications for the kinetic façades which are generally based on motion, mechanical system, operation and material. Even though there are several categorizations for the kinetic façade systems, there are still difficulties to understand those characterizations, requirements and adaptivity of their systems.

Among the examples of the classifications, Loonen et al. (2015) built characterization strategies within "matrix of descriptive characterization concepts for façade adaptivity." The characterization matrix determines the adaptivity of any adaptive systems as the goal/purpose, the responsive function, the operation, the technologies (materials & systems), the response time, the spatial scale, the visibility and the degree of adaptability (Loonen, et al., 2015).

There are some other researches classifying the kinetic façade systems according to the motion. For instance, in Kolarevic and Parlac (2015), the kinetic façade systems can be classified into four categories considering how the motion is produced: motor-based, hydraulic, pneumatic and material-based. Remarkable proposed classification approach and its application made by Basarir and Altun (2017) which is created by using the current approaches to overcome the deficiencies of them. They developed a *Classification Matrix* that classifies the adaptive facade systems into fifteen categories based on the elements of adaptation, the agent of adaptation, the respond to adaptation agent, the type of movement, the size of spatial adaptation, the limit of motion, the structural system for dynamic adaptation, the type of actuator, the type of control/operation, the response time of the system, the degree of adaptability of the system, the level of architectural visibility, the effect of adaptation, the degree of performance alteration and the system complexity (Figure 2.1) (Basarir & Altun, 2017).

Classification Matrix			
Elements of Adaptation	Facade		
	Component		
	Element		
	Material		
Agent of Adaptation	Inhabitants		Individual inhabitants
			Groups of individuals
			Organisations
	Environment	Exterior Environment	Solar radiation
			Outdoor temperature
			Humidity
			Wind
			Precipitation
			Noise
		Interior Environment	Indoor temperature
			Humidity
			Amount and quality of light
			Air exchange rate
			Air velocity
			Sound level
	Objects		Objects passing through
			Objects passing by
Respond to Adaptation Agent	Static		
	Dynamic		
Type of Movement	Folding		
	Sliding		
	Expanding		
	Shrinking		
	Transforming in both size and shape		
	Scaling		
	Rolling		
	Twist		
	Rotation		
	Push-out		
Size of Spatial Adaptation	nm		
	mm		
	cm		
	m		
Limit of Motion	Limited (small units)		
	Partial		
	Inclusive		
	Variable		
Structural System for Dynamic Adaptation	Spatial bar structures consisting of hinged bars		
	Foldable plate structures consisting of hinged plates		
	Strut-cable (tensegrity) structures		
	Membrane structures		

Classification Matrix	
Type of Actuator	Motor-Based
	Hydraulic
	Pneumatic
	Material-Based
	Chemical
	Magnetic
Type of Control/Operation	Internal Control
	Direct Control
	Indirect Control
	Responsive in-direct control
	Ubiquitous Responsive In-Direct Control
	Heuristic, Responsive In-Direct Control
System Response Time	Seconds
	Minutes
	Hours
	Days
	Seasonal
	Several years
System Degree of Adaptability	On-off
	Gradual
	Hybrid
Level of Architectural Visibility (Rush Classification)	Not visible, no change
	Visible, no change
	Visible, surface change
	Visible, with size or shape change
	Visible, with location or orientation change
Effect of Adaptation	Prevent, Reject, Admit or Modulate (Store, Distribute) solar gains
	Prevent, Reject, Admit or Modulate (Store, Distribute) conductive, convective and long-wave radiant heat flux
	Controlled porosity for exchange and filtering of outside air
	Prevent, Reject, Admit or Redirect visible
	Prevent, Reject, Admit or Redirect sound pressure
	Collect and Convert wind energy
	Prevent, Admit or Modulate vision
	Change color
	Change texture
	Change shape
Degree of Performance Alteration	Minor
	Medium
	Significant
	Variable
System Complexity	Level 1(simplest)
	Level 2
	Level 3
	Level 4

Figure 2.1. Classification Matrix (Basarir & Altun, 2017)

In addition to the *Classification Matrix*, the technologies used in the kinetic façade systems can be added to expand the variables of the classification. The technologies used in the kinetic facades can be divided into five sub-categories as the mechanical technology, the electro-mechanical technology, the passive technology, the information technology and the advanced material technology (Matin et al., 2017).

Although many classifications have been proposed by the researchers, there is still no systematic study conducted up to this date in the literature which reveals a clear classification based on the motion of the kinetic façade systems. In this chapter, a new classification is proposed which is divided into three different types as actuator-based, smart material-based (SMB) and passive systems (Figure 2.2). Motion of a kinetic facade system activated by an actuator is categorized under actuator-based systems. These systems are divided into three different types based on motion of the system on the facades as radial motion, translational motion and rotational motion. SMB kinetic facade systems are classified as the second category. In addition to these classifications, actuation of a kinetic system activated by natural environment is categorized under passive systems.

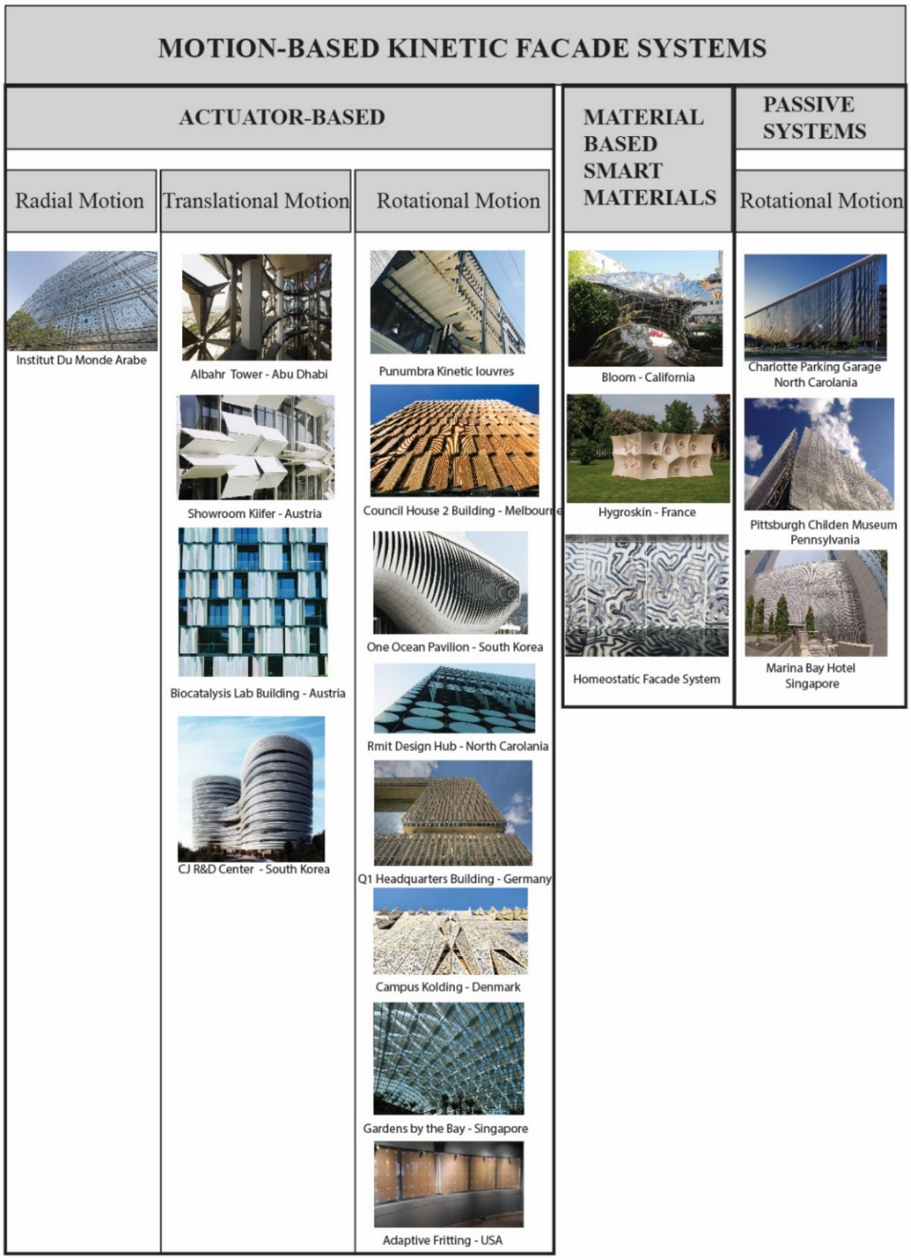

Figure 2.2 Classification of Motion-Based Kinetic Façade Systems.

2.1. Actuator-Based Motion

Changeability of a system can be identified as transformation of a system in progress of a time period. This transformation can be characterized with three elements: the agent of change, the mechanism of change and the effect of change. The agent of change can be described as an activation state for the transformation. The mechanism of change can be described as reaction of the designed steps in order to achieve the transformation from state 1 to state 2 as shown in Figure 2.3. The effect of change can be described as the real difference between prior and post state (Ross et al., 2008). This characterization describes the key role of actuation in kinetic façade systems.

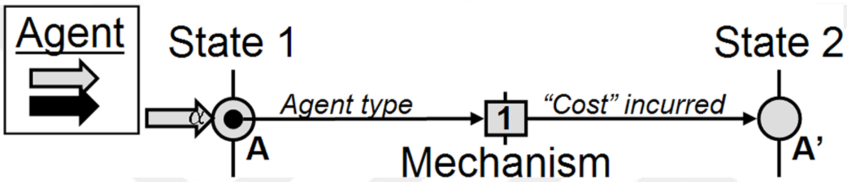

Figure 2.3. The states of the change (Ross et al., 2008)

The designed elements of the façade should have an actuation system to perform an adaptation on building façade by moving, rotating, expanding, folding, shrinking, twisting etc. (Kolarevic & Parlac, 2015).

2.1.1 Radial Motion

Radial motion can be described as a movement from perimeter to the center or vice versa (Study, 2019). Built in 1989 in Paris, Jean Nouvel's *Institut Du Monde Arabe* (Figure 2.5) can be shown as the first example of the kinetic façade systems in radial motion. The *Institut Du Monde Arabe* has 30.000 light sensitive diaphragms as shown in Figure 2.6 which are actuated radially with using photovoltaic sensors and motorizations. Although the façade system blocks the glare and allows up %10 to %30 daylight entering the building (Hansanuwat, 2010; Decker & Zarzycki, 2014; Khoo & Salim, 2013), the mechanical system used on the façade is quite complicated.

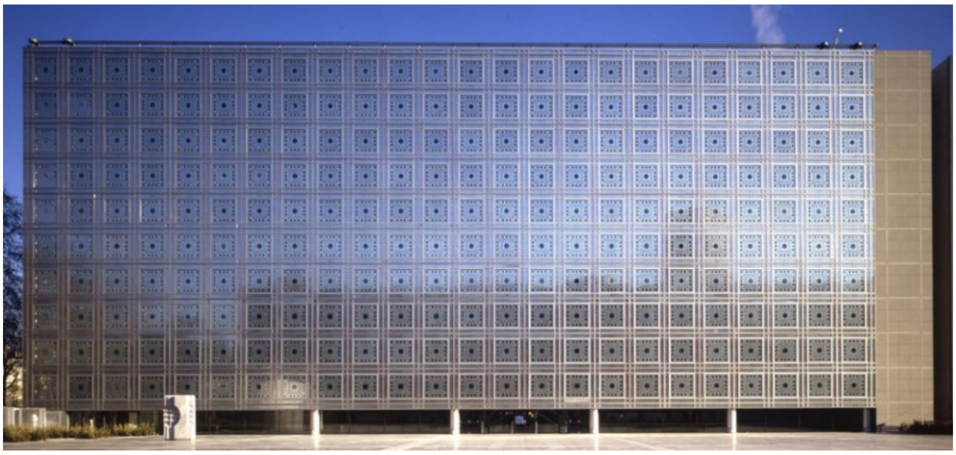

Figure 2.4. Kinetic façade of the *Institut du Monde Arabe* (Architecture-Studio, 2019)

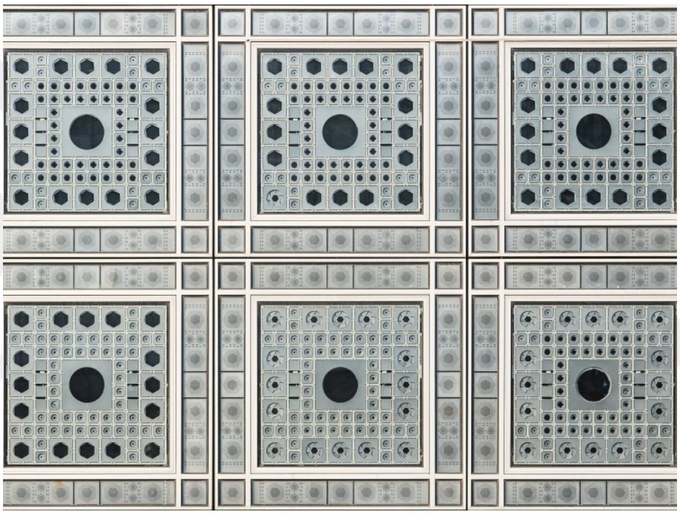

Figure 2.5. Light sensitive diaphragms of the *Institut du Monde Arabe* (Boake, 2013)

2.1.2 Translational Motion

Translational motion is a motion type in which the body moves from one point to another point in space by changing the body properties (G9toengineering, 2019). The translational motion in kinetic façade systems is created by sensors that transmit the required information to multifunctional, smart actuators in order to change its properties (Addington & Schodek, 2012).

Origami, an ancient Japanese handicraft and art style technique, has a translational mobility, has not been used by the designers in facade design. But still, there are some examples of origami used for different applications such as car air bags (Fei & Sujan, 2013), solar panels (Miura, 1994), medical purposes (You & Kuribayashi, 2003) and high tech materials (Urbana-Champaign., 2009). On the other hand, the usage of folded technique in kinetic façade systems is quite new. *Al-Bahar Towers* can be shown as the outstanding example of the kinetic façades which has folded-based translational motion. The folding kinetic façade system of the *Al-Bahar Towers* is generated from hexagonal panels that are inspired from *Mashrabiya* pattern. On the façade, each unit is connected by series of stretched polytetrafluoroethylene (PTFE) panels to Building Management System (BMS) which can be controlled individually or in groups by a linear actuator. Each tower consists of 1049 hexagonal panels that can be unfold in various angels adapt to the sun's angles to protect the building from the direct solar radiation gain (Attia, 2018) (Figures 2.6 and 2.7).

Figure 2.6. Kinetic façade of the *Al-Bahar Towers* (Wagdy et al., 2015)

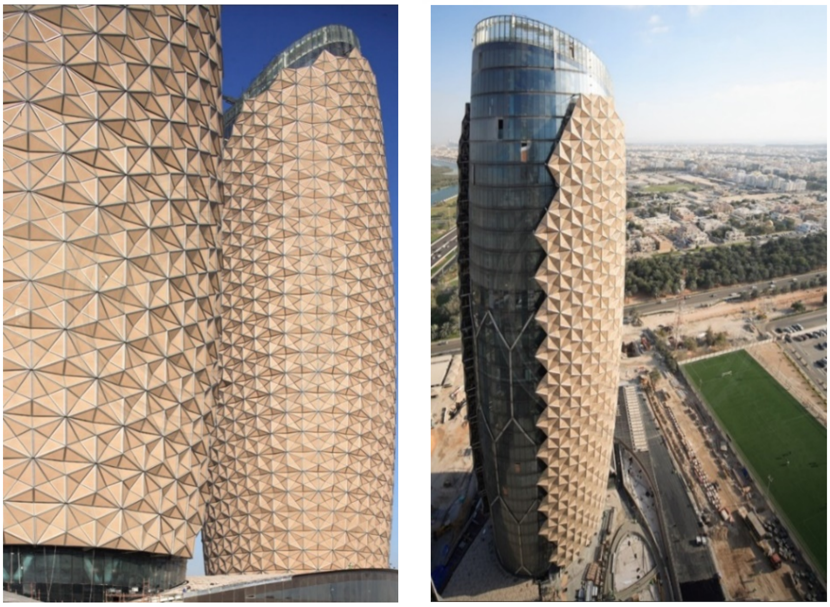

Figure 2.7. Kinetic façade of *Al-Bahar Towers* (Denison, 2012)

Creating a kinetic façade system is a whole new set of challenges. The system should adapt and respond to the changing environment such as both solar radiation and user needs. Shown in Figure 2.8, the *CJ Research and Development Center* façade design in South Korea meets the challenges and requirements. Primarily, the designers used perforated and bendable metal panels to cover the façade by fixing them to selected locations. Thereafter, they improved the design and used a foldable scissor mechanism. The scissor mechanism that is covered by membrane gives flexibility to the system to fold and unfold (Figure 2.9). In order to actuate the whole system, two linear actuators are used to give an ability to control top and bottom of the system independently (Krymsky, 2019).

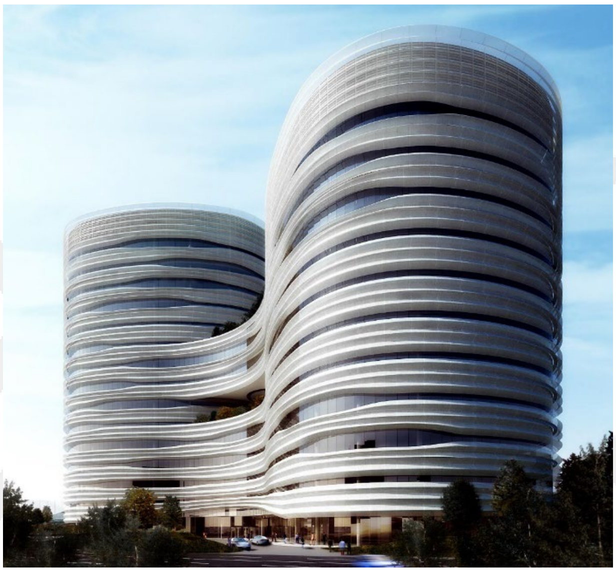

Figure 2.8. The *CJ Research and Development Center* (Krymsky, 2015)

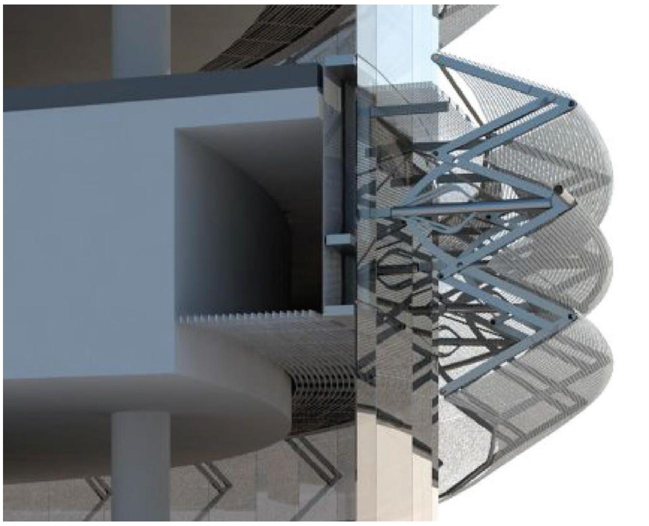

Figure 2.9. Foldable scissor mechanism of the *CJ Research and Development Cente*r (Krymsky, 2019)

Built in 2007, *Kiefer Technic Showroom* is another example of translational kinetic façade system which was made from perforated aluminum panels (Figure 2.10). These panels are controlled centrally by using light sensors and locational weather data which can be also controlled by the occupants of the building to block the direct solar radiation. The dynamic façade system actuated by 56 motors also gives flexibility to create various configurations and to optimize internal climate conditions (Matin et al., 2017).

Figure 2.10. The *Kiefer Technic Showroom* (Ott, 2008)

Another example of kinetic façade system used perforated aluminum panels on façade is *Biocatalysis Lab Building* at Technical University Graz (Figures 2.11 and 2.12). The southern facade of the building is covered by 216 aluminum perforated panels. These foldable panels which are combined in groups of six can be also controlled individually (Worldarchitecture, 2019).

Figure 2.11. *Biocatalysis Lab Building* at Technical University Graz (Ott, 2004)

Figure 2.12. Biocatalysis Lab Building at Technical University Graz (Ott, 2004)

2.1.3 Rotational Motion

Rotational motion can be defined as moving a body around an axis by having angular velocity or rotating an object around a fixed point (Thefreedictionary, 2002). One of the well-known examples of the kinetic facades using rotational motion is the kinetic *Penumbra* shading system that was designed by Tyler Short using traditional shutters on the façade of the building (Figure 2.13). Unlike traditional louvers, the louvers in this design have a rotational motion both vertically and horizontally. The whole system designed digitally can be controlled manually or computer-operated (Frearson, 2019).

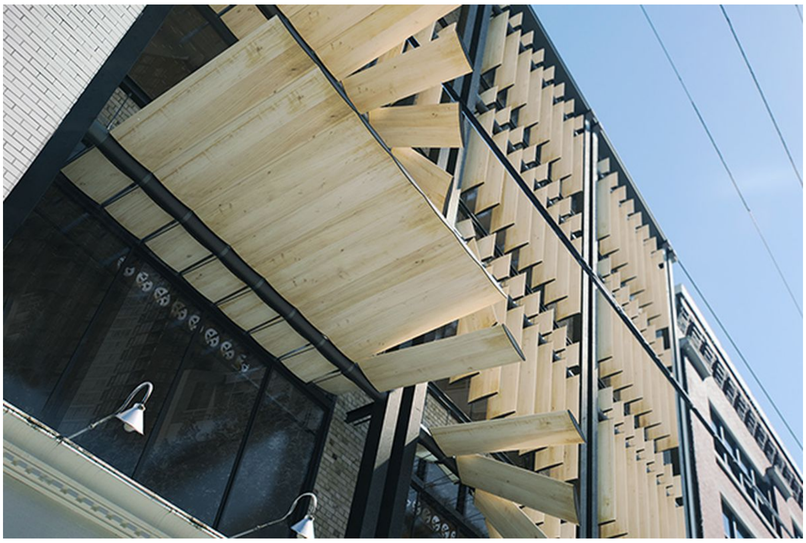

Figure 2.13. *Penumbra* shading system design by Tyler Short (Theverge, 2020)

Another example of using traditional louvers made of timber can be seen on the façade of the *Council House 2* (Figure 2.14). The timber shutters are connected to a vertical axis and has an ability to rotate itself 90 degree. Timber panels moves vertically to protect the building façade from radiation and glare. Even, the design of the shutters traditionally made are controlled by BSM. The whole system controls the environmental changes, heat gain and glare as opening and closing by means of the actuators. West façade of the *Council House 2* is made from 148 timber panels which covers 2.226 m^2 of the façade. They are fully closed when the sun hits the west façade of the building (Balascakova, 2016).

Figure 2.14. The *Council House 2*, (Maltezos, 2019; Cruz, 2019).

Adaptation of the shading panels depends on directly to the sun and its angle. For this reason, the system should be fixed during the nighttime and continuously change during the daytime. Measurement of the continuously change of the position of sun within control system that transmit the data to the actuators of the panels moves by the given date, can increase adaptivity of a shading panel. The façade of *Q1 Headquarters* (Figure 2.15) building in Essen, Germany would be a notable example of the kinetic façade systems. Built in 2010, the building has an external kinetic façade system that is made from combination of 1.280 stainless steel panel. Each shading panels is made of vertical spindle that helps to move the panels. The spindle divides the shading panels into two parts. Each parts of the shading panel can move freely from each other. In addition, the motorized shading panels can be also controlled in a group or individually to move open and close positions within data given by the sun tracking sensors (Figure 2.16) (Sirotnjak, 2016; Kolarevic & Parlac, 2015).

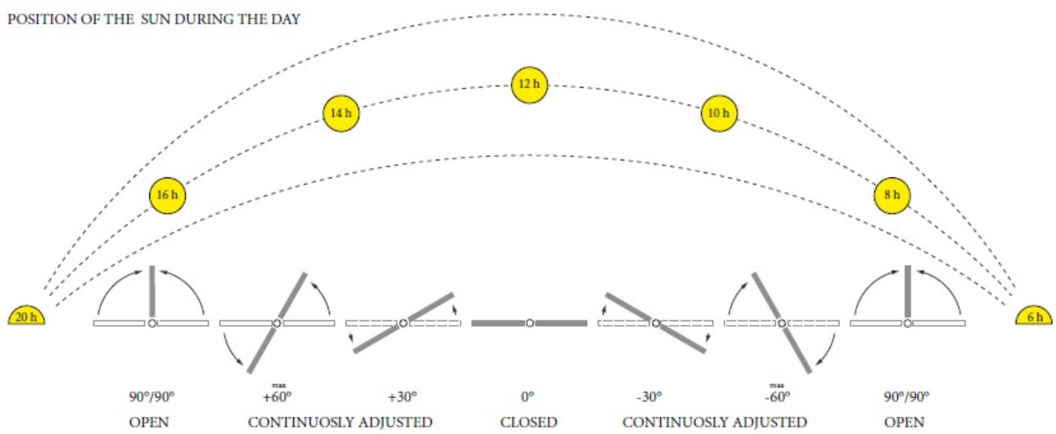

Figure 2.15. Movement of automated façade panels of *Q1 Headquarters Building* during the daytime (Sirotnjak, 2016).

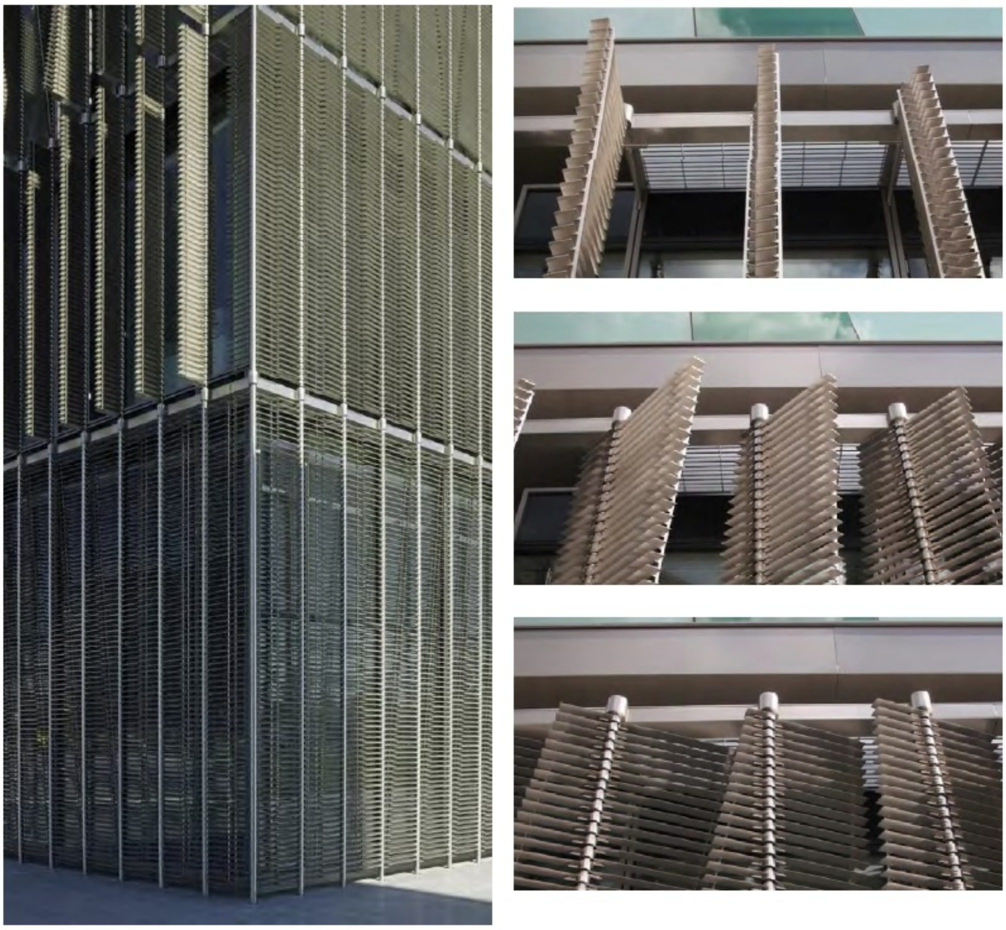

Figure 2.16. Different states of kinetic shading panels of the *Q1 Headquarters Building* (Sirotnjak, 2016).

Curved building facades in contemporary architecture rise difficulties for designing kinetic façade systems (Schleicher, 2015). The façade of the *Garden by the Bay* building in Singapore succeed to solve the difficulties (Figure 2.17). Kinetic façade system of the building was constructed on large-scale curved structures externally. Sensors transmit information to actuators in order to unfold the elements of the system made of membrane which are attached to the facade by using cables to control the indoor temperature. Moreover, the whole unfolding cycle is controlled by an intelligent self-learning algorithm (Figure 2.18) (Barozzi et al., 2016; Kolarevic & Parlac, 2015).

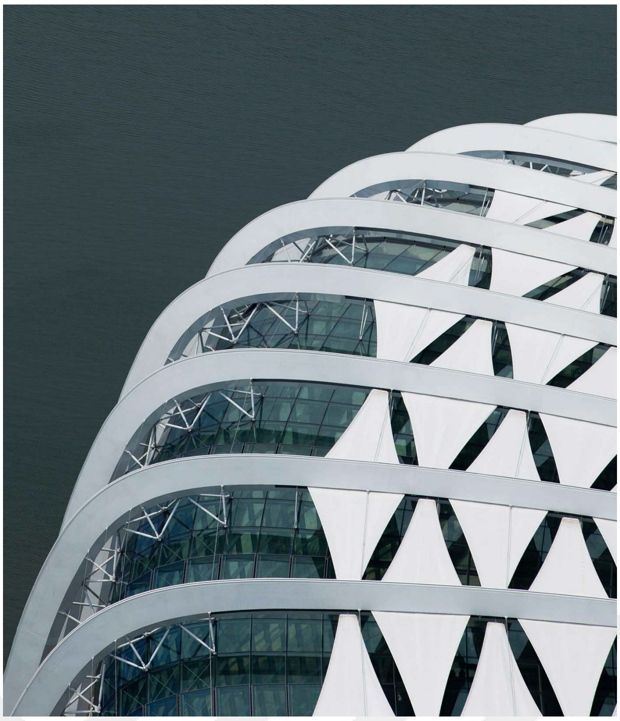

Figure 2.17. Kinetic façade of the *Garden by the Bay* in Singapore (WilkinsonEyre, 2012)

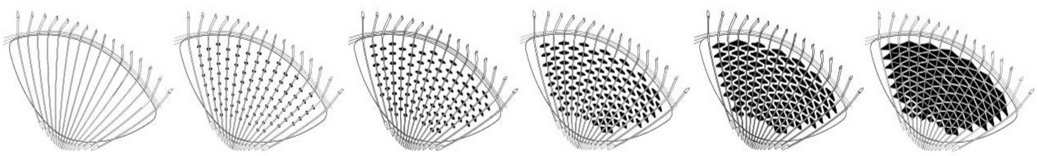

Figure 2.18. Unfolding cycle of kinetic façade (WilkinsonEyre, 2012)

Developed by Buro Happold and Hoberman Associates, the *Adaptive Fritting* façade system is another example of rotational motion in façade systems (Figure 2.19). The system has patterned layers that moves by actuators to control the light transmission. Fritting façade has maximum transparency while patterned layers are aligned with each other. Motion of the patterned layers to different planar directions reduce light transmission and glare; thus, the system gains controlling transparency ability. Each patterned layer is connected to motor-actuators and the environmental change is perceived by the sensors which communicates with centralized control system to send the data to motor-actuators for adaptation of environmental changes like glare (Edupuganti, 2013).

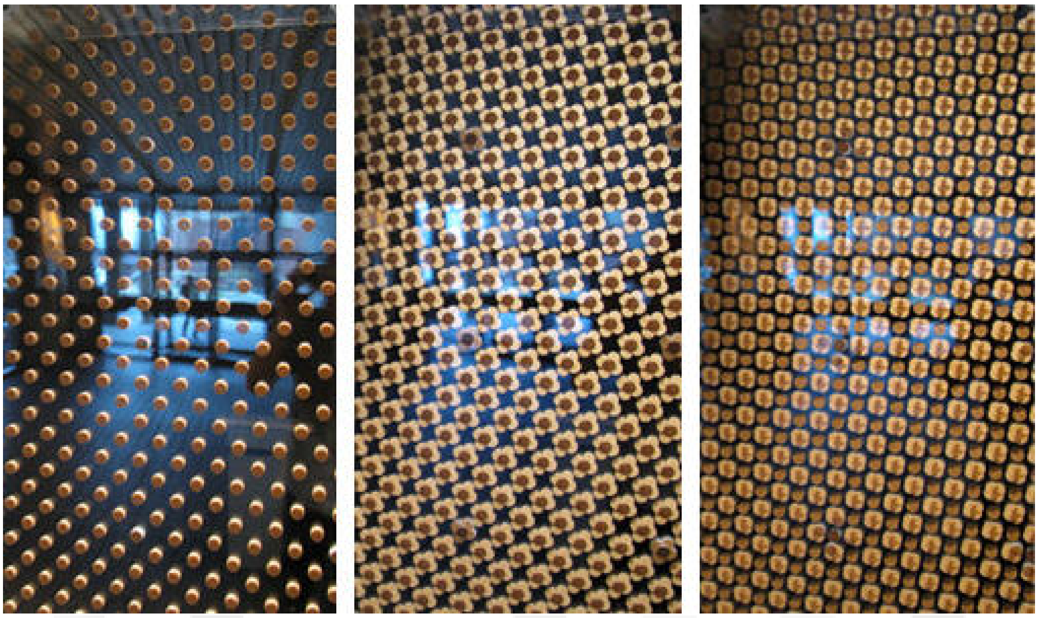

Figure 2.19. *Adaptive fritting* façade system

Fiber reinforces composites (FRC) are used in building industry for many years. Glass fiber reinforced polymers (GFRP) is one of the kinds of FRC which is resistant to high tensile pressure with low bending stiffness. Thus, these properties give reversible elastic deformation ability to GFRP. Kinetic façade of the *One Ocean Pavilion* can be only example of using reversible elastic deformation in kinetic façade systems (Figure 2.20).

Figure 2.20. Kinetic façade of the One Ocean Pavilion (Helbig, 2019)

Made of 108 louvers in total, the kinetic façade has 140 meters length and ranges between 3 to 13 meters high. Each louver is reinforced from top and the bottom edge with actuators to move. Actuators give strong force to the louvers to bend forward to stay in open position then louvers close within the stored energy in deformed elastic louvers (Figure 2.21). Thus, the sun radiation and glare can be arrangeable inside of the building by controlling these reversible elastic deformations (Schleicher, 2015; Knippers & Speck, 2012; Haidari, 2015).

Figure 2.21. Reversible elastic deformation (Helbig, 2019).

2.2. Smart Material Based Systems

Adaptability of smart materials, in other words shape memory systems, depends on the behavior of the materials. Unlike other kinetic systems, these systems use environmental changes as an energy source to change the material properties (chemical, mechanical, electrical, magnetic or thermal) instead of using external forces such as motors and actuators. The other differences between smart and non-smart materials used in building façade are transiency, selectivity, immediacy, self-actuation and directness (Addington & Schodek, 2005).

The *Bloom* is a self-supporting system which has 14.000 pieces of thermo bimetal in 414 hyperbolic paraboloid embodied united elements (Figure 2.22). The *Bloom* can be considered both as a passive and a kinetic system working without artificial energy. When heat rises to a targeted temperature in the elements, the part of the elements changes their position rotationally to open (Figure 2. 23) and close (Figure 2. 24), and to block the direct sunlight. Unlike the other kinetic systems, the *Bloom* is one layered shell that also gives an ability to release the hot air inside of the building (Fortmeyer & Linn, 2014).

Figure 2.22. Bloom (DO|SU, 2019)

Figure 2.23. Elements in open position (DO|SU, 2019)

Figure 2.24. Element in close position (DO|SU, 2019)

Apart from surfaces covered by the bimetals, it is also possible to see other examples in which the most traditional materials are used. For instance, 28 different humidity responsive wood composites were used in the *HygroSkin Pavilion* to sense the humidity level in air for the movement (Figure 2.25). When relative moisture level increases in air or rain, the elements start to close and if it is a sunny day, elements start to open (Figure 2.26). Each wooden element that has self-forming capacity actuates and reacts without any artificial energy (Correa et al., 2013).

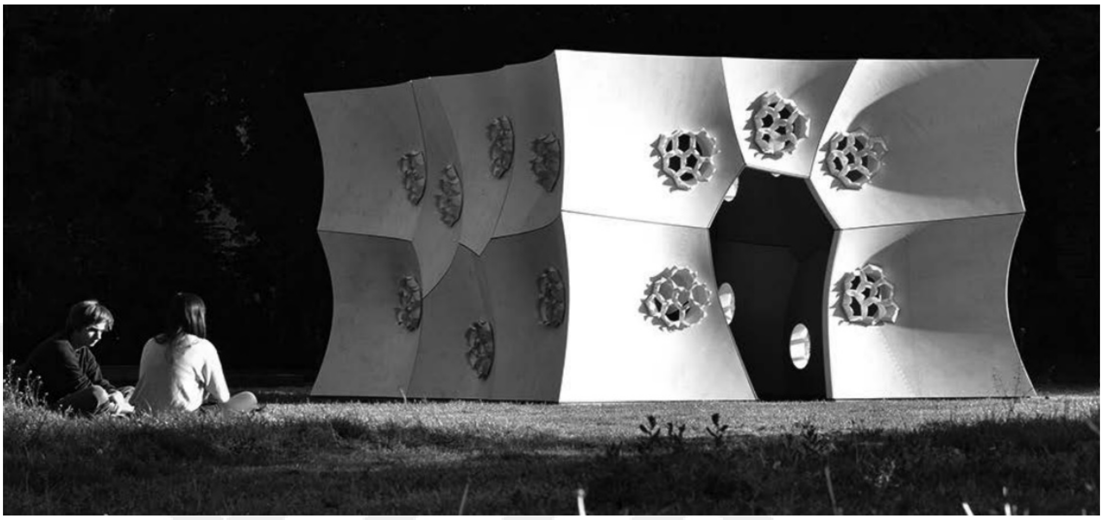

Figure 2.25. *HygroSkin Pavilion* (Correa et al., 2013)

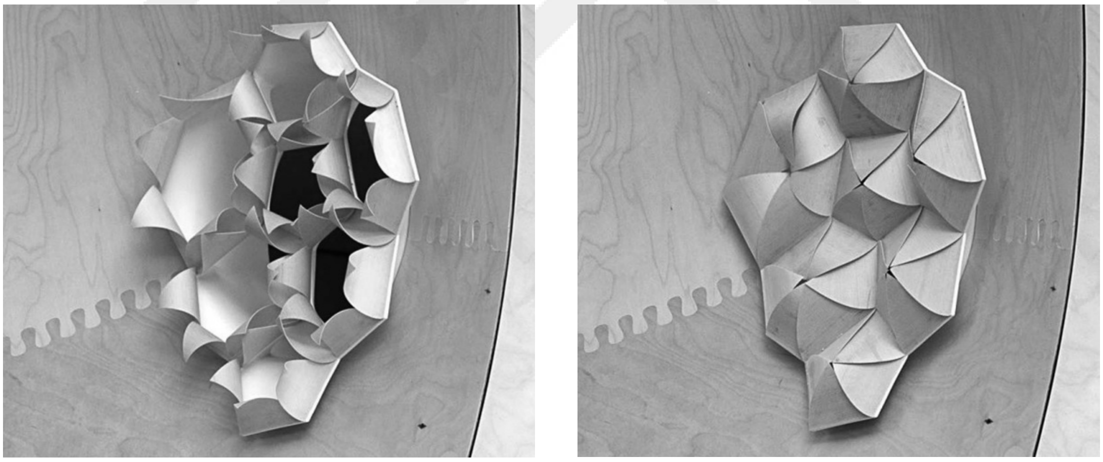

Figure 2.26. *HygroSkin Pavilion* kinetic elements. Left - in open position. Right - in close position (Correa et al., 2013)

The *Homeostatic Façade* is a system that protects undesirable sun inside of the building (Figures 2.27). The system located outside of the exterior wall as a second layer is flexible to bend to open and close (Figure 2.29). Therefore, unlike the other smart materials which is used for kinetic facades, bending powered by low artificial energy without any actuator motors or systems. Each element covered by silver to conduct electricity between dielectric elastomers and to reflect direct sun light (MaterialDistrict, 2014).

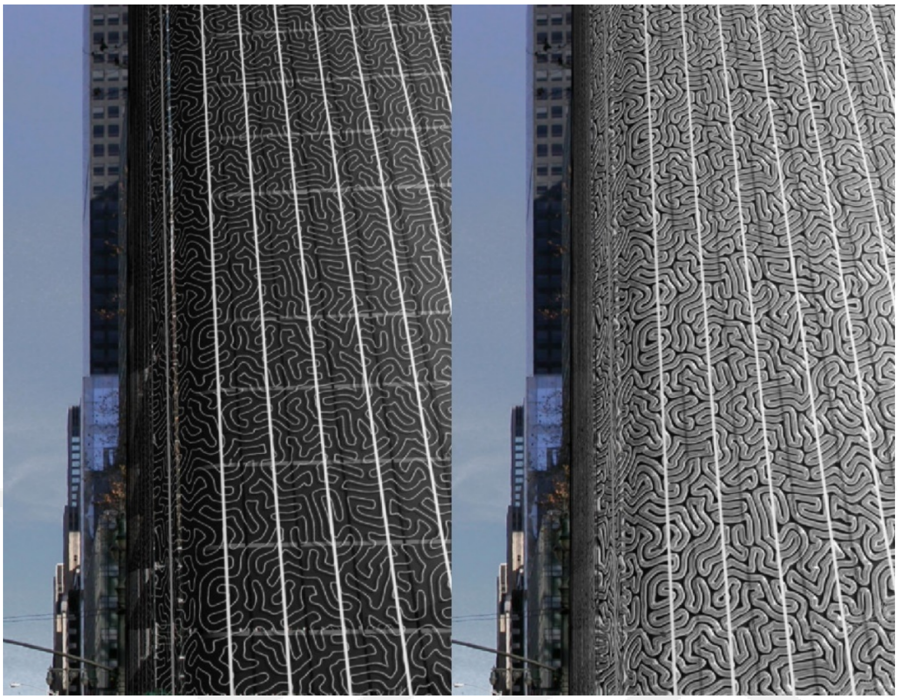

Figure 2.27. *Homeostatic Façade* in open and close position (MaterialDistrict, 2014)

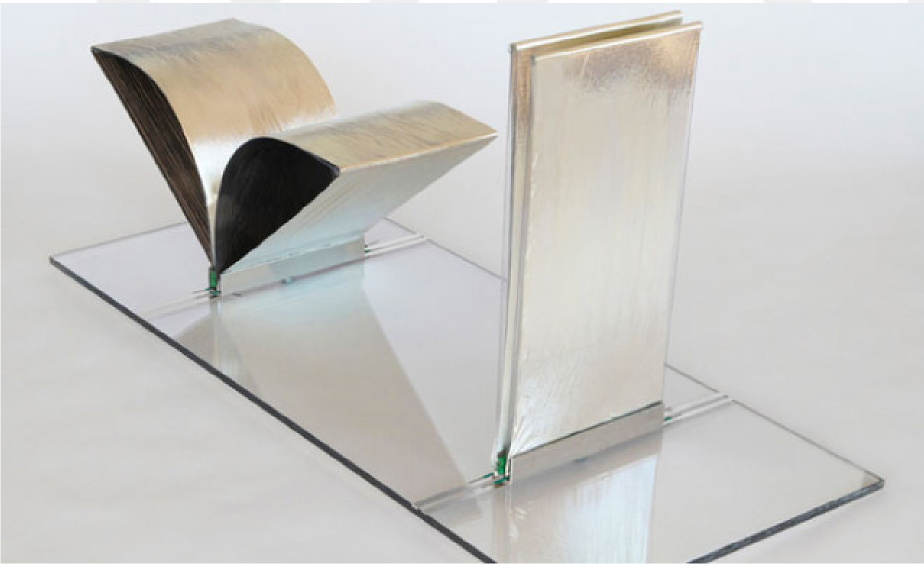

Figure 2.28. *Homeostatic Façade* elements in open and close position (MaterialDistrict, 2014)

2.3. Passive Systems

Passive systems exploit wind, sunlight or temperature differences to produce a movement for intended purpose. Thus, passive systems have not any sophisticated controls, mechanized systems or operational costs (Spacey, 2019).

A dynamic façade can be designed without complex mechanisms and systems. Therefore, the minimalist facade of the *Museum of Children* designed by Ned Kahn has 39.000 acrylic flaps, which are 14 centimeters to 15 centimeters each, are used on the façade (Figure 2.30). They move only with the power of the wind that provides a dynamic look to the façade of the *Museum of Children.* Acrylic fraps, which move without any connection to a complicated mechanism or sensor, have rotational movement based on the wind power. They illustrate a real adaptation of the façade to the wind since each moving element moves freely and independently. In addition, the placement of these elements on the façade of the building reduce daylight and glare inside of the building.

Figure 2.29. *Children's Museum* (Kahn, 2019).

Designed by Ned Kahn, the facades of the *Charlotte Parking Garage* (Figure 2.31) and the *Marina Bay Hotel* (Figure 2.32) are followed by the same principles, but replaced with different numbers of aluminum panels (Fortmeyer & Linn, 2014).

Figure 2.30. *Charlotte Parking Garage* (Kahn, 2019)

Figure 2.31. *Marina Bay Hotel* (Kahn, 2019)

2.4. Discussion

A kinetic façade design process and evaluation of kinetic performance contains many different interconnected areas. Therefore, it is a field of study that requires different disciplines to work together to complete different stages of the design. Simulation of the kinetic facade by using digital tools to understand the mobility is an important part of the design process.

The design of a kinetic façade is a way more complex system than a conventional building system. Designers need to know that they are starting to design a system that works with sensors, actuators, electrical systems, mechanical systems and computer programs to adapt to the changes in environmental conditions. Therefore, the final design is formed by integrating different engineering systems into the design process.

Another issue that needs to be considered in such a complex system is the maintenance costs of the kinetic facade. The maintenance costs vary according to the mechanical system, but the fees could be too high to pay for such a kinetic facade. According to this result, while a kinetic façade is expected to reduce the energy use of a building and the cost of living inside the building, the design cannot answer these tasks because it consists of a very high-tech mechanism. Therefore, to use a low-level or medium-level mechanical and technological system are recommended in kinetic façade design.

CHAPTER 3

TESELLATION

Tessellation can be briefly defined as a mathematical technique or tiling which has been used in science, art and architecture for centuries. Meaning of the tessellation is that a set of shapes closely and repeatedly fitted together to cover a planar surface without any overlaps or gaps. The origin of the word *tessellation* comes from *tessella*. In Latin, *tessella* means small square and cube-shaped piece of clay, stone or glass used to make mosaics (Figure 3.1). The word *tessella* is derived from the word *tessera* which means “four” in Greek (Seymour & Jill, 1989).

Figure 3.1. Tessellation in Roman Mosaics (Newsroom, 2019)

There are many types of tessellation which are regular tessellation, semi-regular tessellation, demi-regular tessellation or monohedral tessellation and aperiodic tessellation (Gazi, 2010). This thesis concentrates on polygonal shapes and their connections. The reason of choosing polygonal shapes for designing a kinetic façade element is that the working surface is to be flat and planar. The planar surface should be divided equally and chosen shape of the kinetic element should repeat itself to cover whole area without any gaps and overlaps.

3.1. Regular Tessellation

Using uniform polygons in the same order without overlapping and gaps in the surface called as regular tessellation. There are only three types of shapes used for regular tessellation which are hexagon, square and triangle (Gazi & Korkmaz, 2015) (Figure 3.2.).

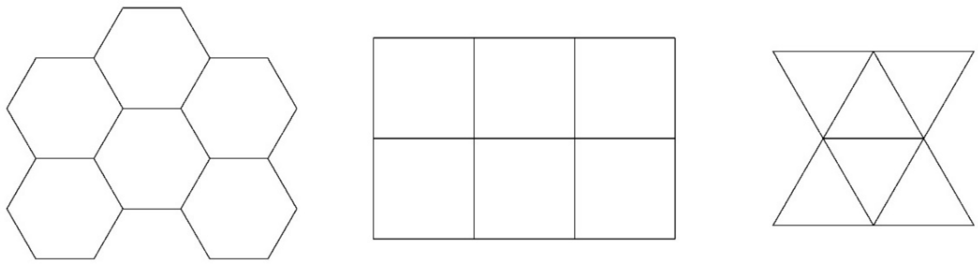

Figure 3.2. Regular Tessellations

3.2. Semi-Regular Tessellation

Semi-regular tessellation is composed of two or more regular polygons in which identical polygons share one edge to generate 360 around each vertex. As shown in Figure 3.3, there are eight types of semiregular tessellations that can be also called as Archimedean tessellations (Jin et al., 2017).

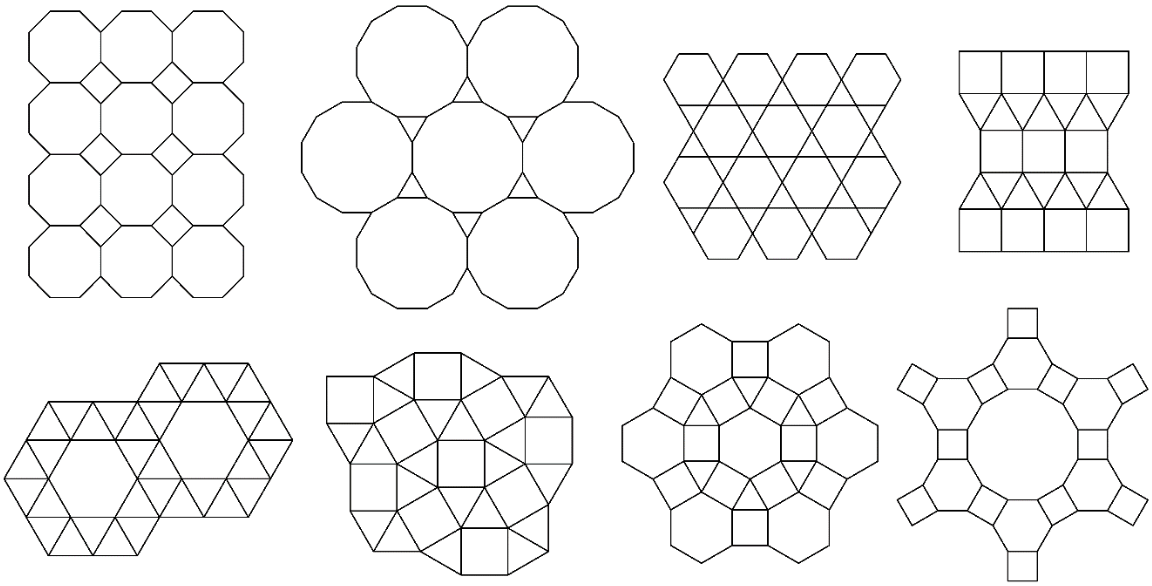

Figure 3.3. Semi-regular Tessellations.

3.3. Demi-Regular Tessellation

Called also as polymorph tessellation, demi-regular tessellation has different meanings in the literature. Some researchers define it as the combinations of regular and semi-regular tessellations while the others describe it as the tessellation that has more than one transitivity class of vertices (Gazi, 2010). There are seventeen types of demi-regular tessellation (Figures 3.4 and 3.5).

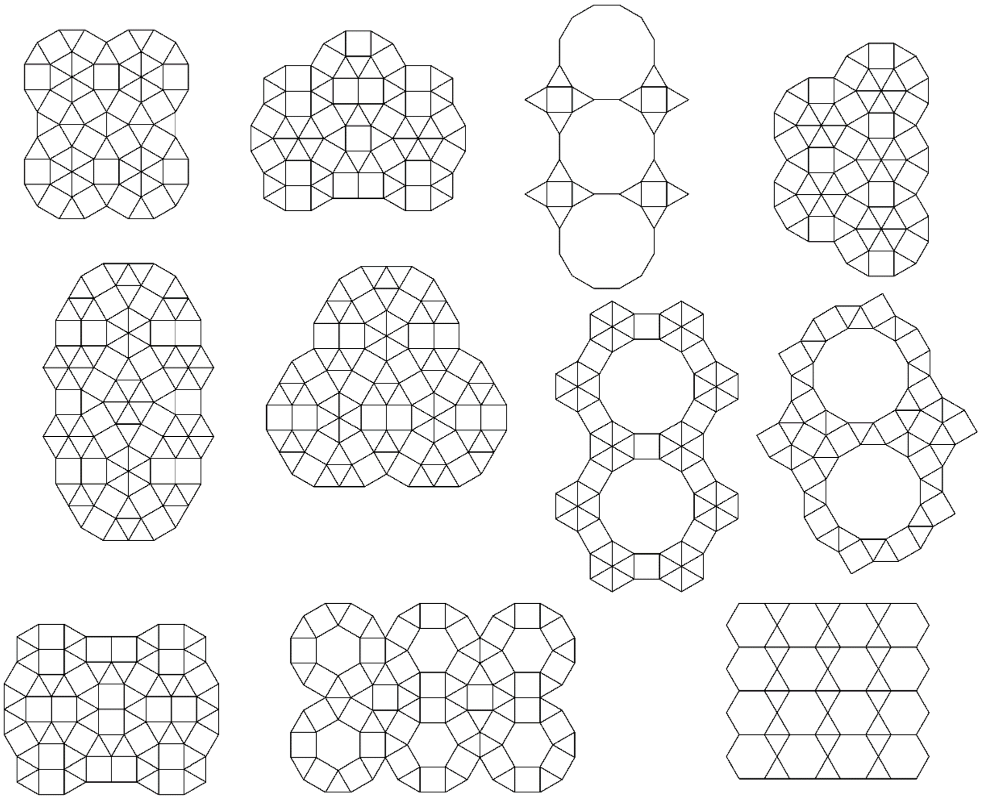

Figure 3.4. Demiregular Tessellations

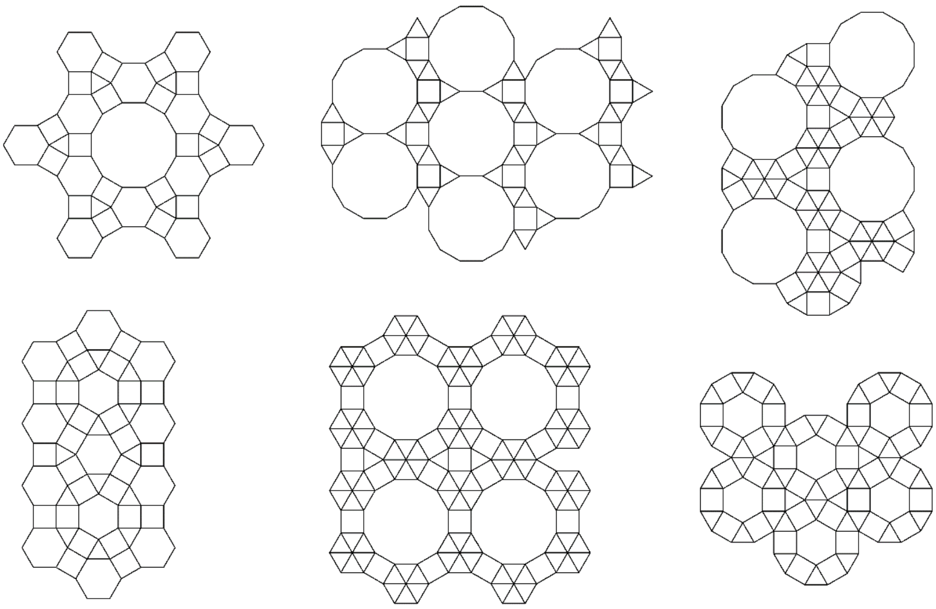

Figure 3.5. Demiregular Tessellations

3.4. Tesellation in Architecture

Designing a surface is one of the areas that architects have been dealing with for centuries. Architects can use mathematical techniques to design surfaces. One of the mathematical techniques for covering the surface is tessellation. The use of this technique in decoration and arts have increased and become widespread.

Tessellation techniques can be seen in many structures made in the history of humanity since these techniques were used to cover the surfaces of the homes, castles and roads. Although the tessellation techniques have been used over time, the areas of the use in each civilization may differ. For instance, Mediterranean and Roman countries have been focused on human portraits and natural sciences in tessellation technique. Alternatively, the Arab and Moors countries have intensified tessellation techniques on complex geometric shapes (Grünbaum et al., 1986). In this section, the usage and the development of the tessellation techniques in the field of architecture are explained.

The use of tessellation techniques as architectural elements can be found in many ancient civilizations in the world, such as Arabia (Figure 3.6), Byzantium (Figure 3.7), China (Figure 3.8), Egypt (Figure 3.9) and Persia (Figure 3.10). The use of tessellation has become largely widespread with the increasing use of ornaments. However, tessellation technique achieved its top level within the usage of mosaics (as shown in Figure 3.11) in the Islamic architecture. (Gazi, 2010).

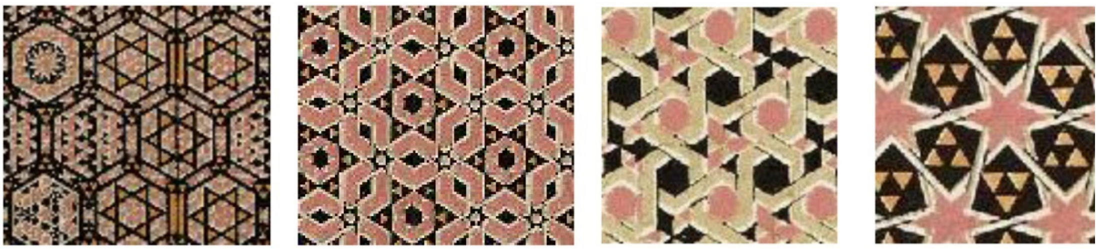

Figure 3.6. Tessellation examples of Arabians (SPSU, 2020).

Figure 3.7. Tessellation examples of Byzantines (SPSU, 2020).

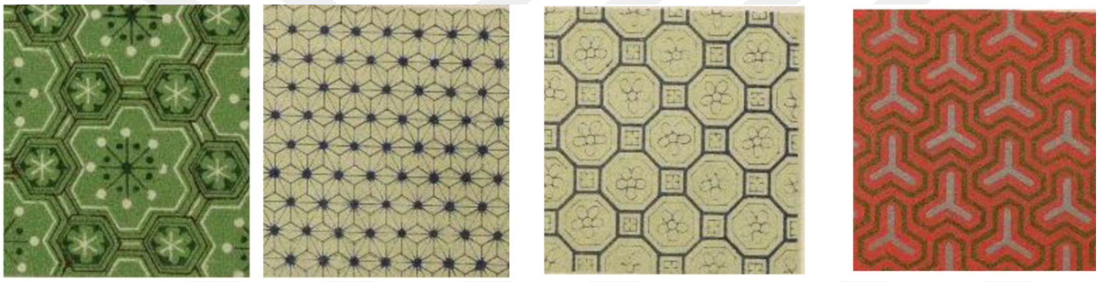

Figure 3.8. Tessellation examples of Chinese (SPSU, 2020).

Figure 3.9. Tessellation examples of Egyptians (SPSU, 2020).

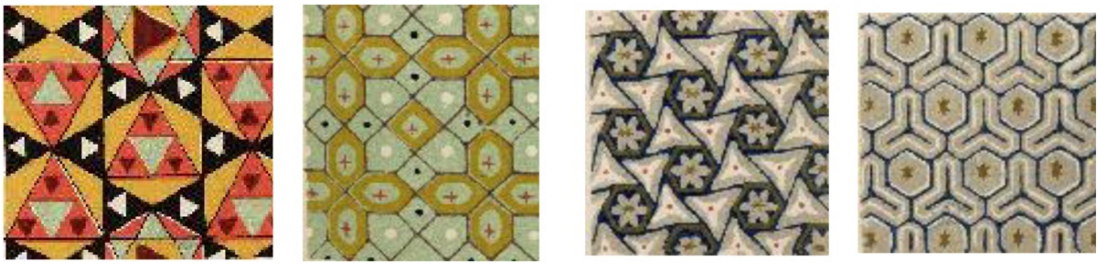

Figure 3.10. Tessellation examples of Persians (SPSU, 2020).

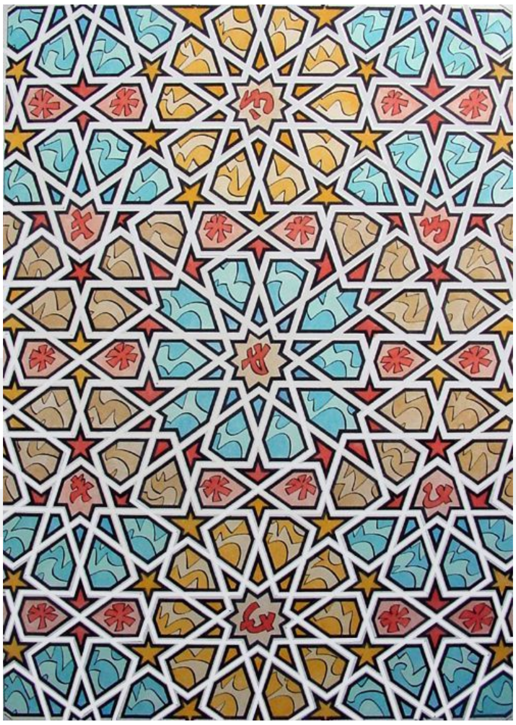

Figure 3.11. Mozaic Tesselation in Islamic architecture. (Ahmed, 2020)

While coating methods were used in the past to cover planar surfaces, today, the tessellation techniques can also be applied on complex and 3D shapes by means of the developments in construction methods, materials and electronic systems.

The *30 St Mary Ax* building (Figure 3.12), which uses both computer-aided parametric modeling and regular-tessellation techniques in its design, was designed by Foster and Partners. Completed in 2004, the building is made of 5.500 pieces of triangular glass panels (Figure 3.13). The height of the *30 St Mary Ax* building is 180m and the total area is 64.469m^2 (Pintos, 2020).

Figure 3.12. 30 St Mary Ax building in London (Fosterandpartners, 2020).

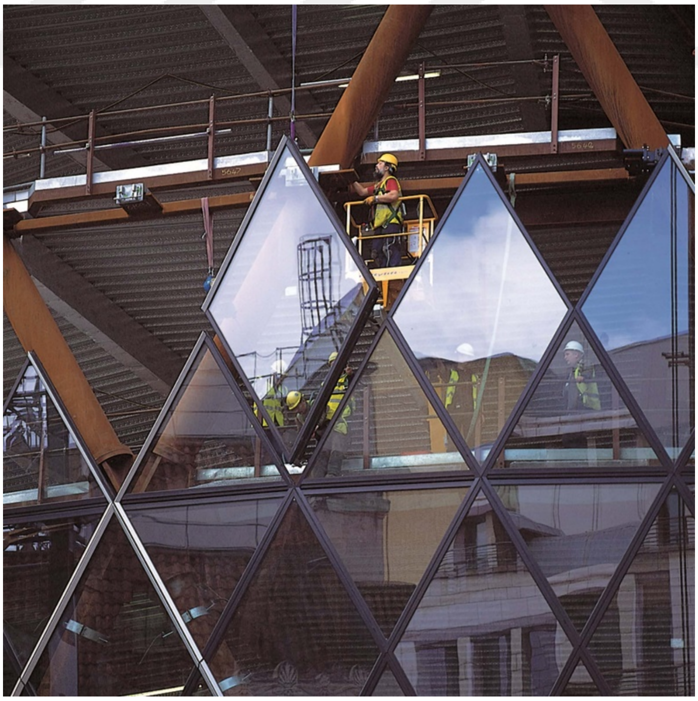

Figure 3.13. 30 St Mary Ax building in London (Fosterandpartners, 2020).

The *Hexalace* is a commercial building (Figure 3.14.) which is designed based on the hexagonal regular tessellation technique. Designed by Studio Artele for extreme hot climate conditions, the construction of this building was completed in 2018 in Mohali, India. 7.62-centimeters hexagonal concrete was coated as a shading element of the building facade which is facing west (Figure 3.15). In addition, another hexagonal hollow layer formed from a metal frame was used to increase shading on the facade which determines the balcony boundaries (StudioArdete, 2020).

Figure 3.14. Commercial building design Hexalace (StudioArdete, 2020).

Figure 3.15. Façade of Hexalace (StudioArdete, 2020).

CHAPTER 4
DESIGN OF KINETIC FAÇADE BASED ON TESELLATION

Early design stages and decision-making are crucial for successfully functioning a kinetic façade. At this stage, misinterpretation of the design may lead to problems such as insufficient selection of mechanism, inefficient selection of the material and incorrect motion ability. Inefficiency in any stages of the design process may also lead the designer to start over from the beginning. The creation of a kinetic façade that works efficiently is a complex process. Proper management of this process can be achieved through a good understanding of the many interrelated professional fields. Other important factors in designing a kinetic façade is that the design should be simple and clear.

Based on the tessellation technique, the kinetic façade system designed in this thesis requires a simple mechanism to move the façade elements. Traditional louvers are blended in the kinetic system and their movements are determined according to environmental changes. The selection of polygonal shape is so important because it should be suitable for façade tessellation without having any gaps and overlaps. After selection of the polygonal shape, the integration of conventional louvers and the motion of these louvers are determined on the kinetic façade. These sunshades must have the ability to move in a way that they protect the building from the sun and allows natural light into the building.

Design principles and methods used in this thesis to design the kinetic façade system are as follows:

- choosing a polygonal shape that repeats itself (modular system) to cover whole surface without having gaps and overlaps.
- selection of the polygonal shape should be simple to remove build-in complications for producing it.
- using traditional shutter systems within combination in kinetics.
- designed kinetic façade system should block whole unwanted radiation gain from the sun.

- natural daylight should reach inside of the building while the system is fully closed for blocking sun.
- simple mechanical solution should be considered to decrease operational cost.

4.1. Geometric Design of Hecagonal Modules

The design process of the kinetic façade system starts with the understanding of the key factors for successful design solution. The kinetic façade system to be designed on a flat surface must be completely covered and there should be no gaps for this system to work efficiently. Therefore, it is necessary to determine the geometric shapes that form the design elements. Design study of this thesis is limited to regular tessellation. As mentioned in Chapter 3, there are three regular tessellations as square, triangle and hexagonal tessellation. The proposed kinetic façade is covered with regular tessellation modules. Hexagonal geometric shape is selected for the modules to be used in kinetic façade design (Figure 4.1).

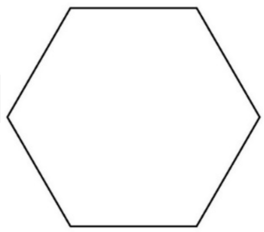

Figure 4.1. Hexagonal Shape.

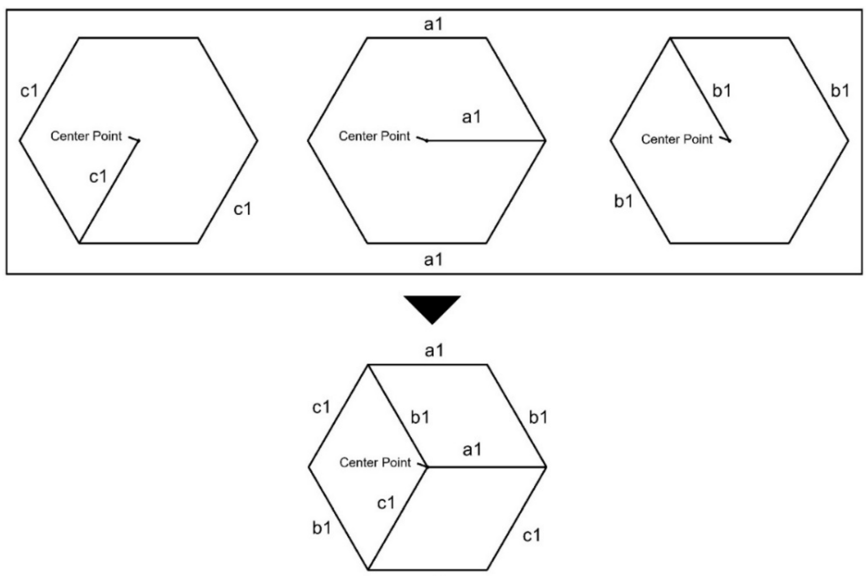

Figure 4.2. Division of hexagonal modules (Parallel edges called a1, b1 and c1).

In the middle of the edges of the hexagonal shape which is parallel to each other, parallel lines drawn to these edges for division of the hexagon (Figure 4.2). The parallelogram shapes are formed by aligning the lines drawn in parallel with the same length as the edges of the hexagon to the midpoint of the hexagon. By this means, the hexagonal shape is divided into three equal parts using the parallel lines to form three identical parallelogram shapes (Figure 4.3). The edges of the shape formed by dividing the hexagon into three equal parallelograms also form the frame of the kinetic façade which carries the load of the façade (Figure 4.4).

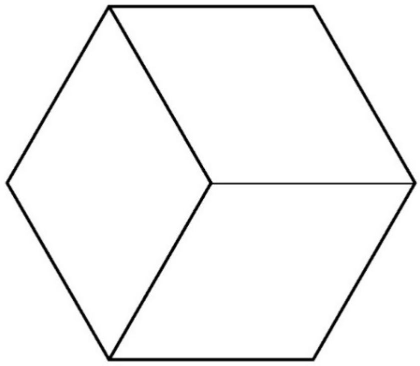

Figure 4.3. Three equal parallelogram parts inside of the hexagon.

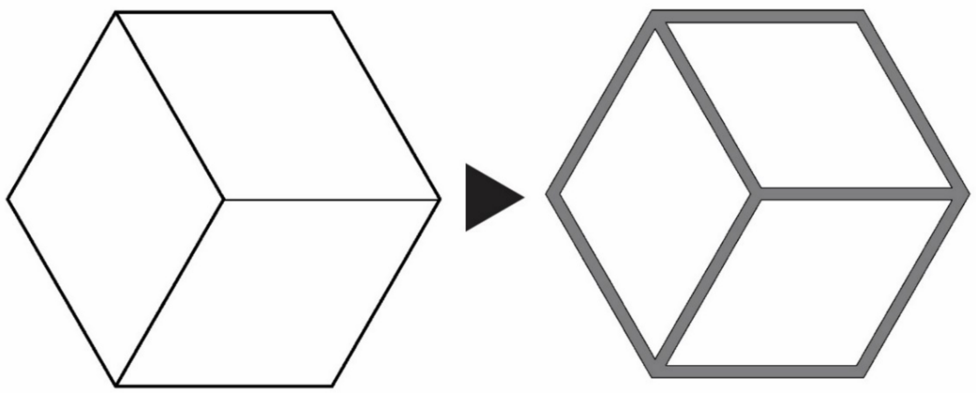

Figure 4.4. Structural frame.

With the formation of three identical parallelograms in the hexagon, it is created where the traditional louvers evenly and vertically are placed (Figure 4.5). Six louvers are placed in a parallelogram, eighteen in total for a hexagonal module. As a result, the modular system is created inside of the hexagon.

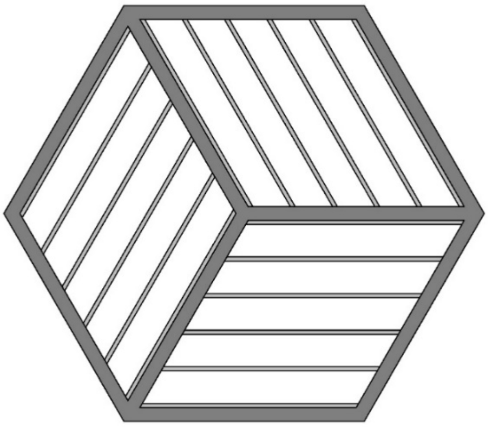

Figure 4.5. Placement of traditional louvers.

After the placement of the traditional louvers, the next stage is to define the relationship between the louvers and the frame when rotational movements are applied to the louvers. The louvers need to be rotated to adapt to the changing conditions; but the frame blocks the louvers during the rotation of the louvers. In order to overcome this problem, it is necessary to leave a working space between the frame and the louvers. As moving the louvers at a certain amount from the frame, they can rotate at an angle (Figure 4.6). This design decision is discussed in detail in the next Section.

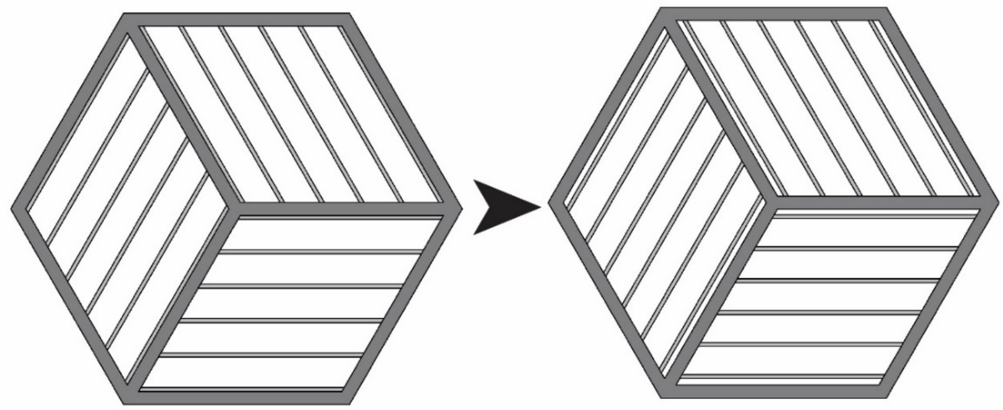

Figure 4.6. Leaving gaps between frame and louvers for angular rotation.

Tessellation of the façade can be started with combining of the hexagons to each other. One of the edges of the identical hexagonal module is combined with adjacent edges of the other hexagonal module to create a hexagonal modular frame for the façade (Figure 4.7). By this means, the tessellation of the kinetic façade is determined as shown in Figure 4.8. The created modular system is a regular hexagonal tessellation.

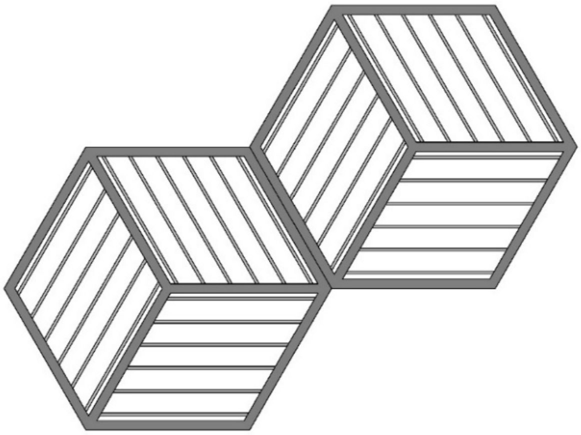

Figure 4.7. Combined hexagonal modules.

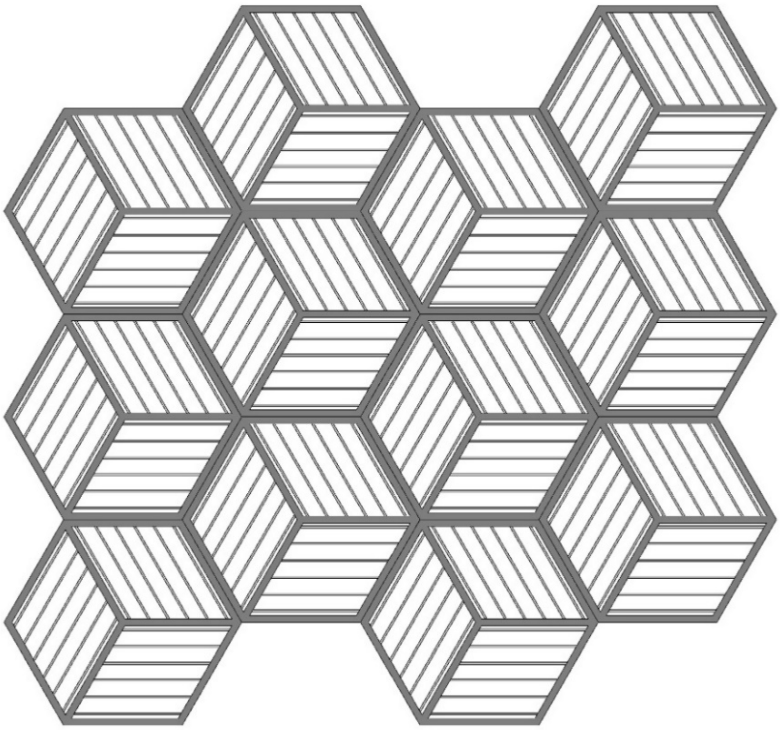

Figure 4.8. Regular hexagonal tessellation

However, when regular hexagonal tessellation is used on a square or rectangular façade, the surface cannot be fully covered with the hexagon shape which exposes triangle and parallelogram gaps at the edges (Figure 4.9). These gaps on the façade can be filled by fixed or movable louvers. But the remaining triangular gaps are covered with static louvers and the parallelogram shaped gaps are covered with kinetic louvers as shown in Figure 4.10.

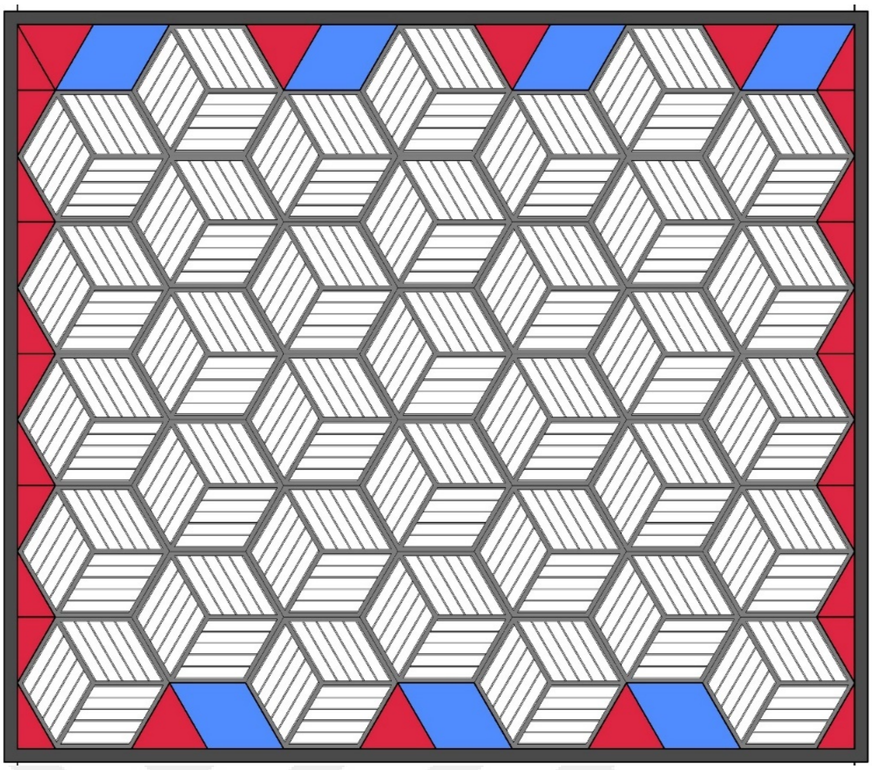

Figure 4.9. Gaps of the regular tessellation on a rectangular façade. Red color represents triangular gaps to be covered by static louvers and blue color represents parallelogram gaps to be covered by movable louvers.

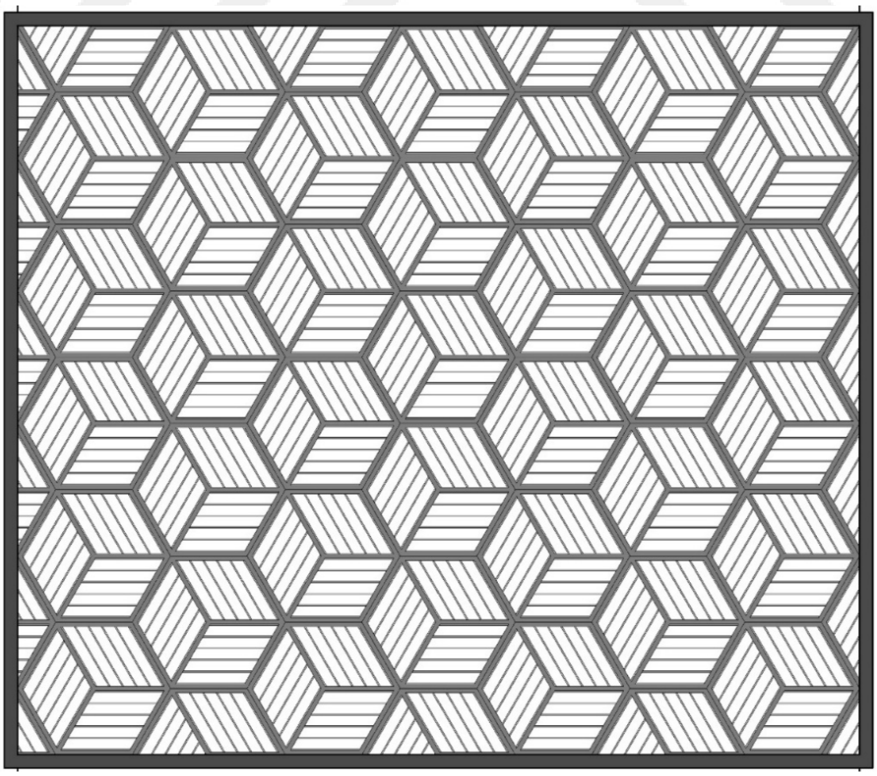

Figure 4.10. Regular hexagonal tessellation design in a rectangular façade.

4.2. Design of the Louvers

In this part of the thesis, the design of the movable elements, their design principles and placements in the formed hexagon are explained in detail. Parallelogram shaped louvres are used as the main element of the kinetic façade with minor design differences. The long edges of the louvers are arranged as parallel to the main frame profiles. Afterwards, fasteners are added to the louvers to create mobility by connecting to the hexagonal profiles (Figure 4.11).

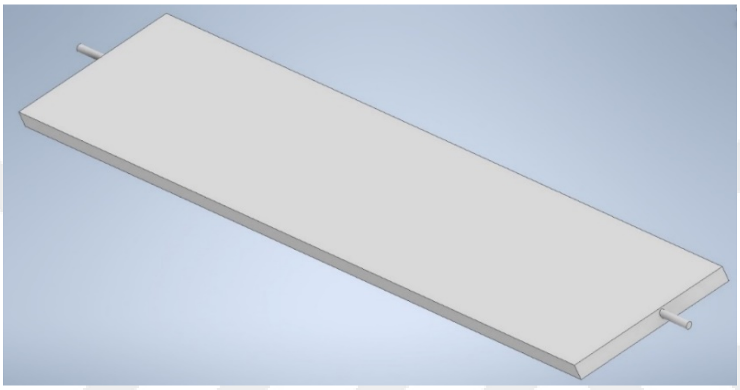

Figure 4.11. Connection of fasteners.

One of the rules of the placement of the louvers on the hexagon is that each louver has equal distance to each other. In this way, eighteen selected louvers are distributed evenly and modularly in hexagon. However, as a result of the parallel placement of the long and short sides of the eighteen louvers inside of the hexagon, eight different design alternatives are created (Figure 4.12). At this stage of the design, the importance of the connectivity of the fasteners are revealed to determine what design is to be used in the process. In this way, the eight design alternatives might be reduced two as creating a rule in which only the louvers formed at the same angles are connected to each parallel profile formed on the designed hexagon. Therefore, the design rules of the moveable blinds are defined, and the placement rules are determined by selecting one of two alternatives (Figure 4.13). In this section, design number 1 is chosen for the further development of the kinetic facade.

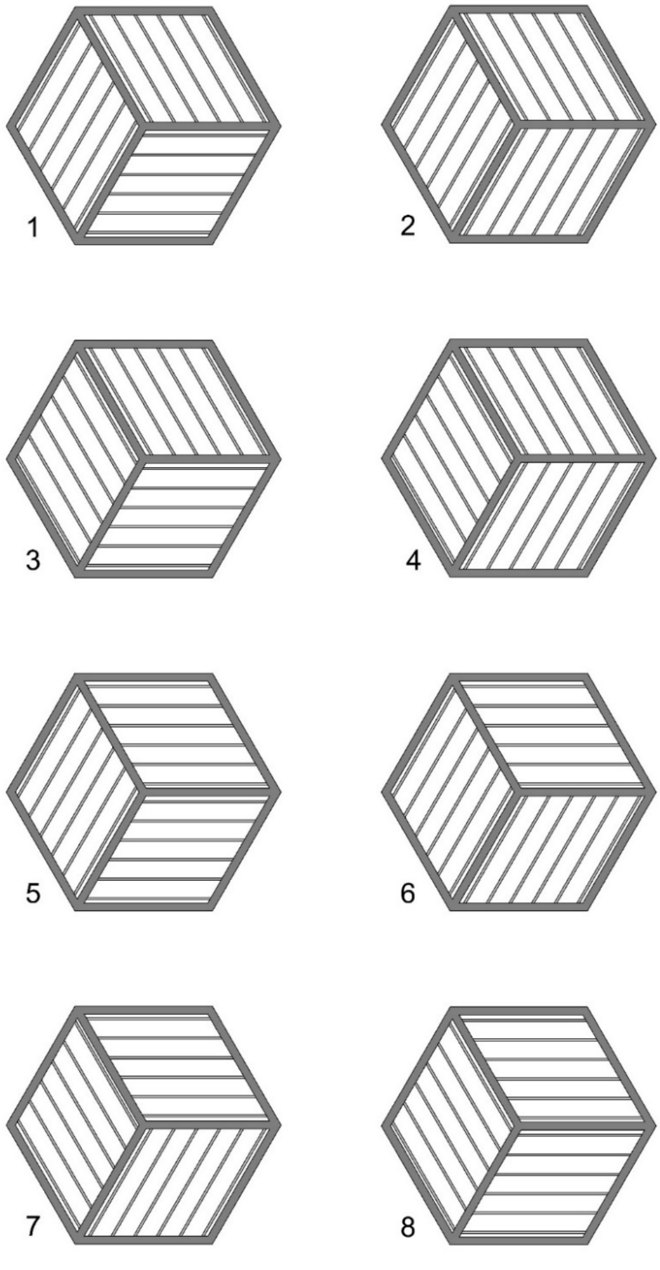

Figure 4.12. Eight different design alternatives

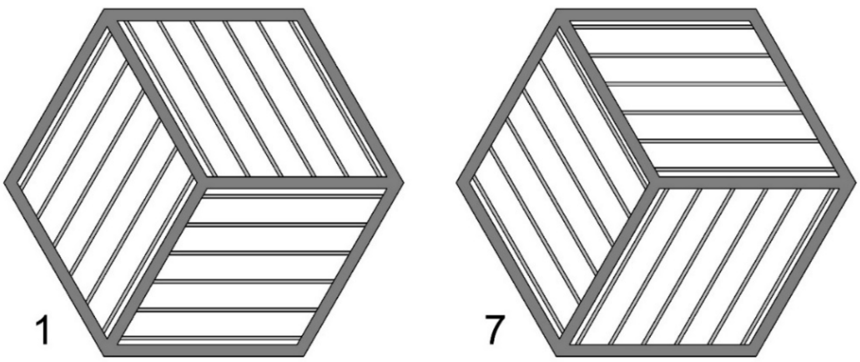

Figure 4.13. Two different design alternatives

4.3. Movement Design of the Louvers

Among the factors of designing a kinetic façade, the determination of the limits of movement and the range of motion are the most important ones. The frame of the parallelograms designed on the hexagons determines the motion limits and the motion surface of the moveable louvers.

As presented in Chapter 2, there are three types of motion which are radial, translational and rotational motion. The louvers of the façade system are designed according to the principles of rotational and translational motions within the determined modular framework. The louvers are placed parallel to the two sides of the parallelograms inside of the hexagon (Figure 4.14). These louvers are placed at equal distance to each other. The kinetic movement begins as the louvers moves towards the parallel side of the parallelogram. When the first louver element reaches to the outer frame boundary of the parallelogram, it stops and determines the movement limit. At the same time, the other louvers terminate the sliding movements by the fact that each louver in front of it touches another louver as a result of the movement of the louvers sliding sequentially at the border of the parallelogram. The system formed as a result of these movements is called closed position (Figure 4.15).

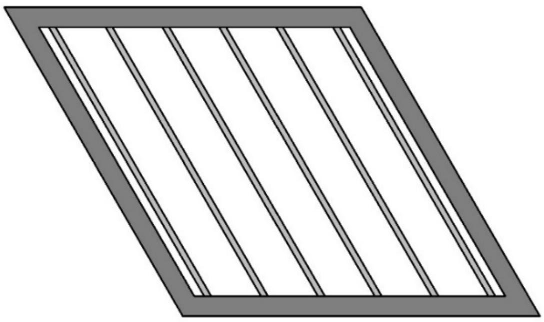

Figure 4.14. Placement of the louvers inside of the parallelogram.

The principle movements of the louvers in the parallelogram shown in Figure 4.16 are applied to all parallelograms in the hexagon to obtain the final stage of the movement. Then, the same movement principles are applied to all the modules in the kinetic facade system.

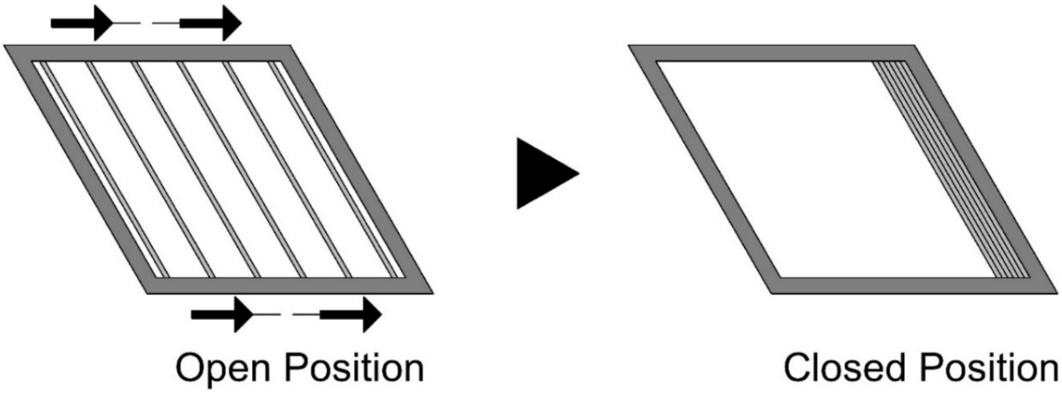

Figure 4.15. Open position (left side) and Close position (right side) of the motion.

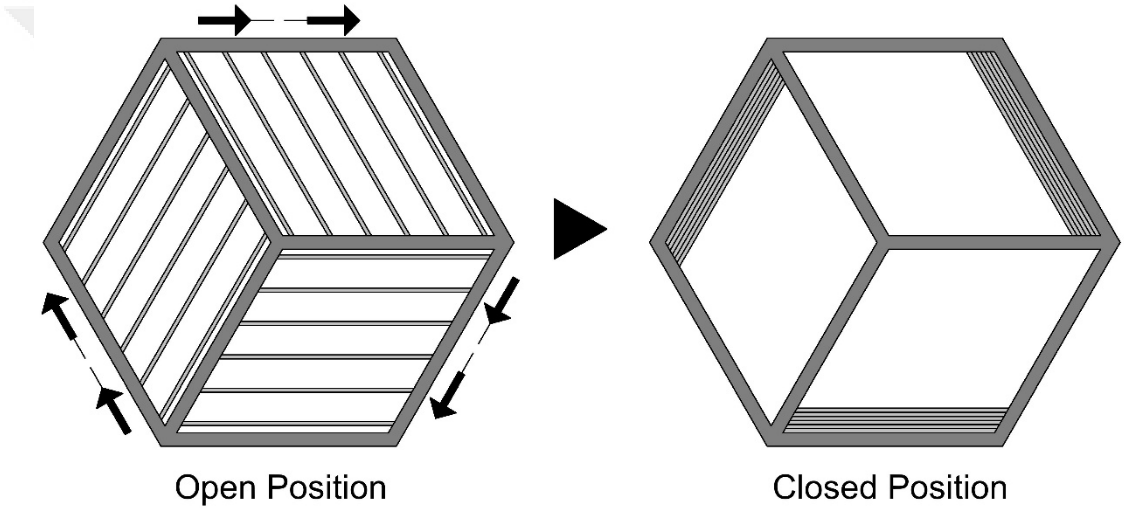

Figure 4.16. Open and Close position of the louvers.

In the second stage of the movement of the louvers, angular movement and its limitations are determined. The louvers designed parallel to the outer frame are able to rotate only in the open position. If the angle of the louvers are set as 0°, the limits of the angular movement are between -40° and 40° (Figure 4.17). In other words, the angular movement capability of the louvers is 80°. These angels are determined by considering that the sun's rays would come right across the designed kinetics facade. On the other hand, it is ensured that the building façade is not completely closed and natural light is taken from the building façade into the building (Figure 4.18).

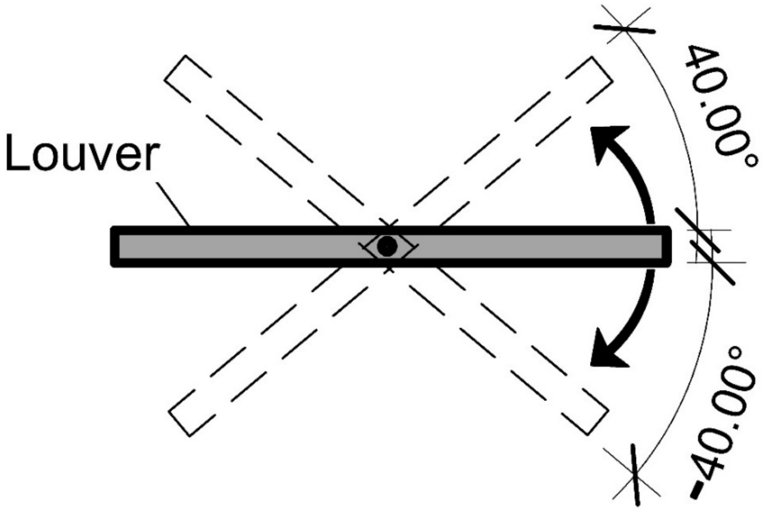

Figure 4.17. Angular motion of a louver.

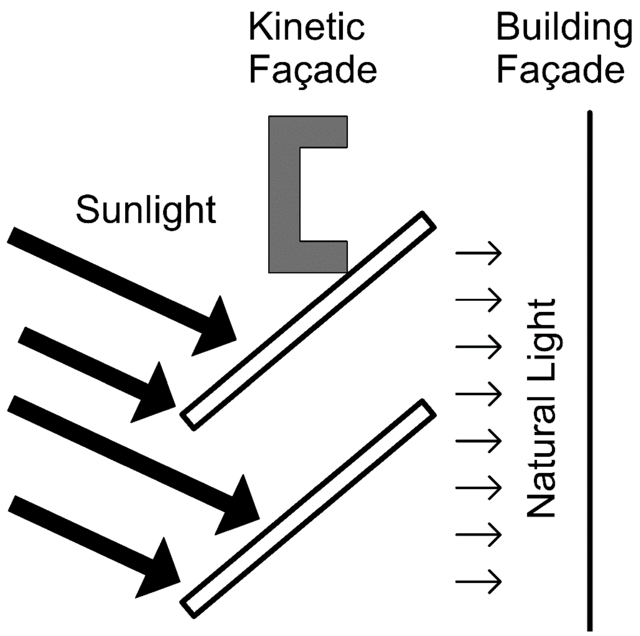

Figure 4.18. Natural light on the façade of the building. Sunlight reach the kinetic façade from right across.

A step-by-step angular movement of the louvers is created to facilitate not only the daylight analyzes in the parametric model but also the positions of the louvers. The angular movements of the louvers are defined in nine different stages depending on their degree. If the angle of the louvers is defined as 0°, they are in the open position which is the first stage. If the angles of these louvers reach to 10 °, 20 °, 30 ° and 40 °, these angles are referred to the second stage, the third stage, the fourth stage and the fifth stage, respectively. Likewise, if the angles reach to -10 °, -20 °, -30 ° and -40 °, these angles are referred to as the sixth stage, the seventh stage, the eighth stage and the ninth stage, respectively. All of the stages are shown in Figure 4.19.

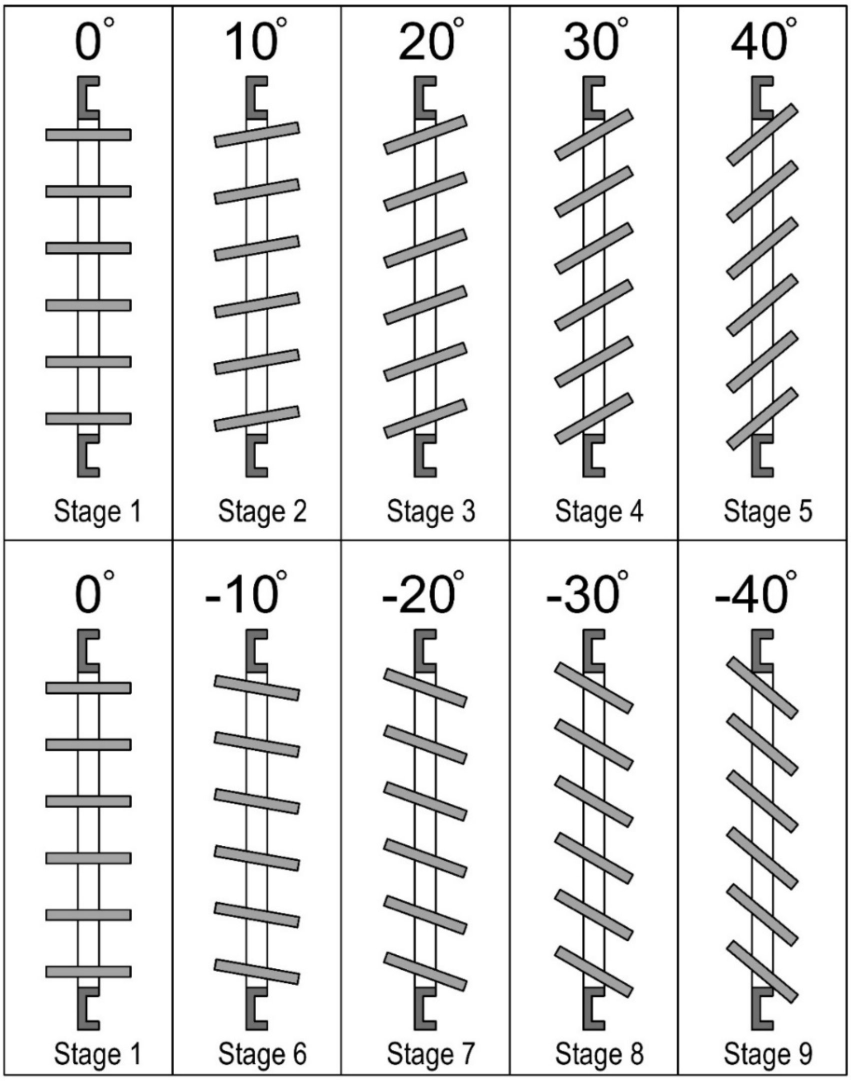

Figure 4.19. Section of angular stages of louvers.

4.4. Parametric Design of Hexagonal Modules

Parametric design in architecture is a mathematical process in which the design parameters, rules, definitions, and relationships of designed objects are determined. In this way, the design of complex geometries and structures in parametric design can be changed with certain rules and the changes in design can be observed. Designers often focus on parametric design for optimization, form-finding or researching the effects of weather conditions on the building. Designers use many different software and applications to achieve the design goals.

Within this thesis, Rhinoceros® (a 3D CAD modeling software) is used to develop accurate design solutions. An algorithmic modeling plugin for Rhinoceros called as Grasshopper® is also used to build the parametric model of the kinetic façade. The design rules and the relationships between the design elements are determined in the parametric model that has two main parts: shape forming and panel creation (Figure 4.20).

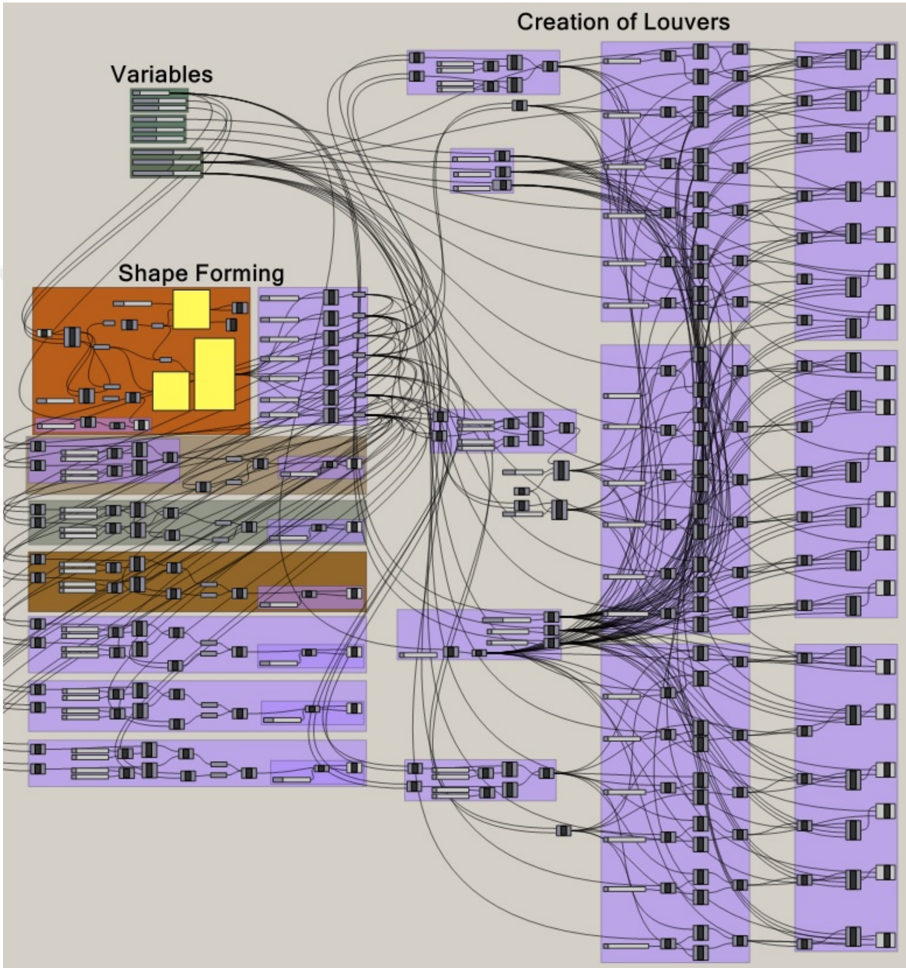

Figure 4.20. Parametric design.

In the part of shape forming, the parametric design of the hexagonal shape to be used in the design is formed. Firstly, a hexagonal frame and the edges of three identical parallelograms in the frame are determined and each edge is formed with a thickness of 5cm for 1m length of the edge of hexagon. Then, the dimensions of the formed frame were connected to a variable element allowing the dimensions to be easily changed. Despite the variable hexagon dimensions, a modular grid system is formed by applying the modular alignment and the reproduction rules of the system (Figure 4.21).

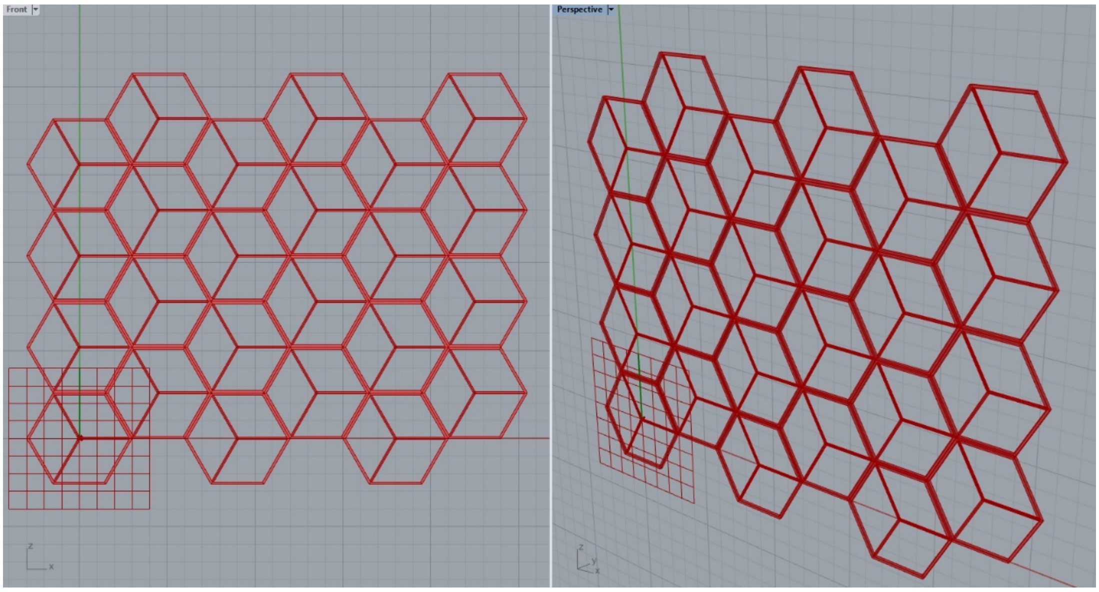

Figure 4.21. Shape forming. Size: 3, *x*- axis: 6, *y*- axis: 4.

The design of movable louvers is made by using the points and axes on the designed frame. In each parallelogram formed in the hexagon, there are six louvers which are parallel to the 2 sides of the frame (Figure 4.22). When forming one side of the hexagon as 1m, the width the louvers is 20cm, the length is 91.34 cm and the thickness is 1 cm (Figure 4.23). These louver dimensions are connected to the side length of the hexagon which change at the same rate as the side length of the hexagon changes.

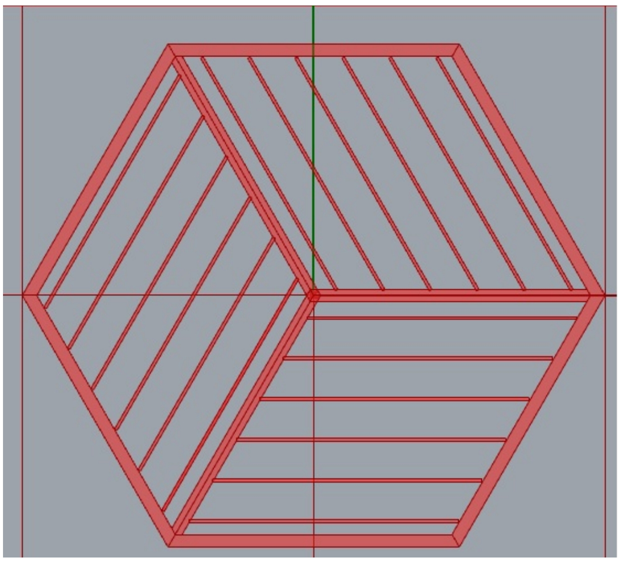

Figure 4.22. Placement of 18 louvers.

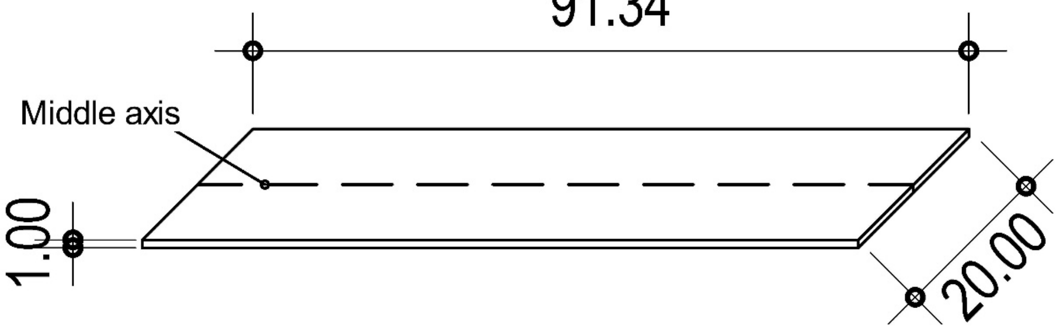

Figure 4.23. Dimensions of a parallegoram louver.

The edge louvers are placed at a distance of 5cm from the edge frame while the intermediate louvers are arranged by dividing the distance between the edge louvers into five. The distance of the other louvers from each other is determined as 12.62 cm. These louver distances between them are connected to the side length of the hexagon which change at the same rate as the side length of the hexagon changes (Figure 4.24).

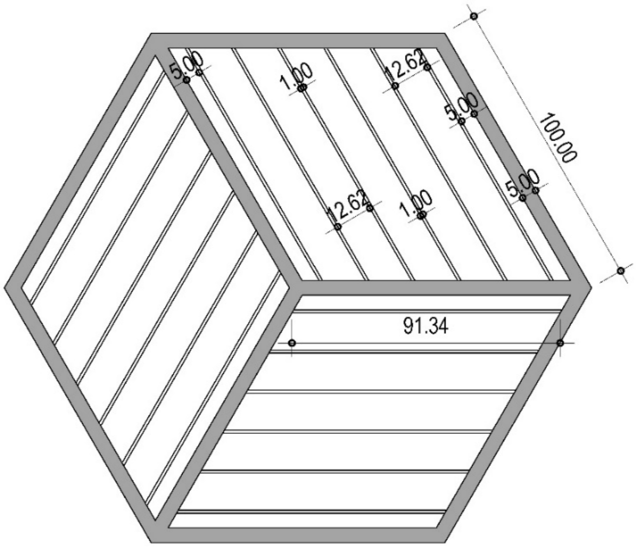

Figure 4.24. Placement of louvers

The louvers form a translational movement that is parallel to the edge frame. The louvers remain in the open position when the distance between the intermediate louvers is 12.62 cm. On the other hand, the closed position is obtained when all the louvers retract to the outer frame as keeping the distance 1 cm between them (Figure 4.25). When the louvers positions are set as 0^0 at the initial configuration, they move between -40^0 angle and $+40^0$ and provide 80^0 rotation capacity in total (Figure 4.26).

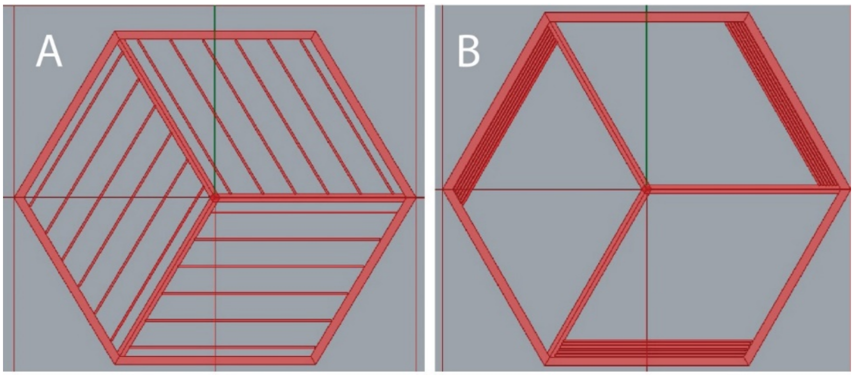

Figure 4.25. a. Open position; b. closed position

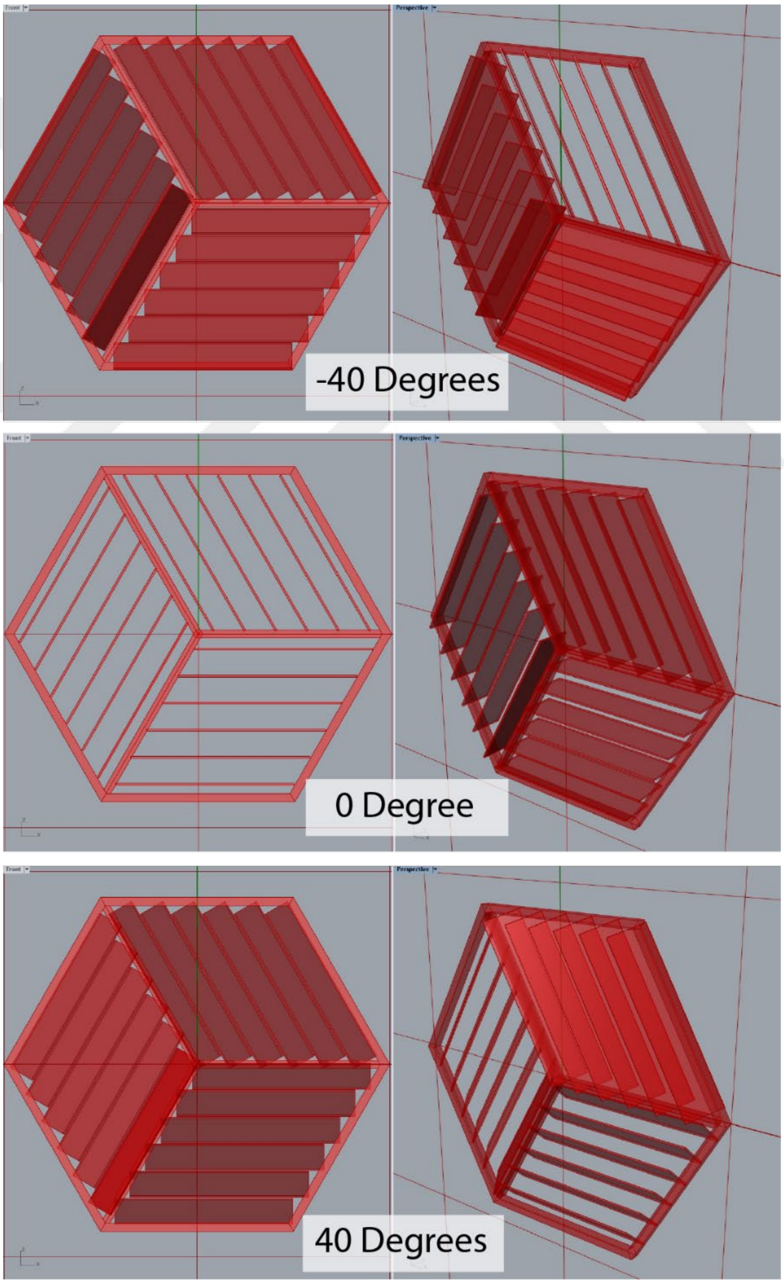

Figure 4.26. Movement process of the louvers on hexagonal modules.

One of the major factors in the parametric model is the design variables that are used to create performative solutions. The variables are classified into two main groups in the parametric model (Figure 4.27). Name of the first group is the dimension and repopulation which increase the size and the number of the hexagonal frame. The change in the dimensions of the frame and the reproduction of the frame on *x*- and *y*-axes can be controlled by the variables in this group.

The variables in the second group is called as "variables of the movements." These variables enable to control the angles of the louvers individually and to locate the louvers in open or close positions. Thus, different values given to movement variables allow creating different types of design alternatives as shown in Figure 4.28.

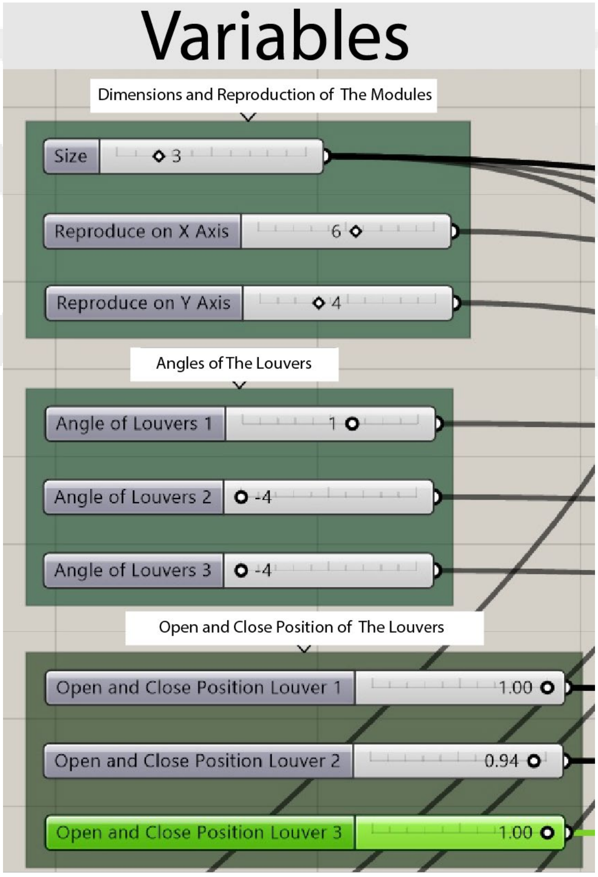

Figure 4.27. Variables in the parametric modelling.

The variables of the dimensions and reproduction of hexagons are

- the length of one edge of the hexagon: between 1m and 9m (selection from 9 alternatives)
- the number of the hexagon on the *x*-axis: between 1 time and 9 times (selection from 9 alternatives)

- the number of the hexagon on the y-axis: between 1 time and 9 times (selection from 9 alternatives).

The variables of the movements are

- the angles of the louvers separately: between -40^0 and 40^0 (selection from 9 alternatives). Each of the alternatives changes the angles 10 degree.
- sliding of the louvers separately: open and close position (selection from 2 alternatives).

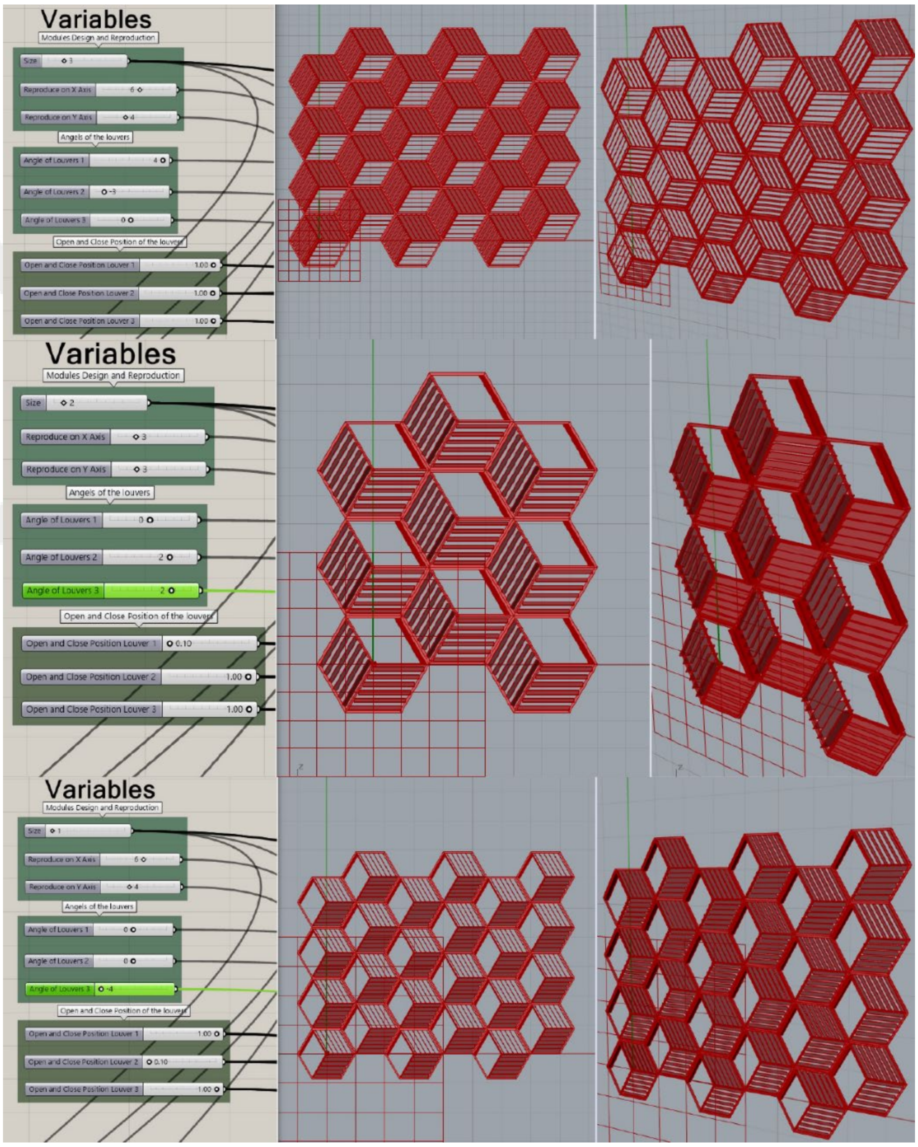

Figure 4.28. Design alternatives in the parametric modelling.

4.5. Mechanism Design

It is required to design a proper mechanism in order to facilitate the movement of the façade system. The first step in the mechanism design is to create a frame profile where the louvers can be easily moved or positioned. For this purpose, U-shaped profiles are used as shown in Figure 4.29. In the second step, the louvers are connected to the frame by using round bars that are parallel to the louver which provide rotational and translational movements (Figure 4.30). This connection is achieved by means of a gap in the U-shaped profiles which is equal to the diameter of the round bar (Figure 4.31).

Figure 4.29. U-shaped profile added the edges of the parallelogram

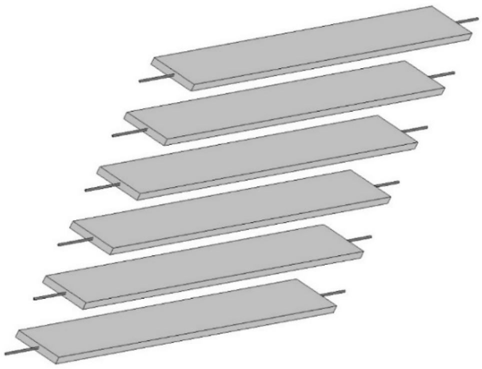

Figure 4.30. Round profiles connected to the louvers

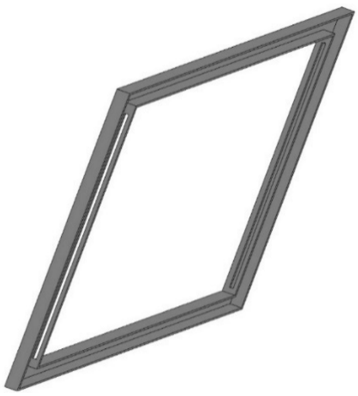

Figure 4.31. Gap is created inside of the U-shaped profiles

Box profiles are placed in the gap of the U-shaped profiles to place motors that are placed in the box profiles to control the rotations of the lovers as rotating the round bars. The mechanism design is completed by controlling the angular movements of the louvers. In addition, these motors also provide a linear movement for the box profiles which determine the positions of louvers to be open or close.

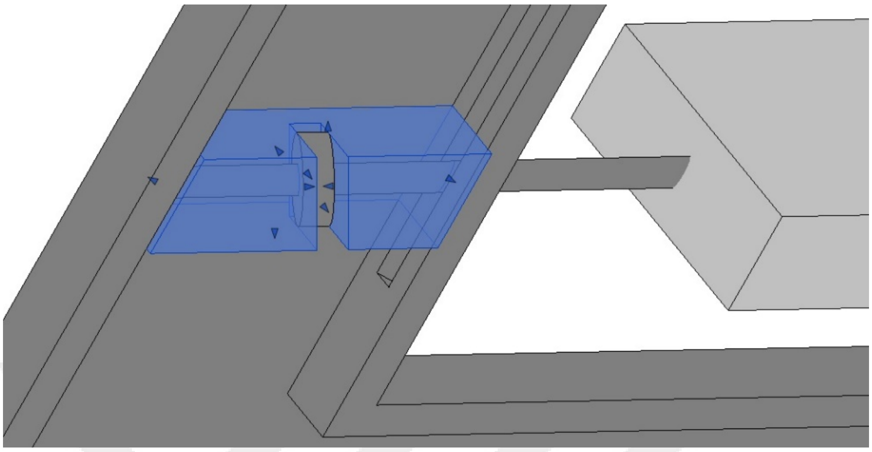

Figure 4.32. A round profile designed to control angle of the louvers.

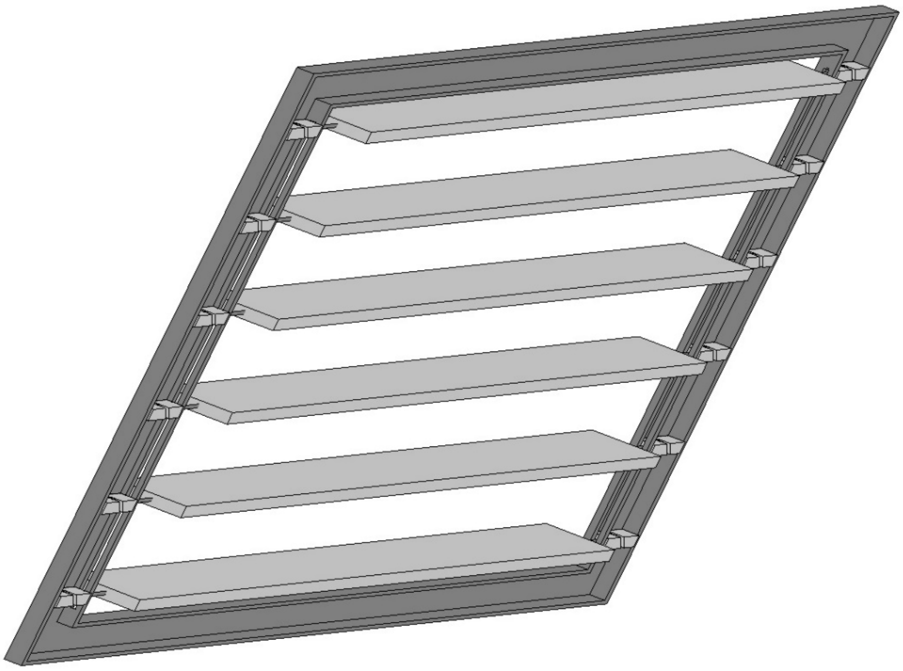

Figure 4.33. Final mechanism design.

CHAPTER 5
COMPUTATIONAL PERFORMANCE AND OPTIMIZATION

Optimization is a process to create functional and effective solutions to the design problem and to achieve the objectives that are desired at the initial design stage. Architects, engineers and researchers have been using many simulation programs for decades in both their scientific researches and real case applications. By means of simulation programs, analysis and evaluation of the design targets can be carried out at reasonable levels. With the development of technology, the interest on optimization techniques from these professional groups is increasing. In a design process, structural analysis, wind analysis, daylight and energy analyses can be performed by using simulation tools and techniques. In this thesis, Open Studio, Energy Plus, Daysim, Radiance, Ladybug and Honeybee software are used for the simulations in Rhinoceros®.

Optimal results can be achieved by optimizing the design variations according to their performance. In order to achieve the optimal goals for a design, optimization tools need to be involved in the process. Optimization tools facilitate to find optimal design solutions among different design alternatives by using algorithms that can automatically analyze the alternative design simulations and optimize the results of analysis for the design purposes. In this thesis, Octopus plug-in is selected for the optimization of the kinetic façade design.

The kinetic façade design presented in Chapter 4 is analyzed, simulated and optimized in Rhinoceros® software using Grasshopper. Covering $40m^2$, the building consists of a ground story only with spatial dimensions of 8m (width), 5m (depth) and 6m (height). %90 of the south façade is covered with glass as shown in Figure 5.1 so that the light can be distributed inside of the building. The proposed kinetic facade is placed 1 meter away from the transparent façade of the building which faces to the south direction for simulations and optimizations as shown in Figure 5.2. In addition, the 3D building model is located in Izmir, Turkey.

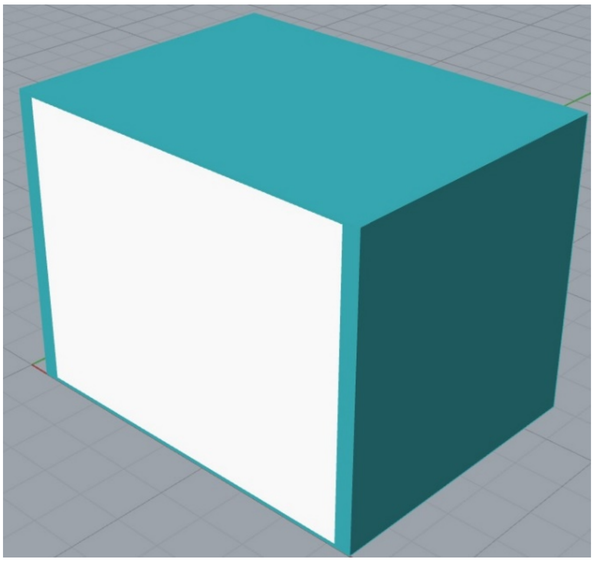

Figure 5.1. Building model (white colored area represents south-faced transparent façade).

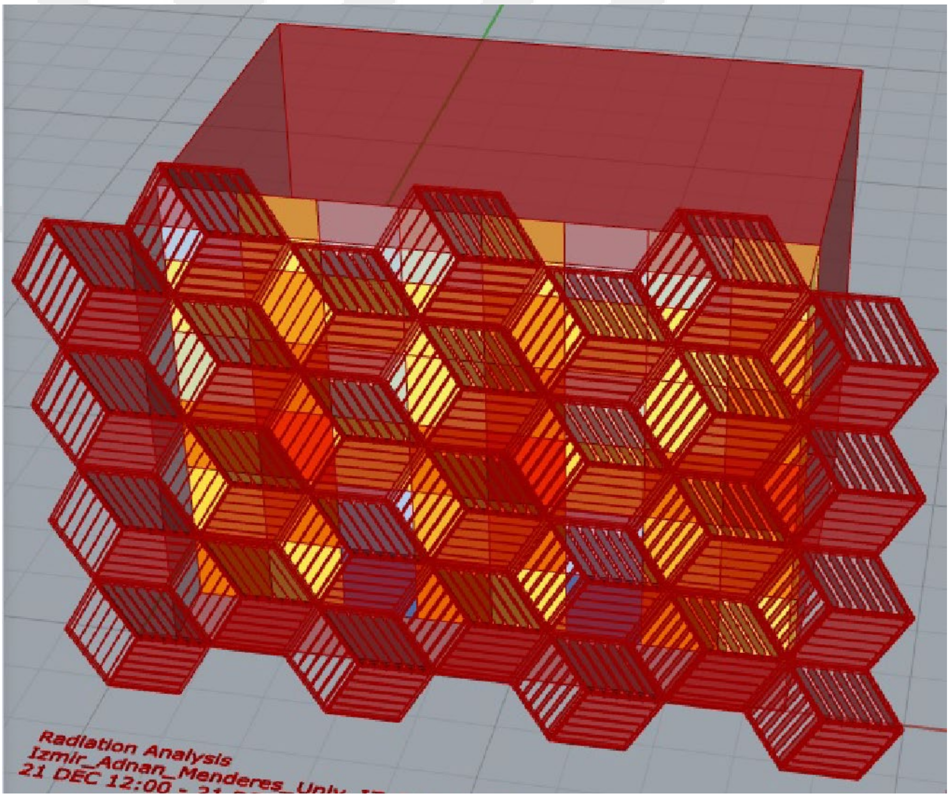

Figure 5.2. Designed kinetic façade placement.

5.1. Illuminance Objectives

Illuminance represents the measurement of the total luminous flux occurring on the surface of an area. According to photometry, this measurement is based on the perception of the brain or human eye (Long, 2020). The luminance measurements are calculated in lux and the symbol is *lx*. In addition, Candela (symbol: *cd*) is the base unit of luminous intensity and one lumen (symbol: *lm*) per square meter is equal to one lux. The formula for the calculation is

$$lx = 1\ lm/\mathrm{m}^2 = 1\ cd\cdot\mathrm{sr}/\mathrm{m}^2 \quad (1)$$

where *lx* is illuminance, *lm* is luminous and *cd* is candela.

The useful daylight level should be in the range of 100-2000 lux according to Nabil and Mardaljevic (2005). They also defined the light level between 500 and 2000 lux as the desired light level or a tolerable level for occupants. According to Lee et al., (1999), if the light level of a working area is higher than 500 lux, it is acceptable on the condition that the working environment does not interact with glare or direct sun. They also recommended the use of shading elements if the working environment is exposed to glare or direct sun. In addition, the UK Chartered Institution of Building Services Engineers (CIBSE, 2019) recommends that the designs for office spaces should be made according to 500 lux. In this thesis, computational optimization of the amount of light in the case model is accepted as 500 lux which is the first design objective.

After completing the simulations and optimizations, the comparison of three results is conducted. First, illuminance level of the indoor environment of the case model is calculated. Second, the proposed kinetic façade placed on the southern façade of the case building is accepted as static and the illuminance level of the indoor environment of the case building is calculated. Third, the computational optimization of the kinetic façade is done in order to calculate illuminance level of the indoor environment. Afterwards, the results are compared with each other.

The case building model prepared for illuminance simulation is designed as 5m to 8m. 40 different points are determined for the illuminance point measurements on the surface and the illuminance measurements are calculated for each point. Result of the illuminance measurements of each point are added and divided by 40 for the result. The results are also the arithmetic mean of the calculations.

The points are located 50 cm away from the walls and 1m away from each other. In addition, the height of the points used for the illuminance level measurements is determined as 75cm which is the working table height.

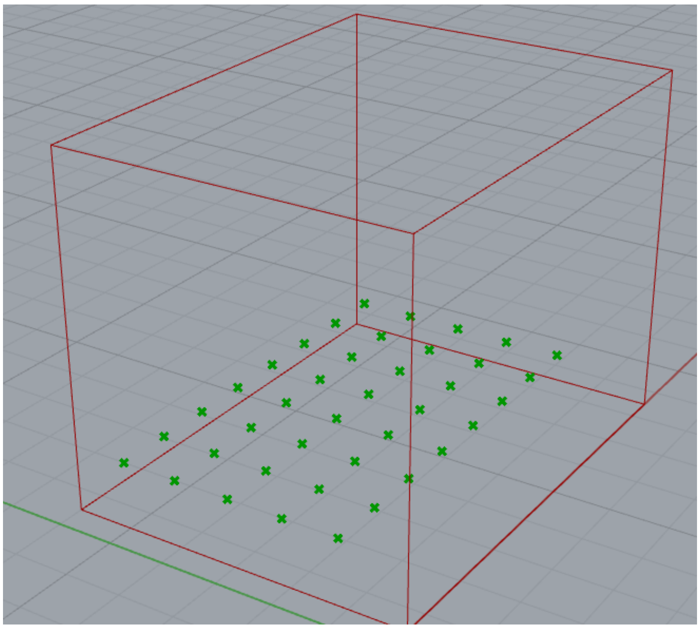

Figure 5.3. Placement of 40 points for the illuminance measurements

Model designs are completed in Rhino and Grasshopper. OpenStudio, Daysim, EnergyPlus and Radiance programs are used for the simulations in which the results are connecting to Honeybee. The weather file (EnergyPlus Location and Day Data-EPW) is used to obtain weather conditions for Izmir region. 21st of June, 21st of September and 21st December at 12.00 are selected for computational optimization and simulations.

5.1.1. Illuminance Level of the 3D Building Model

Before starting the optimization of the kinetic façade, the illuminance level of the building façade is calculated without the proposed kinetic façade. Then, the kinetic façade is applied to the model to make a comparison between two cases in terms of the levels of illuminance.

Table 5.1. Illuminance level results of indor environment of the 3D building model.

Cases	Dates	Selected Time	Results	Figure
Case 1	21st of June	12.00	4154 Lux	5.4
Case 2	21st of September	12.00	18838 Lux	
Case 3	21st of December	12.00	9602 Lux	

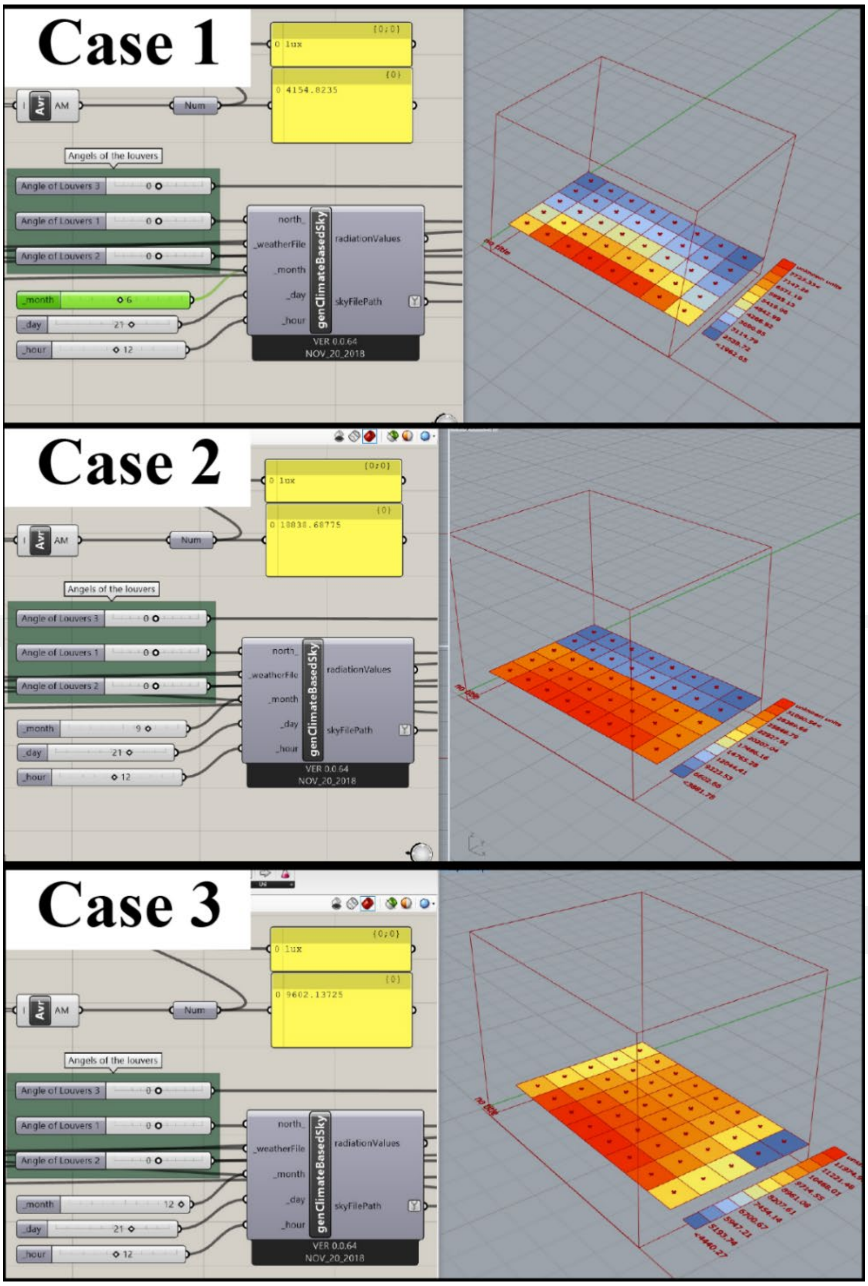

Figure 5.4. Simulations of illuminance level calculations of Case 1, Case 2, Case 3.

5.1.2. Illuminance Level of Stationary Façade Elements Placed On the Building Model

In this section, the proposed kinetic façade elements are considered as stationary façade elements which are placed to the south façade of the building. The angle of the stationary louvers is determined as 0. The illuminance level of the indoor environment is simulated and calculated. A comparison of the illuminance levels is made between stationary and kinetic façade elements.

Table 5. 2. Illuminance results of indor evnironment of the building model by placing the stationary façade elements on to south façade.

Cases	Dates	Selected Time	Results	Figure
Case 4	21st of June	12.00	968 Lux	5.5
Case 5	21st of September	12.00	1771 Lux	
Case 6	21st of December	12.00	2752 Lux	

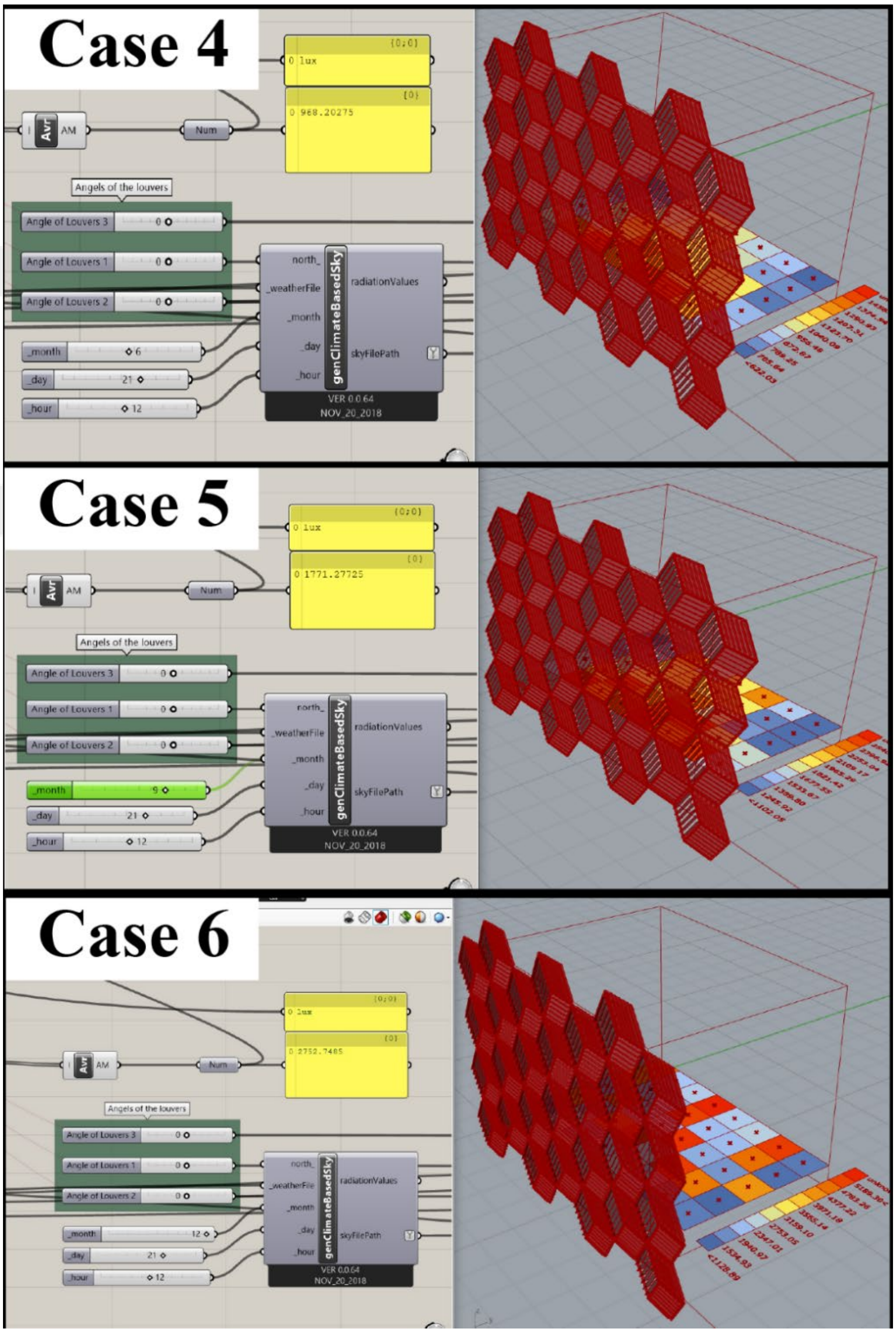

Figure 5.5. Simulations of illuminance level calculations of Case 4, Case 5, Case 6.

5.2. Solar Radiation Objectives

A solar radiation measurement is a measurement of the energy of the solar radiation on a surface at a specified time interval. The unit is *watts* per square meter (W/m^2) or *kilowatt-hours* per square meter (kW/m^2). Within this thesis, the simulation results are given as kW/m^2.

The solar radiation gain of the openings (e.g. windows) on the building facades increases not only the amount of energy used inside of the building but also the inside glare level. In order to minimize direct solar radiation, shading elements are used on the building facades which not only increase the comfort levels of the occupants but also reduces the energy consumption costs. Thus, the second design objective is determined as minimizing solar gain level of the facade.

For the simulations and optimizations, first, the amount of the solar radiation on the southern facade of the building is calculated. Second, the proposed kinetic façade elements are placed to the southern façade of the building which are assumed as static elements to calculate the amount of solar radiation hitting the building façade. Third, the computational optimization of the kinetic façade placed on the southern façade of the building is made to calculate the amount of solar radiation on the façade. Finally, the calculations are compared with each other.

5.2.1. Solar Radiation Level of the South Façade of 3D Building Model

In this section, solar radiation level of the south facade of the 3D building model is calculated and simulated. The designed kinetic façade is not placed to the building for this calculation.

Table 5. 3. Solar radiation results of south facade of the building model.

Cases	Dates	Time Period	Results	Figure
Case 7	21st of June	12.00 – 13.00	0.305496 kWh/m2	5.6
Case 8	21st of September	12.00 – 13.00	0.572309 kWh/m2	
Case 9	21st of December	12.00 – 13.00	0.836801 kWh/m2	

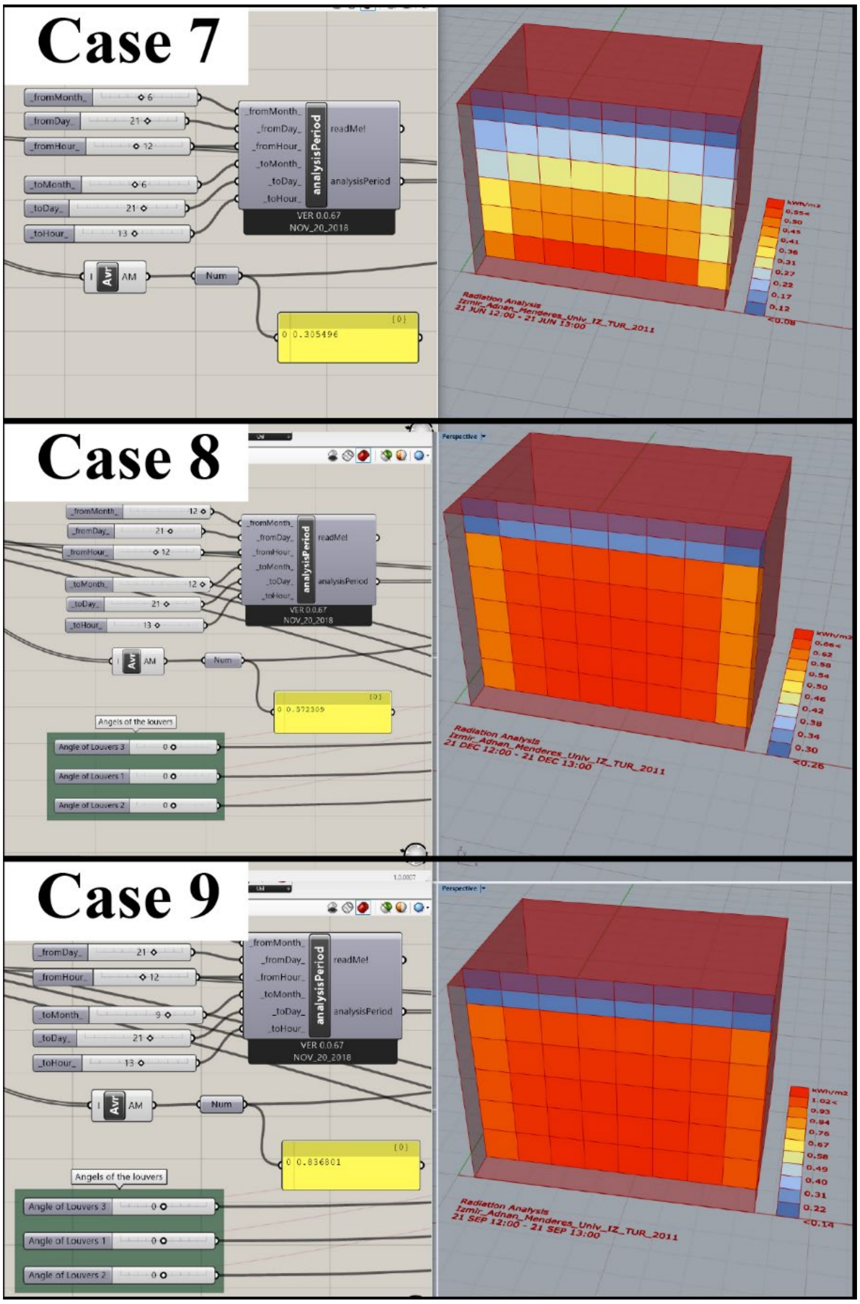

Figure 5.6. Simulations of radiance level calculations of Case 7, Case 8, Case 9.

5.2.2 Solar Level of Stationary Façade Elements Placed On 3D Building Model

In this section, the designed kinetic façade elements are considered as stationary façade elements that are placed to the south façade of the building façade. The solar radiation level of the south facade is simulated and calculated. The comparison of solar radiation level could be made between stationary and kinetic façade elements. In addition, the angle of stationary louvers is determined at 0.

Table 5. 4. Solar radiation results of south façade of artificial building model by placing the stationary façade elements 1 meter away from the façade.

Cases	Dates	Time Period	Results	Figure
Case 10	21st of June	12.00 – 13.00	0.058361 kWh/m2	
Case 11	21st of September	12.00 – 13.00	0.168677 kWh/m2	5.7
Case 12	21st of December	12.00 – 13.00	0.234704 kWh/m2	

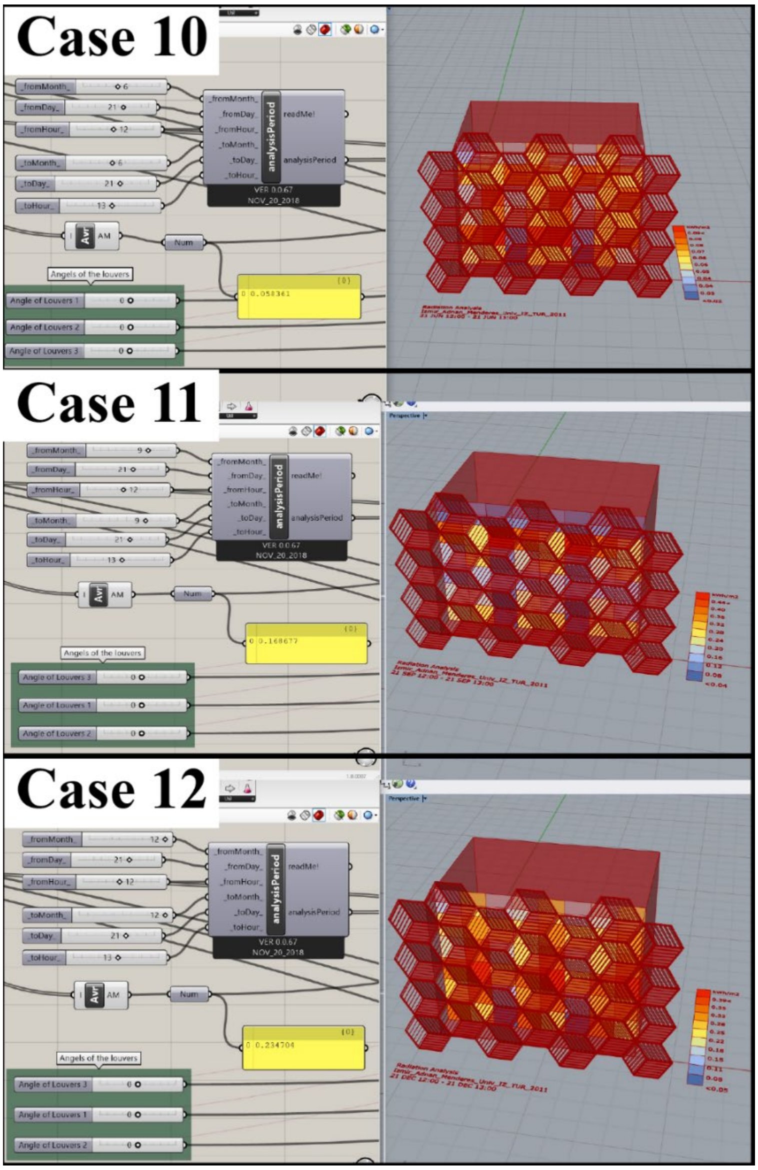

Figure 5.7. Simulations of illuminance level calculations after the placement of the stationary kinetic façade elements.

5.3. Computational Design

Octopus is used for optimization purposes which is a Multi-Objective Evolutionary Optimization plug-in for Grasshopper aiming to optimize several design objectives simultaneously. It is possible to compare the results of design alternatives to obtain optimal results by using Hypervolume Estimation Algorithm (Octopus, 2019). In this thesis, Hypervolume Estimation Algorithm is used for multi-objective design optimization.

Hypervolume Estimation Algorithm is a general reproduction optimization algorithm based on Pareto dominance. In the optimization algorithm, the predicted results determine the quality of the conformity function solutions and each predicted result is marked in a Pareto set. When one Pareto group indicator dominates the other group indicator, the indicators of the dominant group become better. In this way, the algorithm works to generate a better Pareto group by using the data in each Pareto group. Therefore, optimal design results can be achieved in design objectives in Pareto group (Bader & Zitzler, 2008).

5.3.1 Design Objectives and Variables For Optimization

Optimization rules for the use of simulation and optimization are

- the adjustment of the illuminance level in the indoor environment of the building model around 500 lux. for reduction of energy usage.
- minimizing solar radiation gain on the south facade of the building model for reduction of energy usage.

The louvers formed in each parallelogram are grouped separately and named as group 1, group 2, group 3 (Figure 6.8). Each group has ability to rotate for -40^0, -30^0, -20^0, -10^0, 0^0, 10^0, 20^0, 30^0, 40^0. It means that each group has 9 different variations. The three grouped louvers in each hexagon have 729 (9 x 9 x 9) angular movement variations in total.

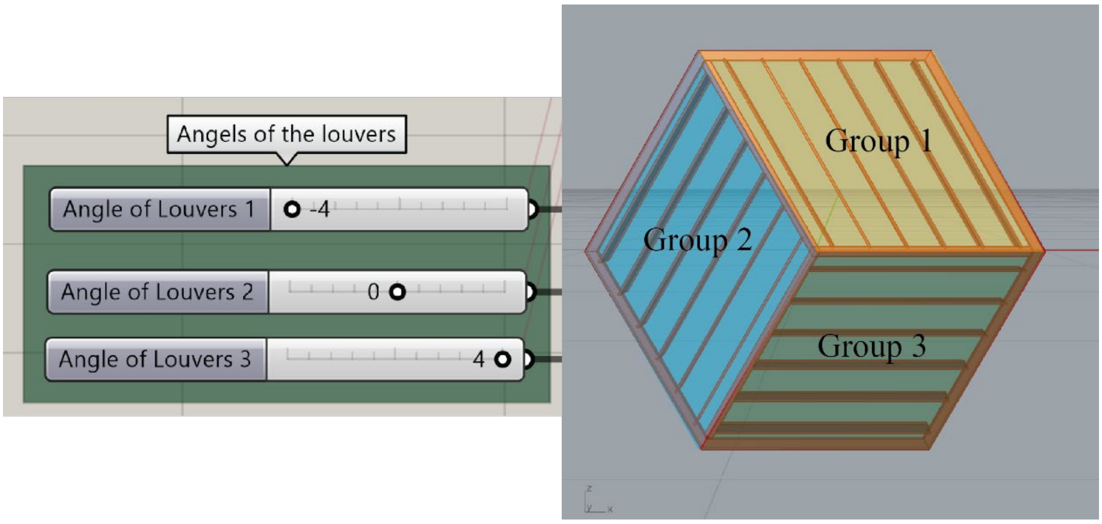

Figure 5.8. Description of grouped louvers.

5.3.2 General Information

In the case studies, the design objectives and the general information about the building in Section 5. are applied to the generative model for the selected date and time that are seen in below.

- Case 13: selected date is 21st of June and selected time is between 12.00 – 13.00
- Case 14: selected date is 21st of September and selected time is between 12.00 – 13.00
- Case 15: selected date is 21st of December and selected time is between 12.00 – 13.00

Optimization tests are performed on a computer with Inter Core-i7 and 16 GB of RAM. Each population took about 30 seconds to produce. 50 populations are provided for each new generation. Octopus optimization settings for the cases 13, 14 and 15 are

- Elitism: 0.5
- Mut. Probability; 0.200
- Mutation Rate: 0.90
- Crossover Rate: 0.50
- Max Generations: 0
- HypE Reduction has been used

- HypE Mutation has been used

In this section, the optimization results for the 3 different days determined are indicated.

5.3.3 Optimization Case 1

At the first generation of the computational optimization, the illuminance level measurements ranged from 450 *lx* to 1562.67 *lx* and the solar radiation measurements ranged from 0.0218 kWh/m^2 to 0.0831 kWh/m^2 are found as shown in Figure 5.9. In the last generation, the illuminance level ranged from 316.79 to 414.31 *lx* and the solar radiation measurements ranged from 0.0158 kWh/m^2 to 0.0197 kWh/m^2 are obtained as indicated in Figure 5.10. However, when the generations are examined according to the design rules determined in Section 5.1.4, the population that is close to 500 *lx* is found in the 8th generation as shown in Figure 5.11. The illuminance level of the selected population is 519.53 *lx* and the solar energy calculation is 0.0209 kWh/m^2. Thus, the computational optimization of the kinetic facade is terminated according to the results.

Table 5. 5. Results for computational optimization for optimization case 1.

Case	Generations	Targeted Population Found in	Illuminance Measurement	Solar Radiation Measurement
Optimization Case 1	19	8th	519,53 lux	0.0209 kWh/m2

Table 5. 6. Angle of Louvers for optimization case 1.

Optimization Case 1	Date	Time	Group 1	Group 2	Group 3	Figure
Angle of Louvers of 8th generation	21st of June	Between 12.00 – 13.00	-20°	-40°	20°	5.12

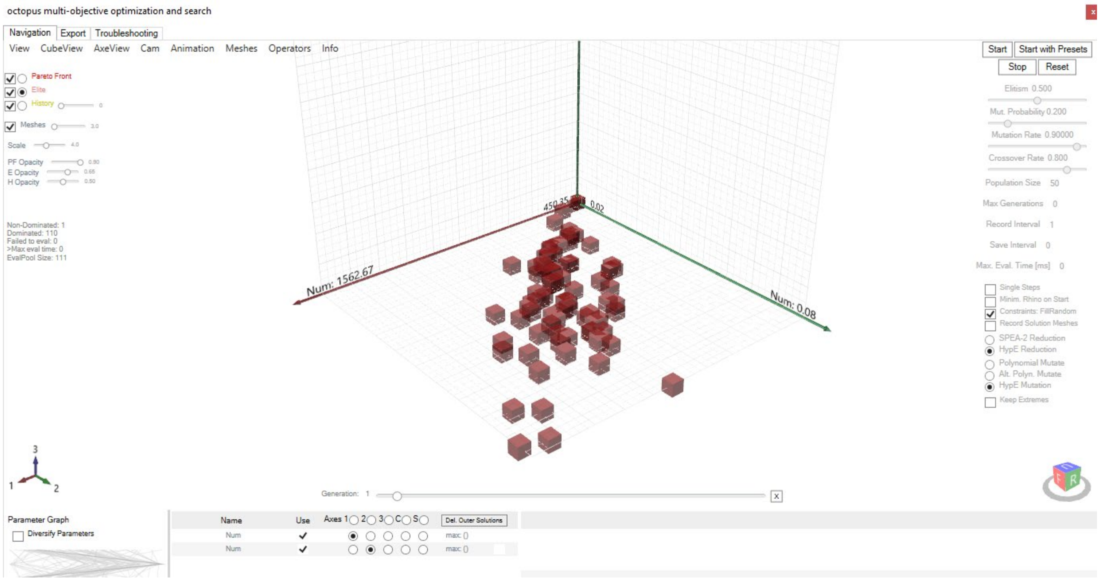

Figure 5.9. Results of 1st generation in optimization case 1. Red cubes represents populations.

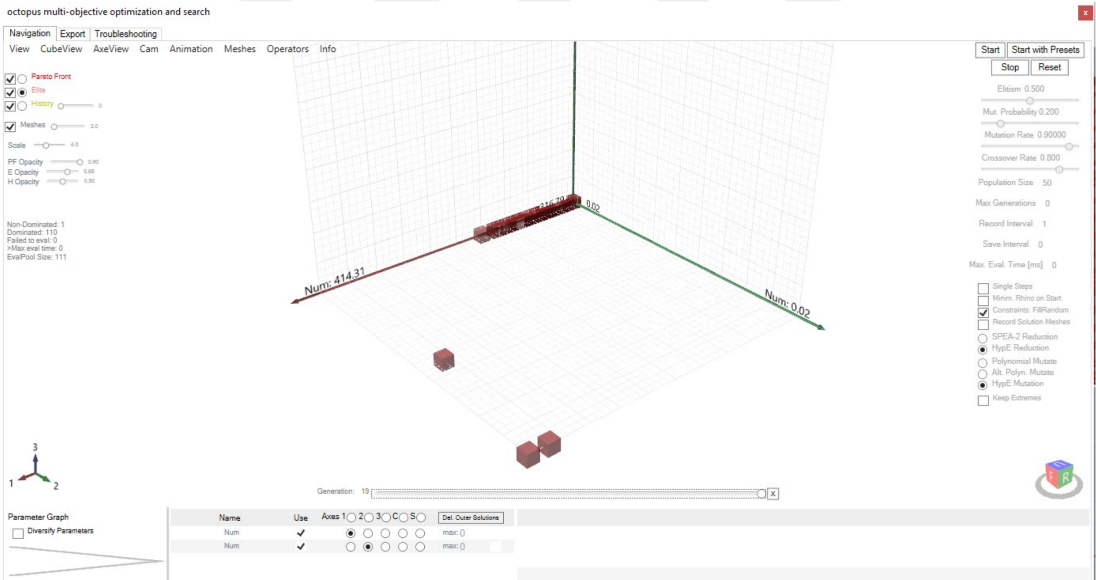

Figure 5.10. Results of 19th generation in optimization case 1. Red cubes represents populations.

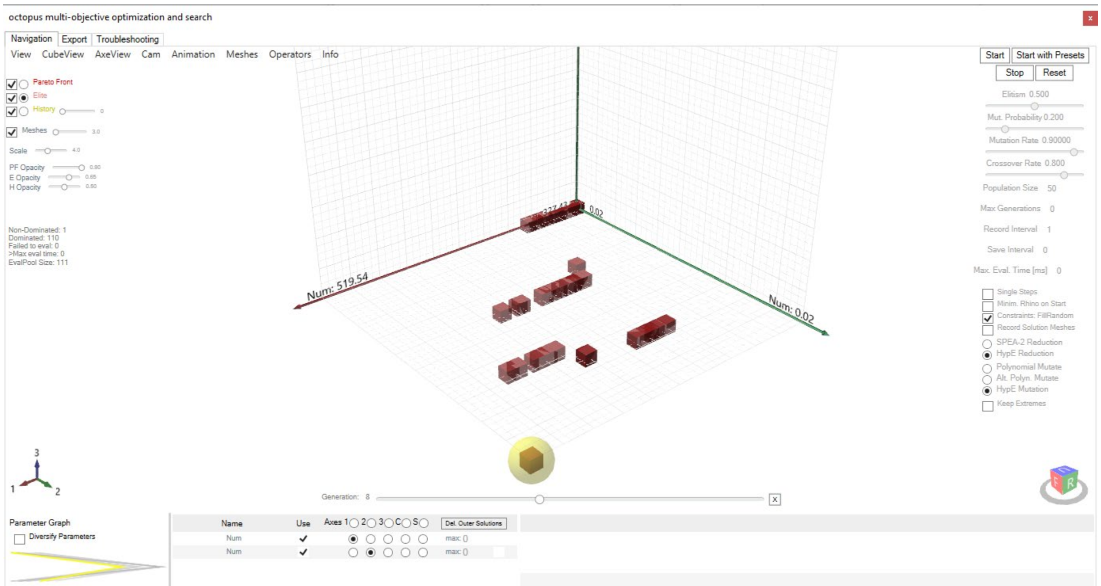

Figure 5.11. Results of 8th generation in optimization case 1. Red cubes represents populations. Yellow marked cube represents the selected population.

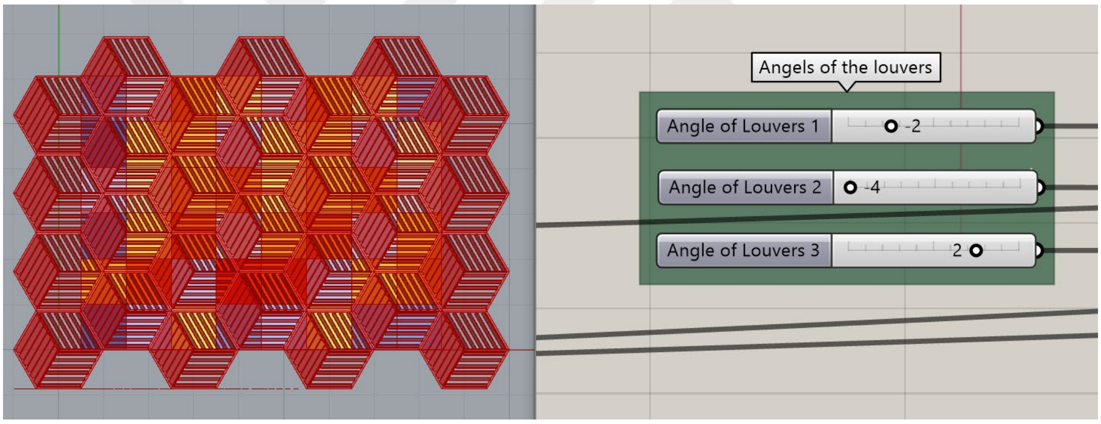

Figure 5.12. Kinetic façade design for the selected population settings in optimization case 1.

5.3.4 Optimization Case 2

Total of 11 generations are produced. At the first generation of the computational optimization, the illuminance level measurements ranged from 521.9 *lx* to 5207,28 *lx* and the solar radiation measurements ranged from 0.0321 kWh/m^2 to 0.2459 kWh/m^2 are obtained as shown in Figure 5.13. In the last generation, the illuminance level ranged from 393.61 to 521.9 *lx* and the solar radiation measurements ranged from 0.0298 kWh/m^2 to 0.0357 kWh/m^2 are found as indicated in Figure 5.14. However, the targeted population found in the 11th generation which is close to 500 lux as shown in

Figure 5.15. The illuminance level of the selected population is 521.9 lux and the solar energy calculation is 0.0357 kWh/m^2.

Table 5. 7. Results for computational optimization for optimization case 2.

Case	**Generations**	**Targeted Population Found in**	**Illuminance Measurement**	**Solar Radiation Measurement**
Optimization Case 2	19	11th	521.9 lux	0.0357 kWh/m2

Table 5. 8. Angle of Louvers for optimization case 2.

Optimization Case 2	**Date**	**Time**	**Group 1**	**Group 2**	**Group 3**	**Figure**
Angle of Louvers of 11th generation	21st of September	Between 12.00 – 13.00	-40°	-30°	40°	5.16

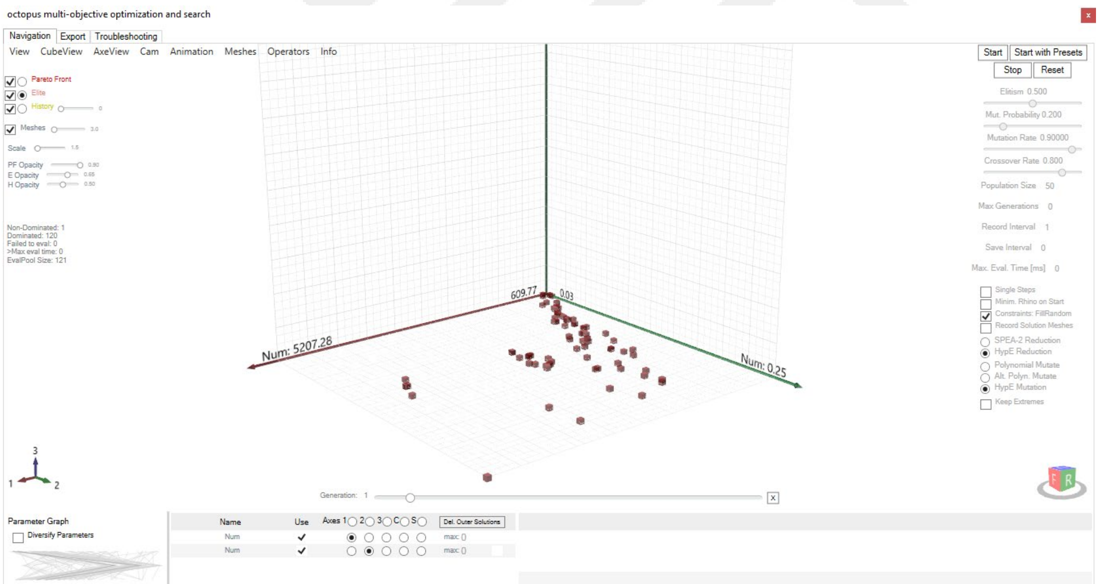

Figure 5.13. Results of 1st generation in optimization case 2. Red cubes represent populations.

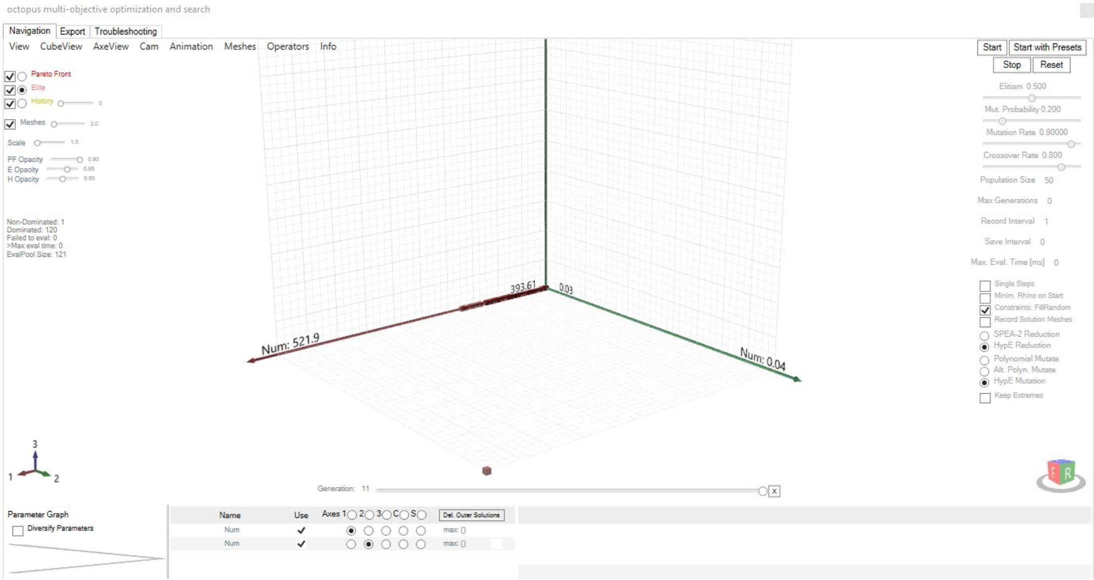

Figure 5.14. Results of 11st generation in optimization case 2. Red cubes represents populations.

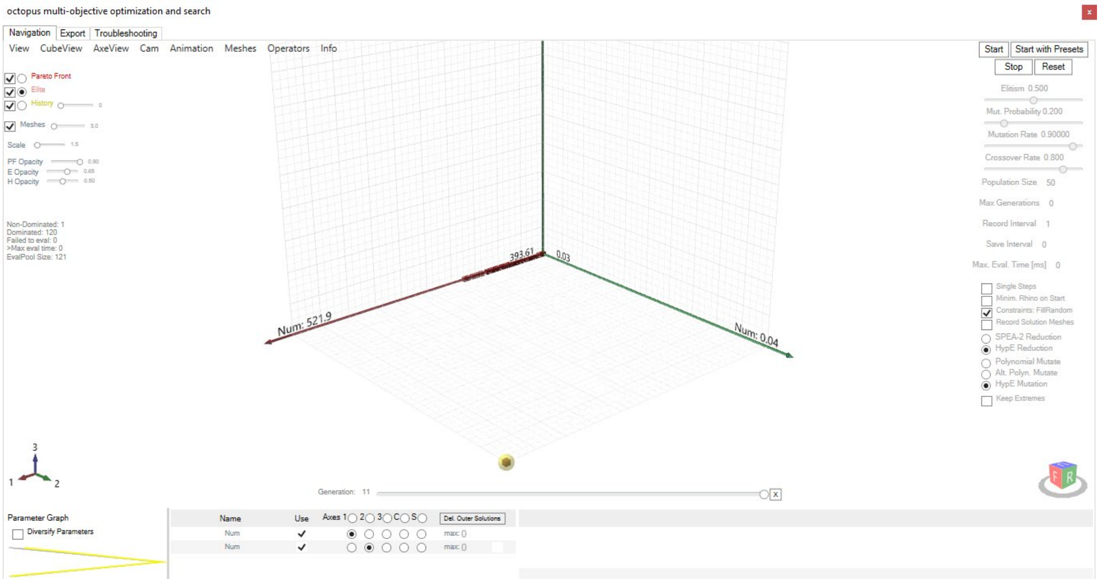

Figure 5.15. Results of 8th generation in optimization case 2. Red cubes represents populations. Yellow marked cube represents the selected population.

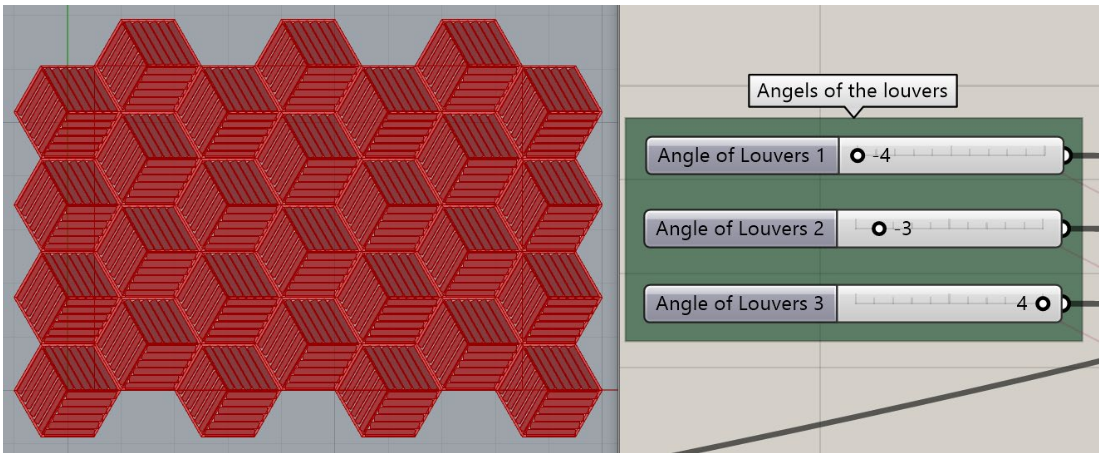

Figure 5.16. Kinetic façade design for the selected population settings in optimization case 2.

5.3.5 Optimization Case 3

In Optimization Case 3, 11 generations were produced in 9 hours. The illuminance level simulations measured between 3111.99 lux and 262.31 lux and the solar radiations level simulations measured between 0.0223 kWh/m2 to 0.0326 kWh/m2 in simulated 11 generations as shown in Figures 5.17 and 5.18. Among the 11 generations, a population found in 7th generation which is in accordance with the design rules.

Table 5. 9. Results for computational optimization for Optimization Case 3.

Case	Generations	Targeted Population Found in	Illuminance Measurement	Solar Radiation Measurement
Optimization Case 3	11	7th	504.10 lux	0.0326 kWh/m2

Table 5. 10. Angle of Louvers for opimization Case 3.

Optimization Case 3	Date	Time	Group 1	Group 2	Group 3	Figure
Angle of Louvers of 7th generation	21st of December	Between 12.00 – 13.00	-30°	-30°	30°	5.20

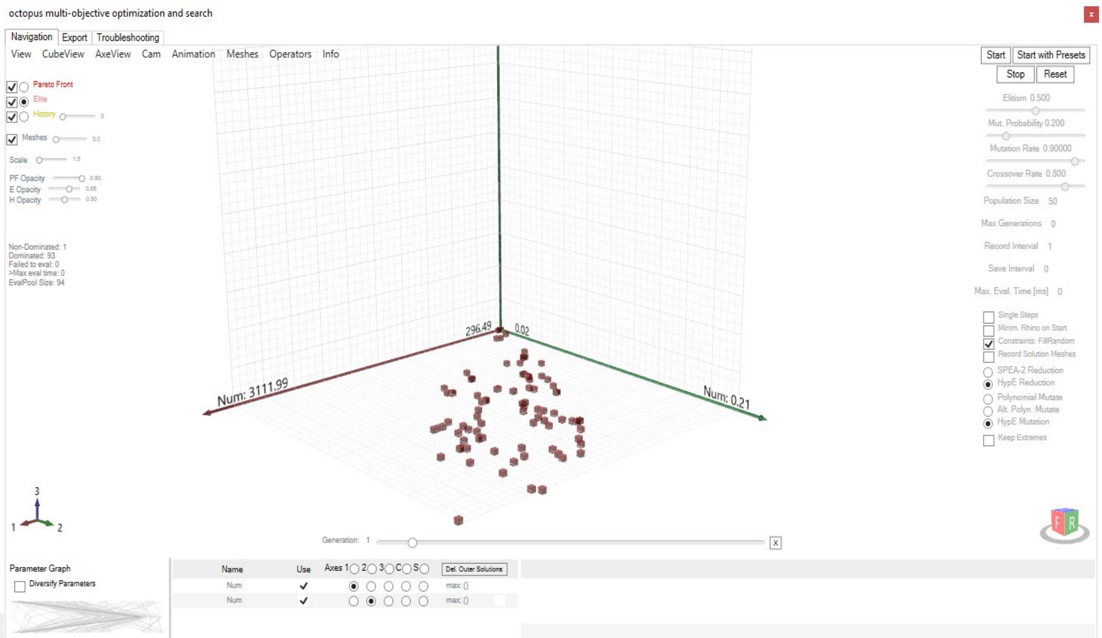

Figure 5.17. Results of 1st generation opimization Case 3. Red cubes represents populations.

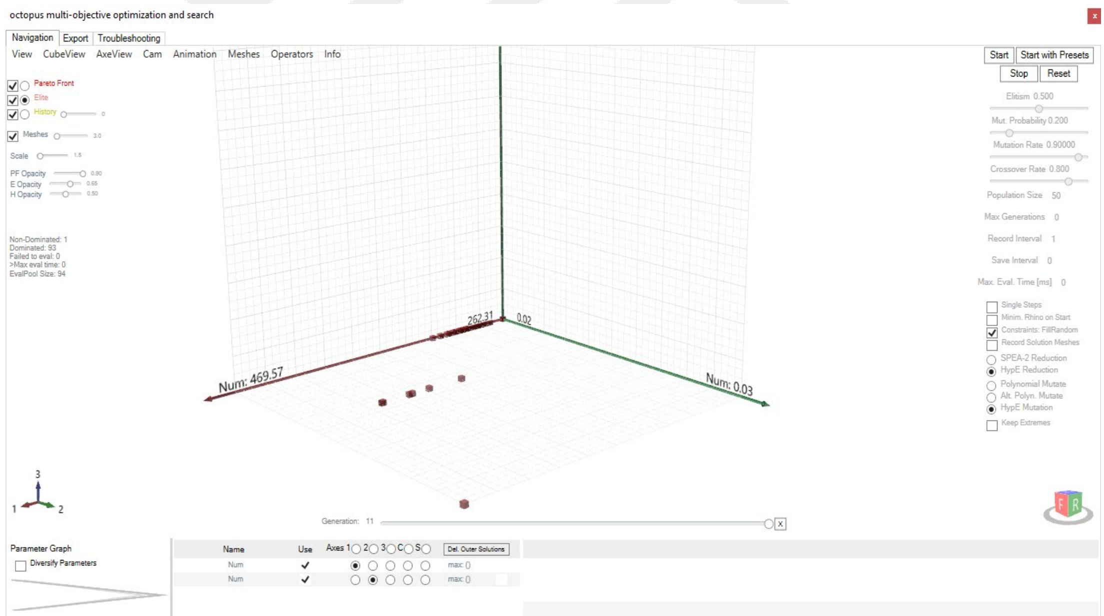

Figure 5.18. Results of 11st generation in case 15 . Red cubes represents populations.

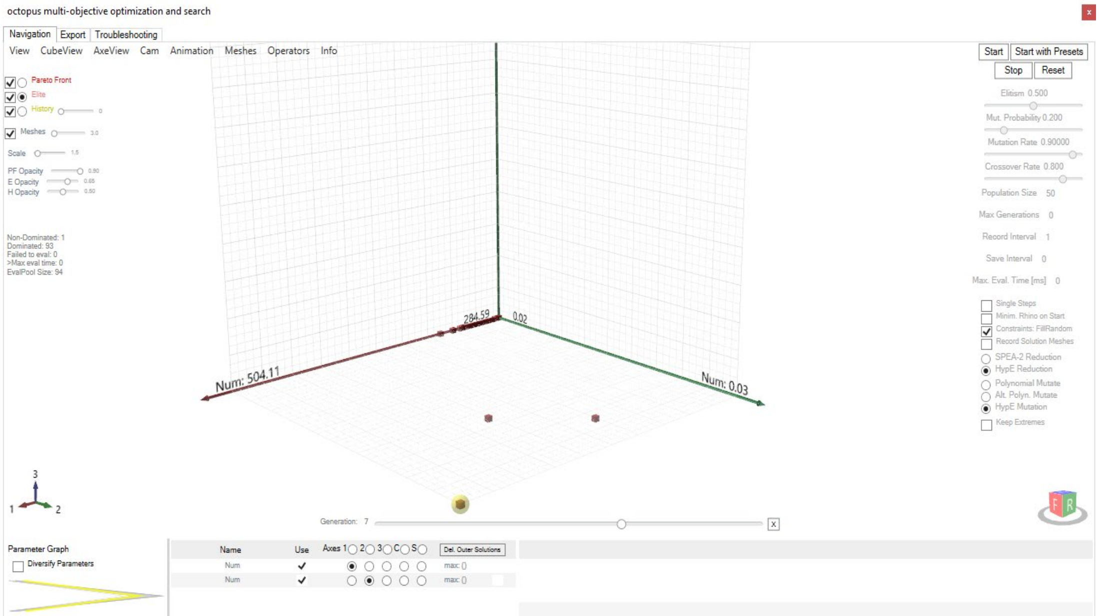

Figure 5.19. Results of 8th generation in opimization Case 3. Red cubes represents populations. Yellow marked cube represents the selected population.

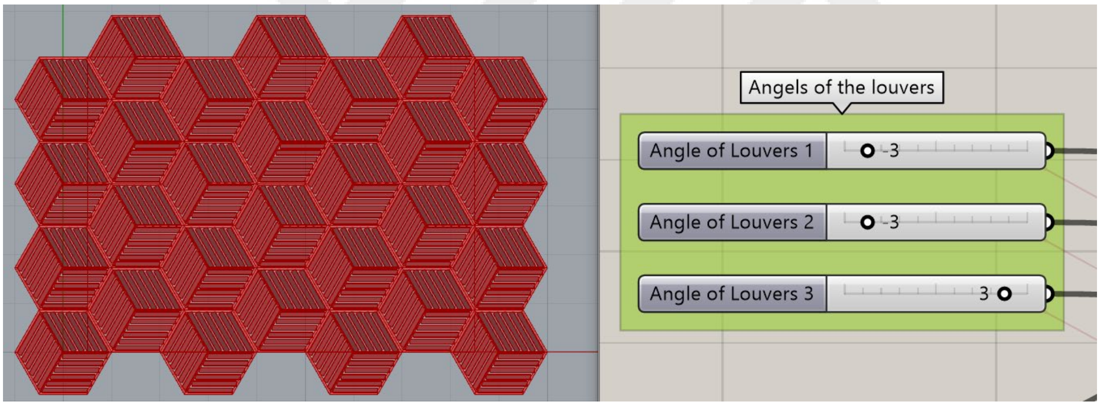

Figure 5.20. Kinetic façade design for the selected population settings in opimization Case 3.

5.3.6 Comparison Results of Simulation

In this part of the thesis, the illuminance simulation results (Table 5.11) and the solar radiation simulation results (Table. 5.12) of the kinetic façade are compared with the generated building model without shading elements and with stationary shading elements.

Table 5. 11. Illuminance level measurement of all cases.

Dates	Without Shading Elements	With Stationary Façade Elements	Optimized Kinetic Façade Elements
21st of June	4154 Lux	968 Lux	**519,53 lux**
21st of September	18838 Lux	1771 Lux	**521.9 lux**
21st of December	9602 Lux	2752 Lux	**504.10 lux**

Table 5. 12. Solar radiation level measurement of all cases.

Dates	Without Shading Elements	With Stationary Façade Elements	Optimized Kinetic Façade Elements
21st of June	0.305496 kWh/m2	0.058361 kWh/m2	**0.0209 kWh/m2**
21st of September	0.572309 kWh/m2	0.168677 kWh/m2	**0.0357 kWh/m2**
21st of December	0.836801 kWh/m2	0.234704 kWh/m2	**0.0326 kWh/m2**

CHAPTER 6
CONCLUSION

This thesis presents the investigations and design methodologies related to the development of a kinetic façade. It provides a new kinetic façade concept with an optimization method that keeps the interior illuminance at the desired level and greatly reduces the solar radiation level on the building façade. This complex optimization process has been developed using the computational optimization tools based on evolutionary algorithms.

The research carried out in this study can be grouped under four main headings: geometric design, mechanism design (determining the types of joints and related motions), parametric design (error checks of both design and movements of the kinetic façade), optimization (increasing the efficiency of the design using computational optimization). This chapter presents main achievements and highlights the future work needed.

6.1. Main Achievements

This research provides important achivements about the use and types of kinetic façades which are as follows:

- a systematic review and a classification on the kinetic façades have been presented.
- simulation programs have been used to understand the effects of environmental changes on the design, the data required for computational design were obtained and the necessary information was provided to create an energy efficient design.
- optimal integration of design rules has been constructed before a design since the optimization methods should be used to improve the performance and efficiency of a design.
- a parametric model has been created using Grasshopper and its add-ons to perform the required simulations, analyzes and optimizations.

6.2. Recommendations For Future Research

- Within this thesis, a regular tessellation method was used to generate the kinetic façade, but other tessellations should also be investigated to create more feasible solutions.
- As well as using different simulation programs at the beginning of the design process, a prototype should be built to understand and test the movements of the units.
- The materials of the façade elements, mechanical and electrical parts should be carefully selected in the design process of the kinetic façade since those choices directly affect efficiency of the system. Different materials can be used and tested for future research.
- In this thesis, certain software and plug-ins have been used. However, the results should be evaluated by comparing different simulation programs and optimization algorithms.
- As the third design rule of computational optimization, energy consumption of the building should be calculated and optimized.
- Compared to the static facades, the efficiency of the kinetic façades are greater. But the energy usage of the kinetic façade should be also considered for energy efficiency.

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