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MASTER THESIS

RESPONSIVE FAÇADE DESIGNS BASED ON TESSELLATION METHOD

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ABSTRACT

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MSc in Architecture
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Advances in building technology, materials science, engineering and robotics have increased the applications of kinetic structures in architecture. The decisions regarding to the building designs have also changed as a result of the interaction between architecture and these areas. The concept of movement has been integrated to the building design to create not only the structures that can transform their shapes but also the facades that can respond to the changing conditions and users' needs. The interest on responsive facades have increased in recent years since they provide many advantages and meet user requirements. Compared to the conventional facade systems, the responsive facades are multifunctional since they can reduce the buildings' heating and cooling loads, control daylight transmission, allow natural ventilation and provide optimal indoor environment for the occupants.

The aim of this study is to develop responsive façade systems based on tessellation method which can adapt to the changing environmental conditions and provide flexibility in shape control and simplicity in mechanism design. For this purpose, first, existing examples of the responsive facades have been systematically analyzed. Second, the tessellation method has been introduced and its types used in architecture have been presented. Then, responsive façades have been designed using four different tessellation patterns. Geometric and parametric design principles as well as movement capabilities of the proposed façade systems have been presented. Finally, the daylight analyses have been conducted to test the performance of the proposed façades. The results show that the proposed façade systems can be easily applied to any facade in desired location whereas the existing ones have limited applicability.

Keywords: façade systems, responsive façades, kinetic architecture, tessellation

ÖZ

TESSELASYON YÖNTEMİNE DAYALI TEPKİSEL CEPHE TASARIMLARI

Kızılörenli, Ecenur
Yüksek Lisans, Mimarlık
Danışman: Dr. Öğr. Üyesi Feray MADEN
Haziran 2021

Yapı teknolojisi, malzeme bilimi, mühendislik ve robotikteki gelişmeler, kinetik yapıların mimarideki uygulamalarını artırmıştır. Mimari ve bu alanların etkileşimi sonucunda bina tasarımlarına ilişkin kararlar da değişmiştir. Hareket kavramı, sadece biçimlerini değiştirebilen yapılar oluşturmak için değil, aynı zamanda değişen koşullara ve kullanıcı ihtiyaçlarına yanıt verebilen cepheler oluşturmak için bina tasarım sürecine entegre edilmiştir. Pek çok avantaj sağlamaları ve kullanıcı gereksinimlerini karşılamaları nedeniyle tepkisel cephelere olan ilgi son yıllarda artmıştır. Konvansiyonel cephe sistemleriyle karşılaştırıldığında tepkisel cepheler, binaların ısıtma ve soğutma yüklerini azaltabildikleri, gün ışığı iletimini kontrol edebildikleri, doğal havalandırmaya izin verdikleri ve kullanıcılar için optimum iç ortamı sağlayabildikleri için çok işlevlidir.

Bu çalışmanın amacı, değişen çevre koşullarına uyum sağlayabilen ve biçim kontrolünde esneklik ile mekanizma tasarımında basitlik sağlayan tesselasyon yöntemine dayalı tepkisel cephe sistemleri geliştirmektir. Bu amaçla öncelikle, tepkisel cephelerin mevcut örnekleri sistematik olarak analiz edilmiştir. İkinci olarak, tesselasyon yöntemi tanıtılmış ve mimaride kullanılan türleri sunulmuştur. Ardından, dört farklı tesselasyon deseni kullanılarak tepkisel cepheler tasarlanmıştır. Önerilen cephe sistemlerinin geometrik ve parametrik tasarım ilkeleri ile hareket kabiliyetleri sunulmuştur. Son olarak, önerilen cephelerin performanslarını test etmek için gün ışığı analizleri yapılmıştır. Sonuçlar, önerilen cephe sistemlerinin istenilen konumdaki herhangi bir cepheye kolayca uygulanabileceğini, mevcut olanların ise sınırlı uygulanabilirliğe sahip olduğunu göstermektedir.

Anahtar Kelimeler: cephe sistemleri, tepkisel cepheler, kinetik mimari, tesselasyon

To my beloved grandmother, who made me the person I am, and to my fiancée Oğuzcan, who brightens my life…

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Ecenur Kızılörenli

İzmir, 2021

TEXT OF OATH

I declare and honestly confirm that my study, titled "RESPONSIVE FAÇADE DESIGNS BASED ON TESSELLATION METHOD" 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.

Ecenur Kızılörenli

16.07.2021

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SYMBOLS AND ABBREVIATIONS

ABBREVIATIONS:

AKE	Acclimated Kinetic Envelopes
AVF	Active Ventilate Facades
BMS	Building Management System
CC	Classification Criteria
CCF	Closed Cavity Facades
IGP	Islamic Geometric Pattern
sDA	Spatial Daylight Autonomy
PV	Photovoltaic
UDI	Useful Daylight Illuminance

CHAPTER 1
INTRODUCTION

1.1. Motivation

Environmental condition is one of the significant factors affecting the architectural design. Due to the limited energy sources and the constantly changing environmental conditions, the conventional design approaches have started to be changed with the developing technology and the energy efficient building solutions have become more important in the design process. This process also includes the façade design since one of the most important building components that regulate energy use in buildings is the facade. Apart from being an interface between inside and outside of the building, the façade can have many functions such as reducing cooling load and solar heat gain, maximizing natural light and controlling ventilation. Therefore, it can be used to meet the required parameters in the building design process in terms of the energy use (Loonen et al., 2013). Indeed, new design solutions have been sought to respond to the climate conditions and the changing needs of users.

Having different morphologic and kinematic properties, many responsive facades have been developed in response to the constantly changing environmental conditions and occupants' needs. Even though different terms have been used in the existing literature to define these facades such as dynamic, kinetic, responsive, active, smart, interactive, transforming and flexible (Loonen et al., 2016; Aelenei et al., 2016; Kolarevic & Parlac, 2015; Addington & Schodek, 2012; Fortmeyer & Linn, 2014), the responsive facades mainly aim to provide optimum indoor conditions for the users (Herzog et al. 2004; Koyaz, 2017).

Since the responsive facades are multifunctional and can reduce carbon emissions and overall energy consumption of the buildings, the interest on these systems have been increased. Although different types of responsive façade systems have already been proposed, there is still a need to develop a new responsive façade system that provides not only form flexibility but also mechanical simplicity.

1.2. Problem Definition

The growing interest on the responsive façade systems have increased both the scientific researches and the applications on this area. However, when the literature on these systems is investigated, it is seen that the classifications are complex, insufficient and not systematic. In addition, these systems are limited to specific solutions and generally have complex mechanisms. Moreover, although the aim is to respond to the constantly changing environmental conditions, some of the existing systems may not meet this purpose since they are designed according to specific locations or orientations. A feasible solution has not been proposed yet which can be applied to the façade facing any direction in any location.

1.3. Aim of the Thesis

This thesis mainly aims to develop responsive façade systems using the tessellation method. Among the types of tessellation, regular triangular and hexagonal patterns have been selected which are duals of each other. Because the thesis also intends that the proposed façade systems should provide form flexibility and mechanism simplicity, a simple mechanism is designed which allows folding the façade panels in different directions based on the selected patterns. Moreover, one of the goals is to ensure that the proposed façade system can be applied to any facades located in any places. Since the proposed façade system has the ability to change its geometric configurations according to the changing environmental conditions and to create an optimum indoor environment by balancing the daylight entering the building, an efficient design solution is obtained.

1.4. Method of the Thesis

Within the scope of the study, a critical literature review and the simulation and modeling have been used as the methodological approaches. First, the existing examples of the responsive façades having different characteristics, movements and functions have been examined. During this examination, the strengths and weaknesses of the responsive facades have been revealed based on their features. The main purpose of this review is to consider the main achievements and the deficiencies in the existing design solutions while proposing the new system. A classification matrix has been proposed for the systematic review which includes many parameters such as type of system, type of movement, type of control system, control type of elements, façade function, response time and visibility of the system. Selected projects have been placed in the categories based on this matrix and a comprehensive classification table has been created.

In the second stage, the tessellation method and its examples used in architecture have been presented. Basic principles have been introduced through regular, semi-regular and demi-regular tessellation samples. It has been discussed in detail how the tessellation used in conventional buildings were applied to contemporary ones especially to the responsive facades with the developing technology.

In the third stage, a geometric design method has been introduced to create the responsive facades using the regular triangular and hexagonal tessellation. Then, a parametric model has been built to study the movement and morphological characteristics of the developed systems.

In the last stage, simulation tools have been used to analyze the daylight performance of the proposed façade systems. In this simulation process, the created models having four different patterns and configurations have been tested. In Figure 1.0.1, the overall design process is demonstrated.

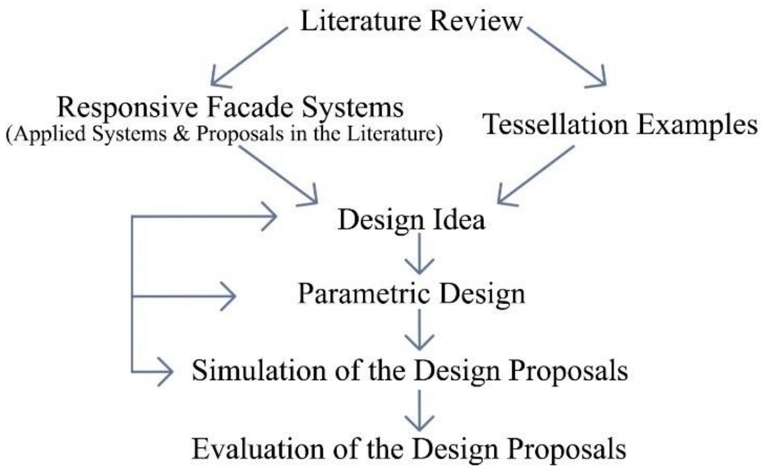


Figure 1.0.1. Design Stages

1.5. Outline of the Thesis

The thesis includes 6 chapters in total.

Chapter 1 explains the motivation of the study, the problem definition, the aim of the thesis and the methods used throughout the thesis.

In Chapter 2, a comprehensive review has been made on the responsive façade systems in which both the applied and the proposed examples have been examined. In addition to this review, a systematic classification for such façade systems have been introduced based on the proposed classification matrix.

Chapter 3 focuses on the tessellation method that has widely been used in architecture from past to present. In this part, first, different types of tessellation have been introduced and then the examples applied in architecture have been presented.

Chapter 4 describes the geometric and mechanism designs of the proposed modules. In this chapter, different tessellated patterns and the mechanism used to create the responsive façade systems have been introduced. The movement capabilities of the proposed systems have been discussed.

In Chapter 5, a set of daylight analyses has been carried out to test the performance of the proposed façade systems. Four different facade patterns have been created which are applied to the south facade of the generic model. The results have been discussed based on the data obtained from the analysis.

Chapter 6 presents the objectives achieved within this thesis and the suggestions for future studies.

CHAPTER 2
A CRITICAL REVIEW ON RESFONSIVE FACADE SYSTEMS

The life has been changing rapidly depending on constantly changing needs which affects also many areas including the architecture. As the activities of the modern society transforms, the concept of movement has become a part of architectural design. Since the existing buildings or building components cannot respond to the changing needs, the design process of the buildings has been started to be questioned. New solutions have been sought even in the façade design to adapt to the changes using the concept of movement.

For centuries, the building facade has been perceived as a static element which acts as a barrier or a separator between exterior and interior spaces. However, it has more than one function since it not only protects the building from external factors but also plays a crucial role in reducing the building's energy consumption and meeting the user needs (Schittich et al., 2012). Despite the aforementioned multi-functionality, the existing static façades neither adapt to the varying climatic conditions nor respond to the needs of the users. The main reason is due to the conventional way of façade design. In fact, it requires a new design approach that provides a real-time response to the changing circumstances. Responsive façade design may offer an efficient solution to the problem (Drozdowski, 2010).

The responsive facades can adapt to the changing conditions without compromising their overall structural integrity. They can respond to the environmental conditions in real time by changing their geometric configurations or positions whereas the static facades cannot adapt to those conditions due to their limited characteristics (Moloney, 2011; Selkowitz et al., 2003). The responsive facades ensure the maximum use of daylight and increase the use of natural ventilation. In addition, these systems can optimize the buildings' energy consumption and provide optimum indoor comfort for the users (Favoino et al., 2014). Considering that the buildings consume more energy than the transportation and industrial sectors (EIA, 2013), it can be said that the responsive façades have positive impacts on reducing the buildings' energy demands (Knaack & Klein, 2009).

Façade systems generally have shutter systems that rotate either vertically (Nielsen et al., 2011; Priatman et al., 2015; Grobman et al., 2017) or horizontally (Ricci et al., 2018) or modular systems balancing daylight performance, controlling heat gain, reducing glare and energy consumption. The facade systems consisting of modular patterns provide air flow, daylight and thermal comfort by means of expansion and rotational movement (Yi, Sharston and Barakat, 2018; Doumpioti, Greenberg & Karatzas, 2010). There are also façade systems that only makes expansion (Katamara and Amdersen, 2014) and the systems have rotational and sliding movements (Grobman and Yekutiel, 2013; Sheikh and Asghar, 2019; Pesenti, Masera and Fiorito, 2015; Mahmoud and Elghazi, 2016) (Table 2.1).

Table 2. 1. Selected Responsive Facade Designs

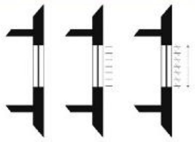
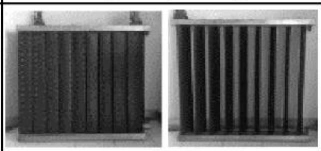
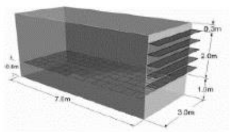
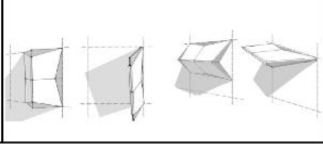
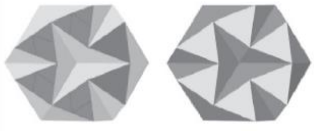
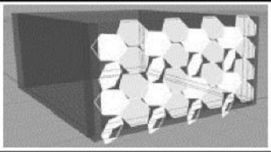
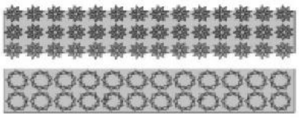
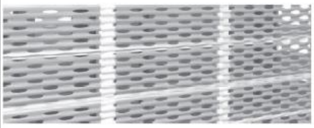
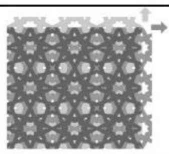
Facade system	System	Movement Type	Function
Automated Dynamic Solar Shading *(Nielsen, Svendsen and Lensen, 2011)*		Rotation	Daylight Performance, Thermal Comfort
Solar-powered Shading Device *(Priatman, Soegihardjo and Loekita, 2014)*		Rotation	Daylight Performance, Thermal Comfort, Generating Energy
Dynamic External Shading *(Grobman, Capeluto and Austern, 2016)*		Rotation	Daylight Performance
Kinetic Cladding Component (based on pantograph principle) *(Grobman and Yekutiel, 2013)*		Folding & Expanding	Air Flow, Daylight Performance
Adaptive Biomimetic Facade (based on foldable modules) *(Sheikh and Asghar, 2019)*		Folding & Sliding	Energy Consumption

Table 2.1. (cont.)

Origami Shading Device (based on the ron resch origami pattern) *(Pesenti, Masera and Fiorito, 2015)*		Folding, Expanding & Rotating	Daylight Performance, Thermal Comfort, Energy Consumption
Kinetic Facade (based on hexagonal modular pattern) *(Mahmoud and Elghazi, 2016)*		Rotating & Sliding	Daylight Performance, Thermal Comfort
Auxetic Structure *(Yi, Sharston and Barakat, 2018)*		Rotating & Expanding	Daylight Performance, Thermal Comfort
Embedded Intelligence (based on ellipsoid openings) *(Doumpioti, Greenberg and Karatzas, 2010)*		Rotating & Expanding	Air Flow, Daylight Performance, Thermal Comfort, Energy Consumption
Shape Variable Mashrabiya as a Shading System *(Katamara and Amdersen, 2014)*		Expanding	Daylight Performance, Thermal Comfort, Energy Consumption

When the existing literature on the responsive facades has been investigated, it has been seen that the façade systems are generally reviewed based on their geometries (Moloney, 2011), materials (Fox & Yeh, 1999; Kroner, 1997), actuation methods (Elkhayat, 2014), mechanism types and levels (Ochoa & Capeluto, 2008; Loonen et al., 2013; Wigginton & Harris, 2002) or interviews conducted with façade experts (Attia et al., 2020). Although most of the papers focus on developing new façade systems (Loonen et al., 2013; Van Dijk 2011; Zhang et al., 2015; Lai & Hokoi, 2015; Fortmayer & Linn, 2014; Schumacher, Schaeffer and Vogt 2010; Kuznik et al., 2011), there are also some studies dealing with simulation and optimization of the facades (Elghazi et al., 2015; Lee et al., 2016; Mahmoud & Elghazi, 2016; Im et al., 2019; Hosseini et al., 2019; Tabadkani et al., 2019). In addition, there are some papers written on the topic to classify the responsive facade systems. However, the existing classification systems are problematic due to the confusion used in the terminology. Even though there are many different types of responsive facades that have various motion properties, they have generally been categorized according to either the system types or the materials. Moreover, there is a lack of clear definition in types of element, movement and control system. Thus, it is not possible to review all the examples of the responsive facades under certain generic titles. This study aims to propose a new classification system in which the existing examples of the responsive facades can be systematically reviewed and analyzed based on the type of system, the type of movement, the type of control system, the control type of elements, the façade function, the response time and the visibility of the system.

2.1. Critical Review of Previous Classification Systems

In parallel with the growing interest in kinetic design and research, the implementations of the responsive facades have increased over the last couple of decades. In recent years, various responsive facades have been constructed in response to the changing environmental, functional or spatial conditions. Although there are many applied examples and studies on the responsive facades in the literature, most of the classifications are limited to control elements, sensor types and system configurations of such facades (Addington & Schodek, 2005; Ochoa & Capeluto, 2008; Ramzy & Fyed, 2011; Wang et al., 2012; Loonen et al., 2013; Loonen et al., 2015; Matin et al., 2017; Başarır & Altun, 2017; Waseef & El-Mowafy, 2017; Attia et al., 2020). No systematic review and classification have been conducted up to this date covering all the parameters such as system type, motion type, control types of system and elements, function, response time and visibility.

In the existing literature, some of the studies focus on the movement of the entire system (Addington & Schodek, 2005; Ramzy & Fyed, 2011; Wang et al., 2012) while other classifications are based on certain criteria such as sensor types, actuating elements or functions (Ochoa & Capeluto, 2008; Loonen et al., 2013; Matin et al., 2017; Başarır & Altun, 2017; Waseef & El-Mowafy, 2017; Attia et al., 2020). Figure 2.1 shows previous classification approaches of the responsive facades conducted between 2005 and 2020 (Table 2.2).

Table 2. 2. Previous Classifications

Addington and Schodek, 2005				
Classification Criteria (C.C)				
Property Changing	*e.g. Color-Changing, Phase-Changing*			
Energy Exchanging	*e.g. Light Emmiting Materials, Thermoelectric Materials*			
Ochoa and Capeluto, 2008				
C.C				
Class	*Category*	*Design Variable*	*Sub-Variable*	*Common Values*
1. Input Elements	*1.1 Sensors*	*No Sensors*	*Illuminance, Luminance*	*None*
		Light		*Internal, Zoned*
		Temperature		*Internal, External*
		Glare/Solar Radiation		*External*
	1.2 User Interfaces	*Switches/ thermostats*	*-*	*On/Off Variable Control*

Table 2.2. (cont.)

2. Control Processing Elements	2.1 Individual Controls	Light Controls	-	Always On	On / Off
				Dimmer	Stepped Lighting
		Shading Controls	Type Blinds	None	Always on, Fixed Slat Angle
				On if high radiation level, fixed slat angle	On if high glare level, fixed slat angle
		Thermal Comfort Controls	Temperature Level	Cooling on if temperature higher than limit	Heating on if temperature lower than limit
		Ventilation Controls	Night Ventilation	No night ventilation	Open air inlet/window on fixed hour
				Open air inlet/window if outside temperature OK	
		-	Active ventilation	No Fan	Fan Assists Night Ventilation (Variable Speed)
		Energy Controls	-	Grid-connected Only	
	2.2 Schedules	-	-	For Non-sensor Operations	
	2.3 Building Management Systems	-	-	Electronic Brain	
	2.4 Synchronized Controls	-	-	One Element Action Turns On/Off Another	
	2.5 Passive Building	-	-	Static Elements Fulfil All Functions	
	2.6 Users Only	-	-	Users Perform Operative Routines	
3. Actuating Elements	3.1 Daylighting Systems	Sun Shading Elements	No Sun Shading Elements	None	
			Horizontal	Opaque	
			External Blinds/Curtains	Opaque	
			Conventional Internal Blinds/Curtains	Opaque	
		Daylight Redirection Elements	No Elements	None	
			Lightshelves	Fixed, External	
			Automatic Reflective Blinds	External	
	3.2 Fenestration Systems	Glazing Elements	Conventional Glazing	Double glazing clear	
				Double glazing Low E	
	3.3 Ventilation Systems	Window Operator	Fixed	No Opening	
			Manual	Different Opening Combinations	
			Mechanical	Different Opening Combinations	
		Fan Ventilation Elements	-	No Fan	
				Electric Fan	
	3.4 Cooling and Heating Systems	Passive	Orientation and sun shade	North, south, east, west	
		Active	Conventional	HVAC systems	

Ramzy and Fyed, 2011

C.C

Kineticism	Control Technique	System Configuration	Control Limit	Cost	Kinetic System
Limited	Direct or Responsive	Embedded	Minor	Small	Skin Units Systems
Medium	Internal or Direct	Embedded	Medium	Medium	Retractable Elements
Major	Direct or Responsive	Dynamic	Significant	Big	Revolving Buildings
Variable	Responsive Indirect	Dynamic of Embedded	Variable	Huge	Biomechanical Systems

Wang, Beltran and Kim, 2012

C.C

Climatic Sources	Solar Responsive	Solar Heat
		Solar Light and Heat
		Solar Electricity
	Air-flow Responsive	Natural Ventilation
		Wind Electricity

Loonen, Trcka, Costola and Hensen, 2013

C.C

Relevant Physics	Thermal	Optical	Air Flow	Electrical	
Time Scales	Seconds	Minutes	Hours	Diurnal	Seasons
Scale of Adaptation	Macro		Micro		
Control Type	Extrinsic		Intrinsic		
Typology	Built Examples	Subsystems and Components	Full-scale Prototypes	Reduces-scale Prototypes	

Table 2.2. (cont.)

Loonen, Martinez, Favoino, Brzezicki, Menezo, Ferla, Aelenei, 2015

C.C

Goal /Purpose	Responsive Function	Operation	Technologies (materials& systems)	Response Time	Spatial Scale	Visibility	Degree of Adaptability
Thermal Comfort	Prevent, Reject, Admit or Modulate solar gains and conductive, convective and long-wave radiant heat flux	Intrinsic	Shading	Seconds	Building Material	No	On / Off
Indoor Air Quality	Controlled Porosity for exchange and filtering of outside air		Insulation	Minutes			
			Swithcable Glazing	Hours	Facade Element		
Visual Performance	Prevent, Reject, Admit of Redirect visible light		PCM	Day-Night		Low	
			Solar Tubes		Wall		
Acoustic Quality	Prevent, Reject, Admit of Redirect sound pressure	Extrinsic	BIPV and Solar Thermal	Seasons	Fenestration		Gradual
Energy Generation	Collect and convert wind energy and sun light into electricity and thermal energy		Shape Memory Alloys	Years	Roof	High	
			Facade Openings				
Personal Control	User Interaction and Adaptation to Individual Needs		Kinetic Systems	Decades	Whole Building		
			Radiant Glazing				

Matin, Eydgahi and Shyu, 2017

C.C	Active Technologies			Passive Technologies	
	Mechanical Technology	Electro Mechanical Technology	Information Technology	Material Based Technology	Passive Technology
Sensing Phase	User's Requrement	Temperature Sensors	Network of Sensors	Material-based Sensing/ Controlling/ Actuating	Autonomus Man-made Structures
		Moisture Sensors			
		Light Sensors			
	User's Performance	Touch Sensors			No Sensors
		UV Sensors			
Control Phase	Hand Operated System	Central-Based Control System	Network of Microcontrollers	Form Changing Materials	No Controlling Technology
		Building Management System		Thermo-bimetal Materials	
Actuating Phase	Pulleys System	Motor-based Actuators	Material-based Architecture	Phase Changing Materials	Natural Phenomena Moisture/ Wind/ Sunlight
	Cables System	Electrical-based Actuators	Motor-based Architecture	Electro Active Polymer	
	Cogs System	Pneumatic Actuators	Hydraulic Actuators	Shape Memory Ally	
	Gears System	Hydraulic Actuators	Pneumatic Actuators	Shape Memory Polymer	

Başarır and Altun, 2017

C.C

Elements Of Adaptation	System Complexity	Respond to Adaptation Agent	Limit of Motion	Degree of Performance Alteration	Size of Spatial Adaptation
Facade	Level 1	Static	Limited	Minor	nm
Component	Level 2		Partial	Medium	mm
Element	Level 3	Dynamic	Inclusive	Significant	cm
Material	Level 4		Variable	Variable	m

Type of Control/ Operation	Type of Actuator	System Response Time	Level of Architectural Visibility (Rush Classification)	Effect of Adaptation
Internal Control	Motor-based	Seconds	Not visible, no change	Prevent, Reject, Admit or Modulate (Store, Distribute) solar gains
Direct Control	Hydraulic	Minutes	Visible, no change	Prevent, Reject, Admit or Modulate (Store, Distribute) conductive, convective and long-wave radiant heat flux
Indirect Control	Pneumatic	Hours	Visible surface Change	Controlled porosity for exchange and filtering of outside air
				Prevent, Reject, Admit or Redirect visible
Responsive in-direct Control	Material-based	Days	Visible with size or shape change	Prevent, Reject, Admit or Redirect sound pressure
				Collect and Convert wind energy
Ubiquitous Responsive in-direct Control	Chemical	Seasons		Prevent, Admit or Modulate vision
			Visible with location or orientation change	Change color
Heuristic, Responsive in-direct Control	Magnetic	Several Years		Change texture
				Change shape

Table 2.2. (cont.)

Agent Of Adaptation				System Degree of Adaptability	Structural System for Dynamic Adaptation	Type of Movement	
Inhabitants	Environment		Objects	On/Off	Spatial Bar Structures consisting of hinged bars	Folding	Scaling
	Exterior Environment	Interior Environment					
Individual Inhabitants	Solar Radiation	Indoor Temperature	Objects Passing Through		Foldable Plate Structures consisting of hinged plates	Sliding	Rolling
	Outdoor Temperature	Humidity		Gradual	Scrut-Cable Structures	Expanding	Twist
Groups of individuals	Humidity	Amount of Light				Shrinking	Rotation
	Wind	Air Exchange Rate	Objects Passing By	Hybrid	Membrane Structures		Push-out
Organisations	Precipitation	Air Velocity				Transforming in Both Size and Shape	Push-out
	Noise	Sound Level					

Waseef and El-Mowafy, 2017

C.C

Accordig to Facade Configuration	Geometric Transformation	
	Pattern Shape	
	Facade Form	
	Facade Material	
Accordig to Facade Function	Energy Generation	
	Environmental Control	Solar Thermal Control
		Daylight Control
		Ventilation Controls
		Noise Control
		Humidity Control
	Aesthetic Function	

Attia, Lioure and Declaude, 2020

C.C

Application / Purpose		Control	Building Type	Technology / Materials
Dynamic shadings				
Shutter or equivalent	Obstruction of sunlight, thermal insulation, security, summer comfort, cooling savings, security, heat retention	Manual, motorized or automated (with different levels of automation)	Residential and nonresidential (schools, hospital, offices, public	Often large wood or PVC, aluminum, integrated blinds in the ceiled glazing
Roller blinds or equivalent	Obstruction of sunlight, thermal insulation, summer comfort, privacy, glare protection, cooling savings	–	–	Cellular shades and fabrics (different types and properties)
Venetian blinds or equivalent	See above	–	–	Tilting slats and glare control, aluminum and ceiled glazing
CCF: natural ventilated	Sunlight adjustment, daylight control, summer comfort, glare protection, privacy, cooling savings	Electric (motorized) or magnetic	Office buildings	Venetian blinds: aluminum / Electrostatic: thin film
Chromogenic glazing				
Electrochromic glazing	Solar gain and daylight control, reduce cooling needs, summer comfort, glare reduction	On demand (active), automated (different levels of automation)	Residential and nonresidential (schools, hospital, offices, public	Suspended particles, organic and nonorganic coating, colloidal nanocrystal
Liquid crystal glazing	Create privacy spaces, projection screen, and control (solar heat, visible light)	–	–	–
Thermochromic glazing	Solar gain and daylight control, reduce cooling needs, summer comfort, glare reduction	Environmentally activated (passive)	–	Thin film or interlayer which changes its crystal structure
Solar active facades				
Double skin facade	Solar gain and daylight control, reduce cooling needs, summer and winter comfort, glare reduction	Active control, environmentally activated, automated	Residential and nonresidential buildings	Two skins with a ventilated cavity (natural or mechanical)
Green facade and roof	See above	Environmentally activated (passive)	–	Different foliage layers and functional substrates for plant growing
Phase change materials	Solar gain control, reduce cooling needs, winter and summer comfort, heat and solar energy store	Environmentally activated (passive)	–	Salt or paraffin materials, micro or macro encapsulated into building components
Active ventilative facades				
CCF: active ventilated	See above	On demand (active), automated (different levels of automation)	Office buildings	–

Addington and Schodek (2005) have proposed a classification for smart materials since the existing classifications are limited to solely properties of the materials. Based on the functions, their classification system has been divided into two regarding to the materials. The first type has been identified as property change materials that allow one or more changes in response to a direct stimulus. On the other hand, the second type has been determined as energy exchange materials that can convert the energy from one form to another. This classification has deficiencies, because it covers a limited number of systems and excludes the systems that have mechanical movements.

Ochoa and Capeluto (2008) have developed another system by classifying the responsive facades into three categories which can be shown as a pioneering study since it is more comprehensive than the previous one. These three categories are input elements, control processing elements and actuating elements. In the first category, it has been examined whether the system movement is provided by sensors or users. Then, the system control processing elements have been evaluated based on six different sub-categories that are individual controls, schedules, building management systems, synchronized controls, passive building and users only. Finally, four different sub-categories such as daylighting systems, fenestration systems, ventilation systems, and cooling and heating systems have been created for actuating the elements according to the function that the system serves. Although the control systems have been presented in detail in this study, a limited review has been conducted.

Another classification system has been created based on a new terminology called *kineticism* that does not exist in any other classification systems (Ramzy & Fayed, 2011). This classification is completely different than the previous ones since the categories such as system configuration, control limit and cost have not been included in other classifications. Defined as the first category, the *kineticism* specifies the limit of the movement whether it is a local or inclusive movement. The second category of the classification determines how the movement starts or is activated. It has been specified as internal control, direct control, indirect control, responsive indirect control, ubiquitous responsive indirect control and heuristic responsive indirect control which has also been used by Kinetic Design Group researchers at MIT (Fox & Yeh, 1999). System configuration, which is the third category of the classification, has been divided into three as deployable kinetic structure, dynamic kinetic structure and embedded kinetic structures as in the study of Fox and Yeh (1999). Control limit and cost are the other categories in the classification system. Unlike previous studies, type of kinetic system has been added to the study as the last category which has four sub-titles. The first has been defined as skin unit systems to cover the limited motion of the elements of the coating system in the structures. This sub-category includes flare skin having manual or automatic movable louvers that move according to the sun during the day to protect the users from the glare. The second sub-category of the kinetic system type has been defined as retractable elements that allow folding or expanding movement. The third sub-category has been named as the revolving buildings that are powered by renewable energy and contain structures providing high performance with their movements. The last sub-category is the biomechanical systems that do not have many examples. These systems are embedded systems that move with sensor systems or other triggers. Although the category of cost has been included for the first time in the façade classifications, this study has also deficiencies in terms of explaining and classifying the movements of the systems.

On the other hand, Wang et al. (2012) have focused on classifying responsive systems in hot climatic zones, and none of the categories in the previous classification systems have been considered. Unlike other studies, this classification is solely limited to climatic resources. It has been stated that kinetic elements on the façade include the systems from automated blinds to smart glazing. The researchers have aimed to divide the responsive systems into two categories as solar-responsive systems and air-flow-responsive systems (Wang et al., 2012). The solar-responsive acclimated kinetic envelopes have been divided into three as solar heat, solar heat and light, and solar electricity. The solar heat includes the systems aiming at maximum heat gain in winter and minimum heat gain in summer. The solar light and heat include the systems that are related to the daylight to control the illuminance level and the user comfort. The solar electricity contains the systems that consist of sliding or rotating panels used to increase energy gain. Air-flow-responsive or acclimated kinetic envelopes have two sub-categories as natural ventilation and wind electricity. The natural ventilation includes motorized acclimated kinetic envelopes (AKE) that can absorb the outside air with appropriate values in parameters such as temperature, humidity and dust. The wind electricity covers integrated wind turbine systems such as roof-top wind turbines rather than stand-alone wind systems. However, these wind turbine systems are problematic due to the noise and aesthetic reasons.

In the first study that was conducted by Loonen et al. (2013), five different categories have been determined which are listed as time scales, relevant physics, scale of adaptation, control type and typology. They have applied proposed classification system to eleven built structures. Then, Loonen et al. (2015) have classified the responsive facade systems according to the function for the first time in the literature. This classification contains the parameters such as thermal comfort, indoor air quality, optimization of visual performance, acoustic quality, energy generation and personal control. The intended use of this system is directly associated with responsive functions. Loonen et al. (2015) have used the terms intrinsic and extrinsic to describe the operation types of the systems instead of using passive and active terminologies. Technologies (materials and systems), another category in their classification, do not contain comprehensive data. Rather, it has been intended to provide general information. It has been stated that the buildings with responsive facades can include one or more materials or systems. Unlike previous studies, response time of the system has been examined ranging from seconds to years. Spatial scale is another category which indicates the size of the system on the façade covering the range from an element of the structure to the whole system. Other evaluation criterion is the visibility that includes not only the outer appearance of the building but also the inner visibility. In the study, the visibility ratio has been determined as no, low and high. The last category is the degree of adaptability that shows the level of adaptation capability of the building envelope based on the changing conditions (Loonen et al., 2015). When two studies have been compared, it can be said that a spatial scale has been used for the first time in the second study. However, the lack of emphasis on system movements and range scale in the categories can be shown as negative aspects of the study.

In another classification, the responsive façade systems have been examined in chronological order (Matin et al., 2017). In this study, the systems have been classified as sensing phase, control phase and actuating phase which have been reviewed whether they have active or passive technologies. Rather than simply defining the operation system as intrinsic or extrinsic as used in Loonen et al. (2015), they have specified five different groups for active and passive systems: mechanical technology, electromechanical technology, information technology, material-based technology and passive technology. However, it is difficult to understand the movements and other features of the systems since the classification has been presented solely in chronological order.

Another study has been conducted by Başarır and Altun (2017) to classify the responsive façade systems according to the changing events. In this study, the researchers have combined the categories and terminologies used in previous studies. They have determined fifteen variables: elements of adaptation, system complexity, respond to adaptation agent, limit of motion, degree of performance alteration, size of spatial adaptation, type of control, type of actuator, system response time, level of architectural visibility, effect of adaptation, agent of adaptation, system degree of adaptability, structural system for dynamic adaptation and type of movement. Although they have compiled each category in previous classification systems, new categories have also been added to the proposed system which cause misclassification. In addition, the general kinetic system classification causes confusion. Another obvious confusion is that the movement types have not been clearly defined in this study.

Recently, Waseef and El-Mowafy (2017) have proposed another method to classify the responsive façade systems. The classification criteria are façade configuration and façade function. The façade configuration has been reviewed under four parameters such as geometric transformation, pattern shape, facade form and façade material while the façade function has been categorized as energy generation, environmental control and aesthetic function. Unlike previous studies, this study has focused on the geometry and movement of the systems. However, compared to the previous studies, it can be said that a limited examination has been made in this study due to the restriction in the classification system.

The latest research has been presented based on the interviews conducted with façade experts to reveal main concepts and technological trends of the responsive facades (Attia et al., 2020). Compared to the previous studies focusing on system types, actuators, sensors or materials, it can be said that the researchers have a different approach than the others since they have created the proposed categorization system by interviewing with the experts in the field. Based on these interviews, they have determined four main categories such as dynamic shadings, chromogenic glazing, solar active facades and active ventilate facades (AVFs). There are 12 system types under those four categories which are roller blinds, shutters, venetian blinds, closed cavity facades (CCF), electrochromic glazing, thermochromic glazing, phase change materials, building integrated photovoltaic (PV) double skin facade, liquid crystal glazing, green facade and roof, automated operable windows and actively ventilated CCF. The dynamic shadings are based on moving parts that can be actuated by a motor or controlled manually. These are shutters, venetian blinds, roller blinds and naturally activated CCF which serve for the purposes of thermal insulation, daylight control and thermal comfort. The chromogenic glazing includes integrated technologies on glazing, not the systems that are internally or externally integrated into the structure. This category includes three sub-categories such as electrochromic glazing, thermochromic glazing and liquid crystal glazing. These elements can change their transparency according to the sensors. The third category determined by the authors has been named as solar active facades. There are four technologies under this category which are building integrated PV, green facades and roofs, double skin facades and phase change materials. While the first three main categories in this study are directly related to the daylight, the last category of the classification (AVFs) includes two technologies such as automated operable windows and actively ventilated CCF. Although both are based on ventilation, they are different. The CCFs aim to direct the air inside the cavity while the automated operable windows are related to the entry of the air. Compared to the previous classification systems, this classification is quite complex since it covers many other system types.

When all the existing studies on the responsive facades are evaluated, it can be said that most of the classifications are limited to certain focus points, and some of them are very general and superficial. There are also some studies having complex classification systems. In some cases, the examples cannot be reviewed under the defined categories, because the type of movement is different than the type of system. In fact, the main problem is that the criteria included in those classifications are ambiguous and complex to create an accurate classification. Thus, it is not possible to systematically analyze and classify all the applied examples according to those classification proposals. It requires a simple and clear classification matrix to define all parameters.

2.2. Proposed Classification System

To classify and analyze the responsive facades systematically, a new classification matrix has been proposed (Figure 2.1). It has been created based on the movement of the responsive façade systems since the movement is the main parameter which can be used to identify different façade systems. Five movements have been defined in the classification matrix such as rotation, deforming, folding, sliding and hybrid. In addition, there are also other parameters in the matrix which are the type of system (active or passive), the type of control system (hand-operated control or central control), the control type of elements (individually or total movement), the function of the façade (daylight control, thermal control or air flow), the response time of the elements in the system (seconds, minutes or hours) and the visibility of the façade system (low, medium or high).

Type of System		Type of Movement						Type of Control System		Control Type of Elements		Function of the Facade			Response Time			Visibility		
		Rotation																		
Passive	*Active*	*Full Rotation*	*Oscillatory Motion*	*Deforming*	*Folding*	*Sliding*	*Hybrid*	*Hand-Operated Control*	*Central Control*	*Individually*	*Total Movement*	*Daylight Control*	*Thermal Control*	*Air Flow*	*Seconds*	*Minutes*	*Hours*	*Low*	*Medium*	*High*

Figure 2.1. Proposed Classification Matrix

- *Type of System:* The responsive facades have been reviewed under two main categories as active and passive systems. The active system has a mechanical system that controls the movement of the façade elements according to environmental data or user needs. On the other hand, the passive system can change its configuration without the need of actuators, sensors or control systems. Rather, it uses the power generated by wind, sun or temperature differences to produce the required movement.

- *Type of Movement:* The type of movement defines the motion of the elements in the responsive façade systems (Figure 2.2). The movement types have been examined under five main headings: rotation, deforming, folding, sliding and hybrid. Rotation defines the movement of the element that rotates around an axis. The elements can make either a full rotation around the defined axis or an oscillatory motion that allows moving back and forth along an arc. Deforming refers to the shape deformation of the element under applied forces. Folding indicates the folding movement of the system that consists of rigid panels. The elements moving back and forth along a certain axis is defined under the sliding category. Finally, the systems that have more than one movement have been specified as hybrid.

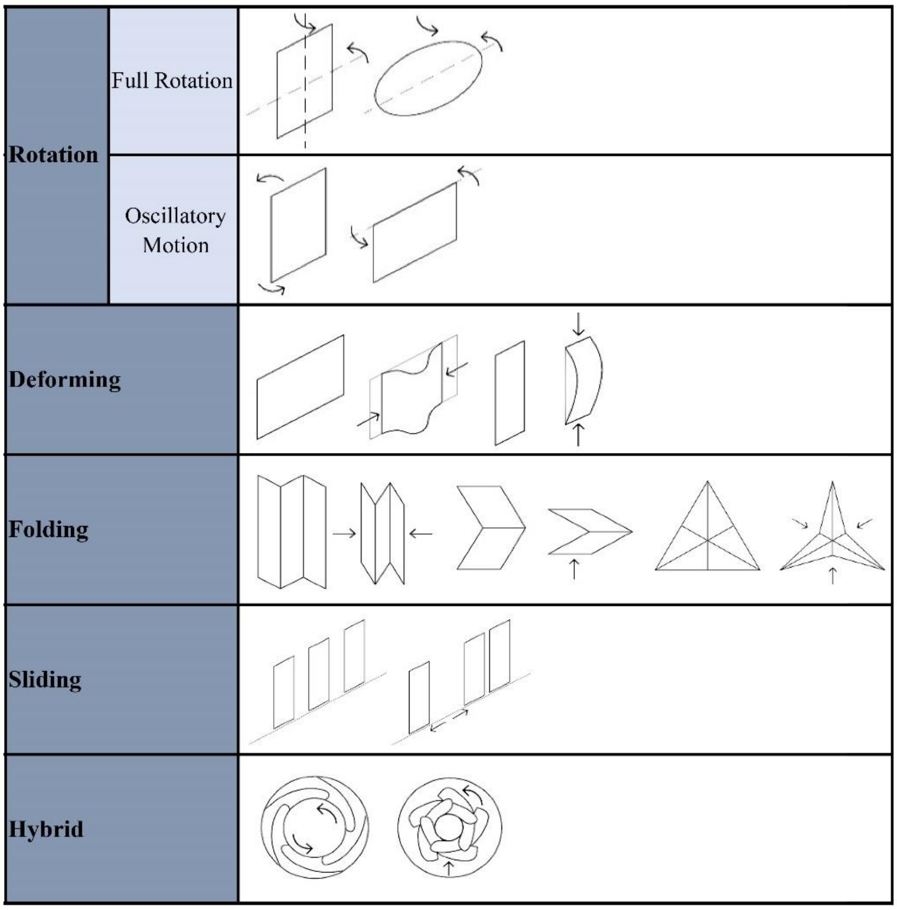


Figure 2.2. Movement Types

- *Type of Control System:* The factor that provides the movement of the system has been examined under this category. The responsive facades have been classified into two systems as hand-operated control or central control.
- *Control Type of Elements:* Unlike the previous category, the focus is on the control of the elements to investigate whether the elements in the system can move individually or not. If the elements have relative motions depending on each other, then a total movement is obtained since all the elements move together.
- *Function of the Facade:* In this category, the functional purpose of the façade system has been defined such as daylight control, thermal control and air flow.
- *Response Time:* The response time refers to the time required for the elements in the responsive façade system to perform their actions. This time scale ranges from seconds to hours. Although many responsive façade systems generally

complete their movements in minutes, there are also some systems that can move in seconds in response to the wind or sun movements.

- *Visibility:* The façade and its elements affect not only the outer appearance of the building but also the interior. Some façade systems do not change the visibility from interior on the condition that the moving elements are either transparent or not blocking the view. However, some of the façade systems prevent visibility to a large extent. In this category, the responsive facades have been designated as low, medium and high visibility. If the structural elements carrying the façade panels block the view partially when the system is folded or opened, the visibility is considered as medium.

Based on the aforementioned parameters in the comparison matrix, Table 2.3 has been created to examine the existing applied examples of the responsive façade systems. In total, twenty-three responsive facades have been reviewed in which sixteen of them are active while the remaining four are passive.

Table 2. 3. Proposed Classification System

Project	Project Location/ Year	Image of The Facade	Type of System		Type of Movement						Type of Control System		Control Type of Elements		Function of the Facade			Response Time			Visibility		
					Rotation																		
			Passive	Active	Full Rotation	Oscillatory Motion	Deforming	Folding	Sliding	Hybrid	Hand-Operated Control	Central Control	Individually	Total Movement	Daylight Control	Thermal Control	Air Flow	Seconds	Minutes	Hours	Low	Medium	High
Kiefer Technic Showroom	AT / 2007	 Source: Matin, Eydgahi, and Shyu 2017		x				x				x	x		x	x			x				x
Al-Bahr Towers	UAE / 2012	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x				x				x	x		x	x			x			x	
OPEN Café-Restaurant	NLD / 2008	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x				x				x	x				x		x				x
Mokyeonri Wood Culture Museum	KR / 2017	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x				x				x		x	x				x		x		
ThyssenKrupp Headquarters	DE / 2010	 Source: Spiegelhalter 2017		x		x						x	x		x	x		x				x	

Table 2.3. (cont.)

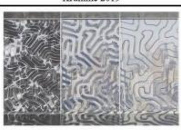
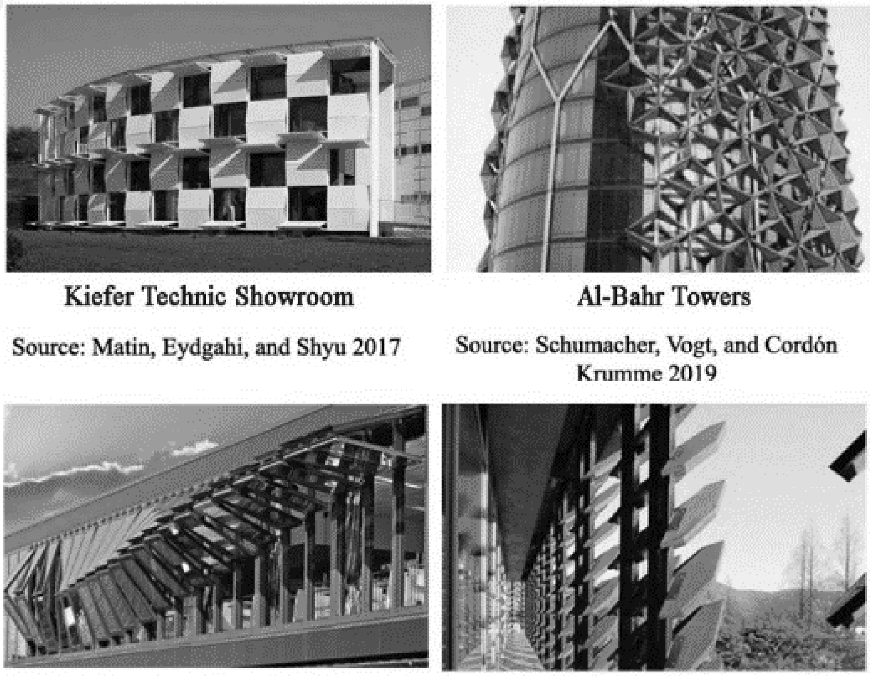
Sebrae Headquarters	BR / 2010	 Source: Singhal 2011		x		x						x	x		x	x		x				x	
Mpavilion 2014	AUS / 2014	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x		x						x	x				x		x				x
Ballet Mechanique	CHE / 2017	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x		x						x	x		x	x			x				x
Council House 2 Building	AU / 2006	 Source: Matin, Eydgahi, and Shyu 2017		x	x							x	x		x	x			x		x		
Chicken Point Cabin	USA / 2002	 Source: Matin, Eydgahi, and Shyu 2017		x	x						x			x			x	x					x
Dancing Pavilion	BR / 2016	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x	x							x	x		-	-	-	x			x		
Livraria da Vila	BR / 2007	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x	x						x		x				x		x				x
California Gallery	USA / 2012	 Source: Matin, Eydgahi, and Shyu 2017		x					x		x			x			x	x					x
Duke of York Restaurant	UK / 2019	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x					x			x	x				x		x				x
One Ocean - Thematic Pavilion	KR / 2012	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x			x					x	x			x	x		x		x		
Institute Du Monde Arabe	FR / 1989	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x						x		x	x		x	x			x		x		
Homeostatic Façade System	USA / 2013	 Source: Matin, Eydgahi, and Shyu 2017	x				x					x		x	x	x		x				x	

Table 2.3. (cont.)

Pittsburgh Children's Museum	USA / 2004	 Source: Fortmeyer and Linn 2014	x			x					-	-	-	-	-	-	-	x				x	
Wind Arbor	SGP / 2010	 Source: Matin, Eydgahi, and Shyu 2017	x			x					-	-	x		-	-	-	x				x	
Breath Box Waterfront Pavilion	FR / 2014	 Source: Walker 2015	x			x					-	-	x		-	-	-	x			x		
Windswept	USA / 2011	 Source: Schumacher, Vogt, and Cordón Krumme 2019	x		x						-	-	x	-	-	-	-	x			-	-	-
Latvia Pavilion Expo 2010	CN / 2010	 Source: Jordona 2016	x			x					-	-	x	-	-	-	-	x				x	
Wave Wall	USA / 2006	 Source: Schumacher, Vogt, and Cordón Krumme 2019	x		x						-	-	x	-	-	-	-	x			x		



Kiefer Technic Showroom

Source: Matin, Eydgahi, and Shyu 2017

Al-Bahr Towers

Source: Schumacher, Vogt, and Cordón Krumme 2019

OPEN Cafe-Restaurant

Source: Schumacher, Vogt, and Cordón Krumme 2019

Mokyeonri Wood Culture Museum

Source: Schumacher, Vogt, and Cordón Krumme 2019

Figure 2.3. Examples of Folding Category

Among those eighteen active systems, the facade systems that have folding movement are the *Kiefer Technic Showroom*, the *Al-Bahr Towers*, the *Open-Café Restaurant* and the *Mokyeonri Wood Culture Museum* (Figure 2.3). Having 1049 hexagonal panels and 4 linear actuators, the responsive façades of the *Al-Bahr Towers* are controlled by a central building management system (BMS) (Cilento, 2012). The system operates in real time and mainly provides daylight and thermal control. The *Kiefer Technic Showroom* consists of 112 folding panels that are controlled by 56 engines (Ahmad and Alibaba 2019). The façade system serves for the daylight and thermal control (Ahmad & Alibaba, 2019). On the other hand, the *Open-Café Restaurant* has a glazed façade on which each element can move independently by means of a motor. It allows cross-ventilation when the windows are folded. The panels on the facade of the *Mokyeonri Wood Culture Museum* consist of hexagonal leaves connected in pairs on a black metal profile. An engine controls the movement of the leaves that perform a folding movement in minutes. The main function of the façade is the daylight control. While the visibility is high in the *Kiefer Technic Showroom* and the *Open-Café Restaurant*, it is at medium level in the *Al-Bahr Towers* since the frames of the hexagonal modules somehow block the view even in fully opened configuration. It is at low level in the *Mokyeonri Wood Culture Museum*.

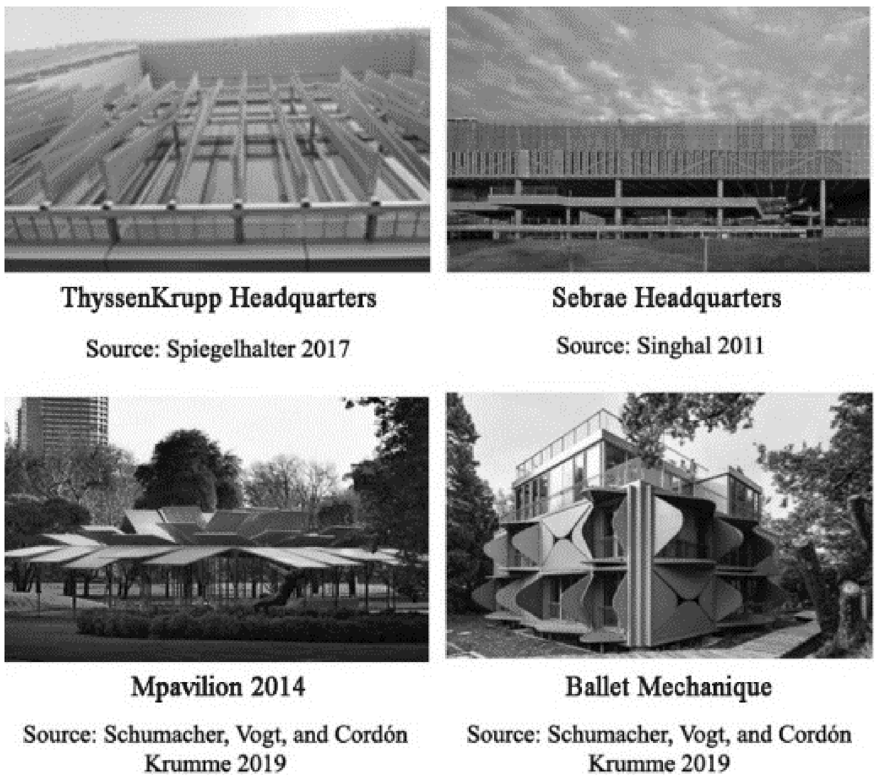


Figure 2.4. Examples of Oscillatory Motion Category

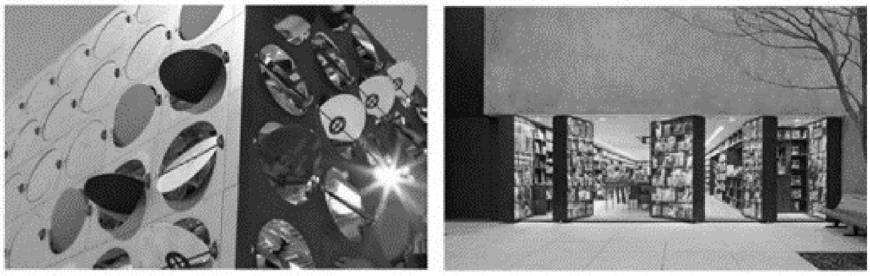
There are eight façade systems examined in the rotational movement category (Figure 2.4). Four of them are active systems while the rest are passive. Composed of stainless-steel feather-like elements, the façade of the *Q1 ThyssenKrupp Headquarters* changes its shape according to movement of the sun throughout the day (Loonen et al., 2013). Completing its movement in seconds, this façade system not only provides a regulation of the light entering the interior but also prevents unwanted solar heat gains. Likewise, the façade elements of the *Sebrae Headquarters* are made of metal panels that can be opened independently. Each panel makes a rotational movement around the vertical axis placed on the long edge of the elements. The main purpose of using these elements are to protect the structure from overheating and to reduce cooling load of the building. In both examples, the visibility is at the medium level. On the other hand, there are also other examples in which the visibility level is high. In the *Mpavilion 2014*, the metal panel elements on the façade move independently which can be opened or closed to create different configurations by means of an electric actuator. The panels can be opened in few minutes up to 90 degrees with the help of the hinge located on the short sides. In the *Ballet Mechanique*, the façade elements are multifunctional in such a way that they create new spaces for the users when unfolded and serve as shading roof elements. The façade has been formed by rounded triangular-shaped panels that are placed horizontally and vertically. While the vertical panels can provide privacy, the horizontal panels not only serve for shading purposes but also become balconies. Controlled by hydraulic cylinders, the façade elements provide thermal and daylight controls. The visibility of the façades of the *Mpavilion 2014* and the *Ballet Mechanique* are high since there is no structural element blocking the view.

Council House 2 Building

Source: Matin, Eydgahi, and Shyu 2017

Chicken Point Cabin

Source: Matin, Eydgahi, and Shyu 2017



Dancing Pavilion

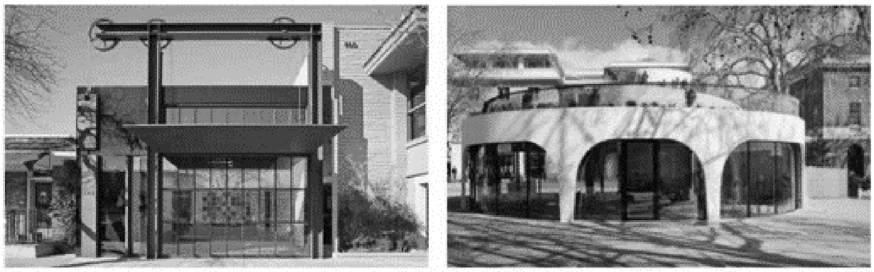
Source: Schumacher, Vogt, and Cordón Krumme 2019

Livraria da Vila

Source: Schumacher, Vogt, and Cordón Krumme 2019

Figure 2.5. Examples of Full Rotation Category

Four of the façade systems in which the elements make full rotation around a central axis are the *Council House 2*, the *Chicken Point Cabin*, the *Dancing Pavilion* and the *Livraria da Vila* (Figure 2.5). The west facade of the *Council House 2* building is covered with blinds made of recycled wood. It was built to protect the offices from the sun in the afternoon and to utilize the daylight as much as possible when the sun is in east direction. Composed of a large pivoting window, the façade of the *Chicken Point Cabin* building has a movable system that maximizes the user's visibility as opening the main living space to the landscape. The movement of the façade is controlled by a hand-cranked mechanism in which a set of gears was used to minimize the load distribution (Kundig 2015). In another example implemented in Brazil, the *Dancing Pavilion*, there are 345 round mirror elements that make full rotation in horizontal direction. There are sensors inside the building which capture the music and the movement of the dancing people. The data collected by the sensors activates the motors, and thereby the mirrors on the façade. Since this building was constructed for a temporary usage, there is no functional objective of the façade like thermal control or daylight control as in the previous systems. The *Livraria da Vila* is a book store in Brazil. Five rotating bookcases are located on the main façade which are attached to the floor and ceiling along the middle axis to create special entrance and to provide air flow.



California Gallery

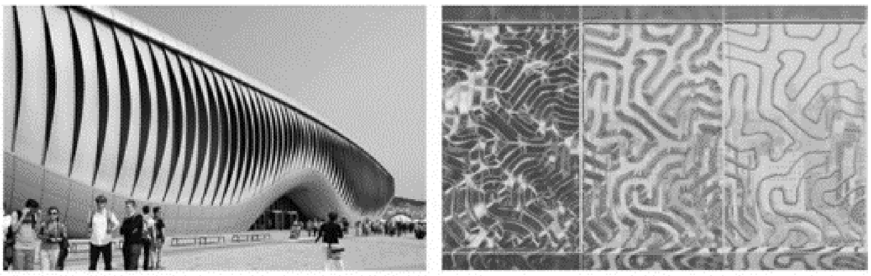
Source: Matin, Eydgahi, and Shyu 2017

Duke of York Restaurant

Source: Schumacher, Vogt, and Cordón Krumme 2019

Figure 2.6. Examples of Sliding Category

The other type of movement presented in the comparison matrix is the sliding movement (Figure 2.6). The façade of the *California Gallery* is similar to the design of the *Chicken Point Cabin* building. Gears and pulleys were used to move the glass facade. Opened in seconds, the system allows natural air flow as creating an entrance to the structure without blocking the view. Another example of the category is the *Duke of York Restaurant* in London. The building has a retractable curved glass facade that enables not only to open the main space to the public but also to ventilate that space naturally throughout the year. It uses a simple mechanism like a weighted sash window which allows sliding the glass panels up or down. Guide rails of the structural mechanism are located underground. The engine moves the panels through two deflection rollers and a counterweight with a simple crane drive (Schumacher et al., 2019).



One Ocean - Thematic Pavilion

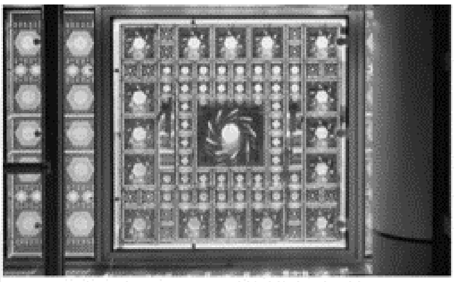
Source: Schumacher, Vogt, and Cordón Krumme 2019

Homeostatic Façade System

Source: Matin, Eydgahi, and Shyu 2017

Figure 2.7. Examples of Deforming Category

Although there are many realized examples of the responsive facades having folding, rotating or sliding movements, the examples of deforming category are limited (Figure 2.7). The *One Ocean Pavilion Expo 2012* is one of the examples in the deforming category. The façade elements are flexible lamellas that move according to the daylight. As the lamellas move one by one on the surface, they create different patterns on the façade. The other systems in the deforming category are made of smart materials. Unlike the previous example, the *Homeostatic Facade System* is a passive system that regulates itself according to environmental factors such as sunlight and temperature changes, and provides optimum conditions for the users. The system consists of engineered ribbon placed inside the double skin glass façade which are made of dielectric elastomers. These dielectric elastomers are coated by silver layer that reflects the light coming to the surface. The material deforms as it distributes the electric charge through the material.

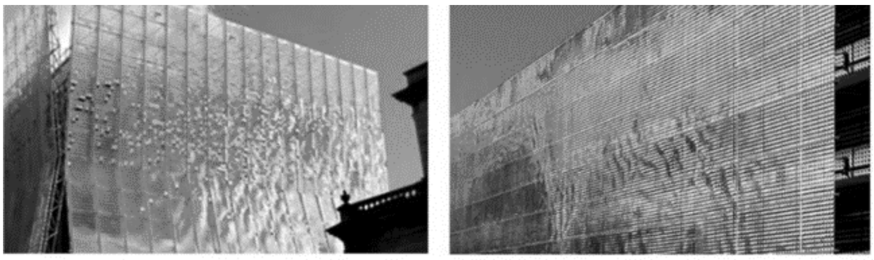


Institute Du Monde Arabe

Source: Schumacher, Vogt, and Cordón Krumme 2019

Figure 2.8. Example of Hybrid Category

Apart from the previous examples, there is also a façade system that has hybrid movements such as rotation and translation (Figure 2.8). Inspired from the Islamic pattern, Mashrabiya, the *Institute Du Monde Arabe*'s south façade consists of camera-like diaphragms. The diaphragms open at low altitude levels while they close in opposite direction when the sun shines brighter. The expansion and contraction mechanism of these diaphragms are regulated by the sliders to automatically control the amount of light entering the building (Schumacher et al., 2019).



Pittsburgh Children's Museum

Source: Fortmeyer and Linn 2014

Wind Arbor

Source: Matin, Eydgahi, and Shyu 2017

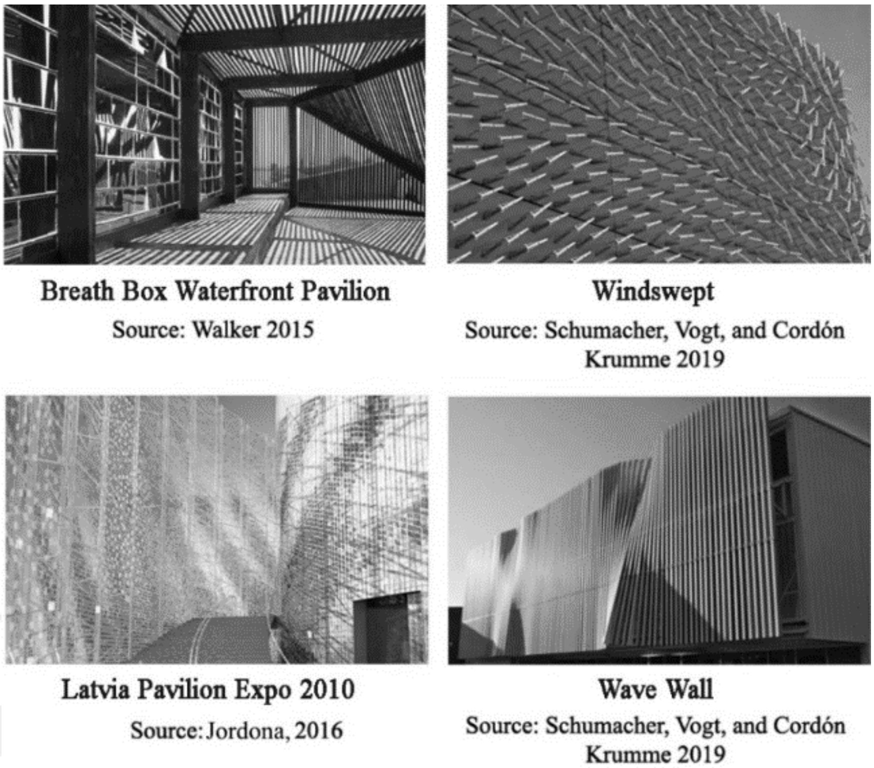


Figure 2.9. Examples of Passive Rotation Category

Apart from the active systems, there are also passive façade systems which can move without requiring any actuator, motor or sensor. Six samples have been examined in the passive responsive system category which are the *Pittsburgh Children's Museum*, the *Wind Arbor*, the *Breath Box Waterfront Pavilion*, the *Windswept*, the *Latvia Pavilion Expo 2010* and the *Wave Wall* projects (Figure 2.9). Designed as a second façade skin in the *Pittsburgh Children's Museum*, the façade elements move slightly with wind pressure without the need of energy or additional support. These elements, which create a light and bright effect on the facade, are located on the aluminum space frame structure (Fortmayer & Linn, 2014). Likewise, the façade of the *Wind Arbor* has same design principles and goals as in the first example, but the elements are positioned on a thin cable net. Consisting of 260.000 aluminum metal fins in total, the system covering the glass façade of the hotel lobby shades the interior, blocks the sunlight and heat entering the building. On the other hand, the panels positioned in the *Breath Box Waterfront Pavilion* are reflective modules that strengthen the wave effect as reflecting the sea based on the light during the day. Having similar movement behaviors in the elements, the *Latvia Pavilion* is composed of 100.000 colored and transparent plastic elements that are positioned to represent the nature (Jordona 2010). Designed on the south facade of the *Windswept Museum*, the responsive façade consists of 612 wind indicators and 25 brown panels that are free to move independently according to the wind, and remain at their initial configurations when there is no wind (Schumacher et al., 2019). All the aforementioned façade elements sway in the wind and move independently. Various configurations can be seen on the facades in a short time.

CHAPTER 3
TESSELLATION METHOD

The word “tessellation” derives from the Latin word “tessella,” which means square stone used in ancient Roman mosaics. Meaning as a cube-shaped piece of clay, stone or glass used in making mosaics, the word “tessella” is based on the Greek word “tessera” that means small square (Seymour & Britton, 1989). In fact, tessellation is a method mostly used in mathematics, art and architecture which can be defined as covering a surface by using one or more geometric shapes without overlapping or gap. In other words, patterns are created by repeating certain shapes (Gijerde, 2008).

The tessellation has a significant role in architecture since the ancient times (Chang, 2018). Throughout the history, different patterns have been used by many cultures for structural elements, decorative surface coverings, non-structural elements and floor coverings. It is known that one of the first studies on this topic was conducted by Johannes Kepler who studied the polygonal tessellations systematically and defined the minimum set of tessellations as regular and semi-regular (Kepler, 1997). Another pioneering study on the tessellation types was conducted by Fedorov in 1891. In addition to these studies, Graünbaum and Shephard (1986) attempted to define and visualize the concept of tessellation. The studies on tessellation has continued in the twenty-first century as well (Greco, 2014; Lu & Steinhardt, 2007; Goodman-Strauss, 2016). It is possible to see impressive examples of the tessellation in contemporary architecture not only as a static building element but also as kinetic ones.

3.1. Shapes That Can Tessellate

According to Seymour and Britton (1989), the tessellation can be created with any type of triangle if the surface has not a regular pattern. However, there is a rule to create a pattern with regular polygons. First, the side number of the polygon is divided to 360 to find the exterior angle. If the interior angle of the polygon is a factor of 360, then the polygon can tesselate. For instance, the side number is equal to 3 in triangle and the interior angle is 60 which means it is a factor of 360. In square, the interior angle equals to 90 that is a factor of 360. Likewise, the interior angle is 120 in hexagon which is again a factor of 360. A regular pattern can be created using triangle, square or hexagon. However, it is not possible to generate a regular tessellation with other polygons since the interior angles are not a factor of 360 (Figure 3.1).

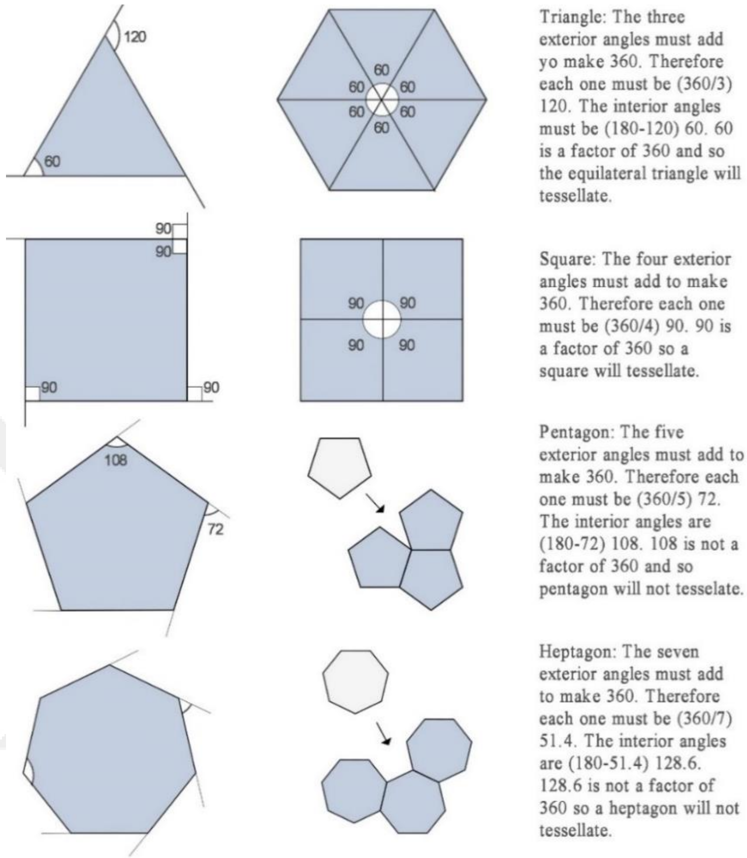


Figure 3.1. Properties of the Regular Polygons

3.2. Types of Tessellation

To create a tessellation, any point selected on the pattern must have the same configuration as any other point. A simple method is used to determine the type of tessellation. First, a vertex on the pattern is chosen and then the number of sides of the polygons positioned around that vertex is written side by side in a clockwise or counter clockwise direction. For instance, the tessellation composed of hexagons is called as 6.6.6 tessellation since there are 3 hexagons at each vertex. It should be noted that regular geometries can merge edge to edge. Grünbau and Shephard (1987) used a formula using regular *n*-gon (n) to calculate the probabilities of the combinations:

$$\frac{n_1-2}{n_1}+\cdots+\frac{n_r-2}{n_r}=2 \qquad \text{(Eq. 1)}$$

According to this calculation, if the side number of a regular polygon (n_1) is subtracted at each step, the result is equal to 2 when n_r is 1. That means the polygon can cover the surface. Unlimited repetition of the tessellation is associated with the rotational axes being on the reflection axes. There are mainly three types of tessellation which are regular, semi-regular and semi-regular.

3.2.1. Regular Tessellation

In regular tessellation, the same number of specific *n*-gon are found at each selected vertex. A regular polygon having equal sides and interior angles must be used while creating this type of tessellation (Kinsey & Moore, 2002). There are only three examples of this defined category which are 3.3.3.3.3.3 tessellation consisting of triangles, 4.4.4.4 tessellation consisting of squares and 6.6.6 tessellation consisting of hexagons (Figure 3.2).

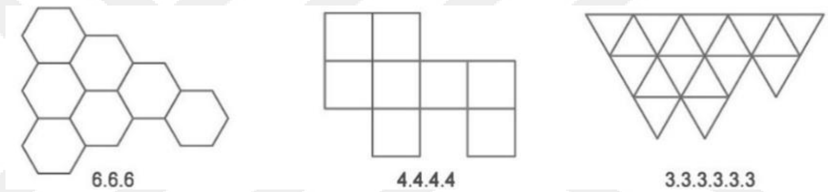


Figure 3.2. Regular Tessellations

3.2.2. Semi Regular Tessellation

It consists of two or more regular polygons arranged in the same at each vertex. The side lengths of the polygons in the semi-regular tessellation must be the same length for the pattern to form and iterate. There are only eight types of semi-regular tessellations (Figure 3.3).

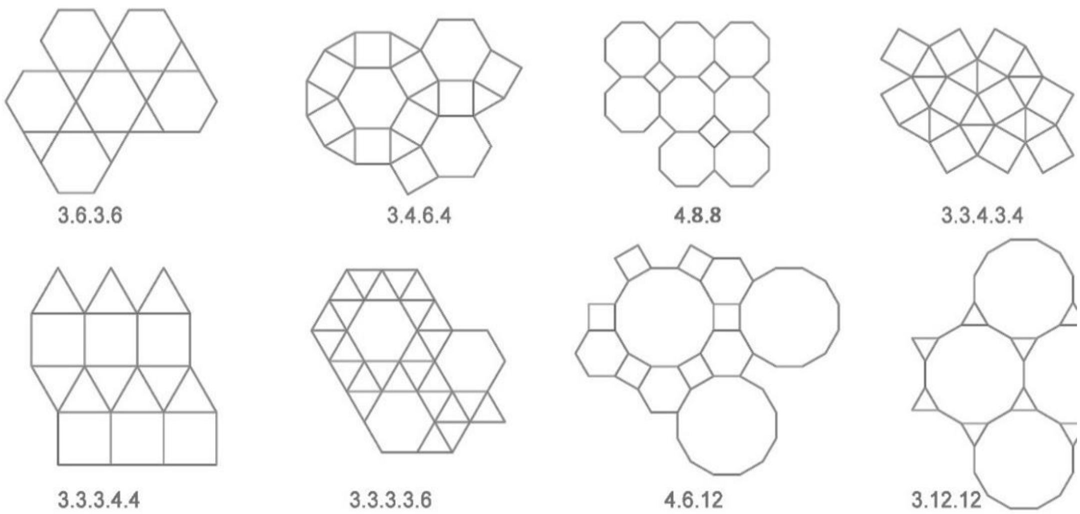


Figure 3.3. Semi Regular Tessellations

3.2.3. Demi Regular Tessellation

The semi-regular tessellation has been defined by some researchers as the combination of regular and semi-regular tessellations. There are 20 examples of this category (Figure 3.4).

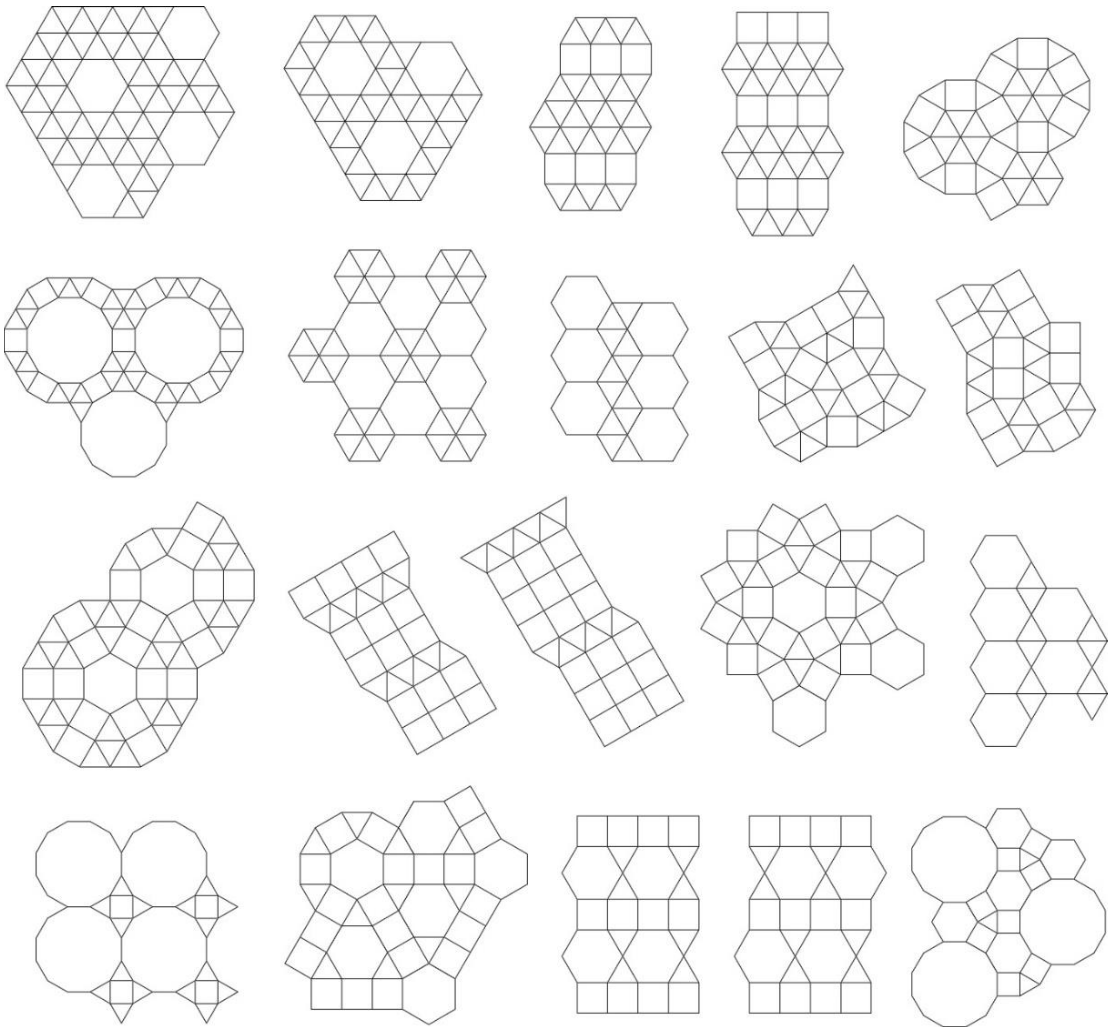


Figure 3.4. Demi Regular Tessellations

3.3. Tessellation in Ancient Times

The use of tessellation in architecture dates back to ancient times. It is possible to find different tessellated patterns in buildings not only as surface covering but also as decoration element. One of the earliest examples was found on wall decorations in 4000 BC which was used by the Sumerians (Pickover, 2009). It is known that the tessellation was also used by other civilizations such as Egyptians, Persians, Romans, Greeks, Arabs, Japanese and Chinese, but the used patterns varied from culture to culture. For instance, mosaics made of square blocks were used in antiquity while more complex geometric patterns were used in Arab culture (Dunbabin, 1999; Field, 2017; Hull Museum Collections, 2021). Some tessellation examples from those periods are shown in Figures 3.5 - 3.9.

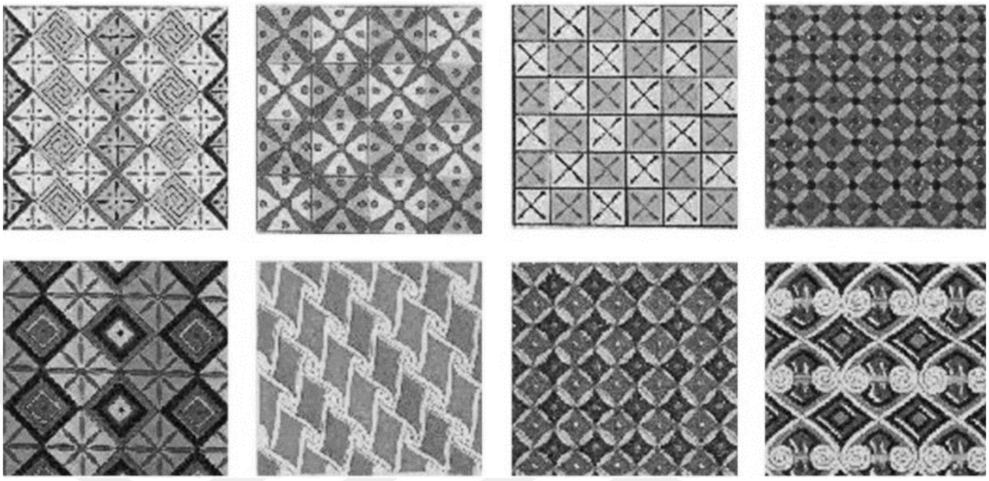


Figure 3.5. Egyptian Tessellation Examples

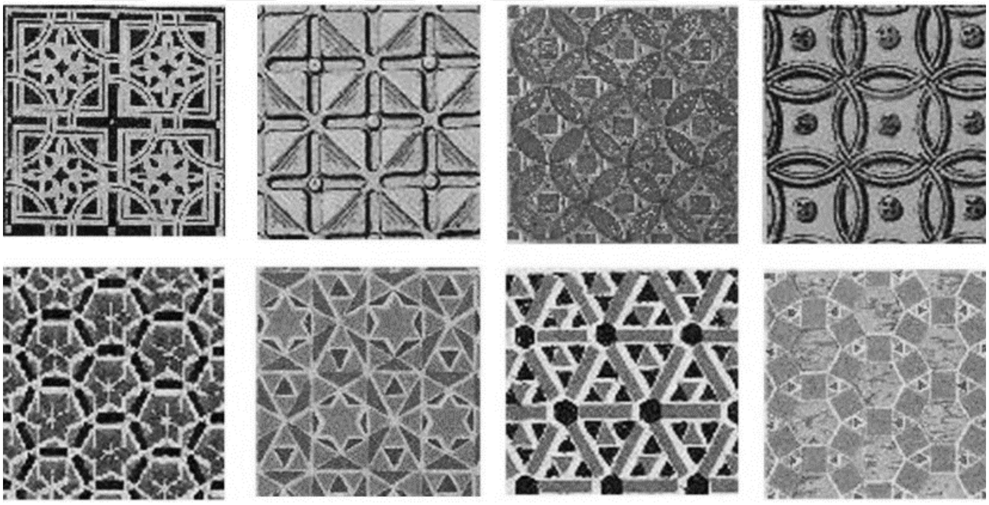


Figure 3.6. Byzantine Tessellation Examples

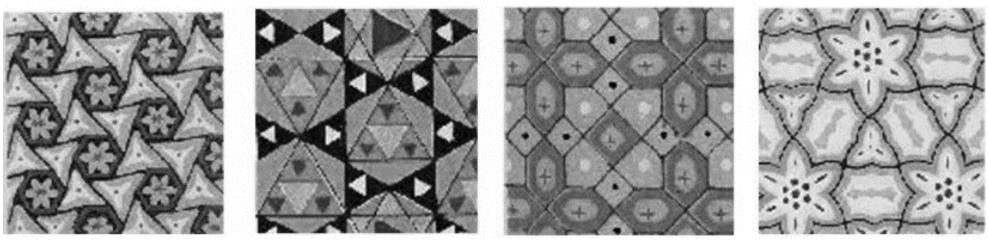


Figure 3.7. Persian Tessellation Examples

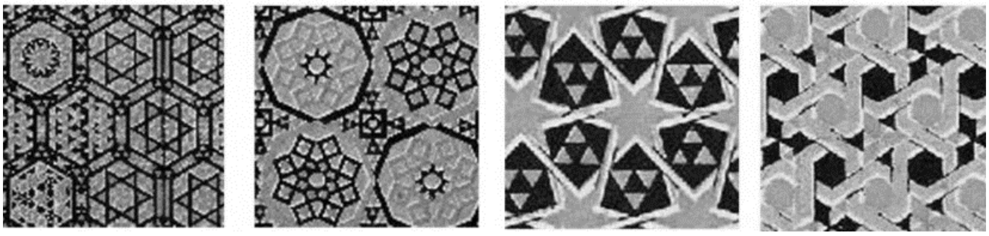


Figure 3.8. Arabian Tessellation Examples

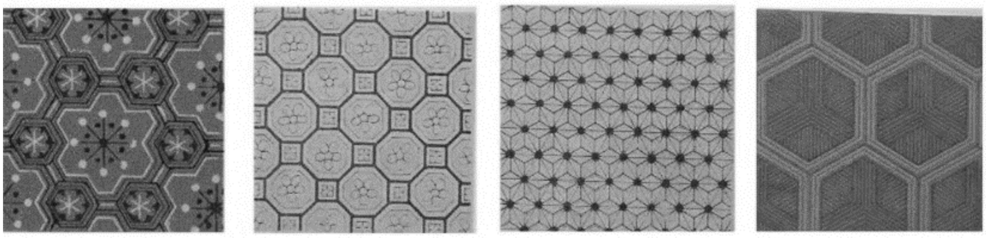


Figure 3.9. Chinese Tessellation Examples

3.4. Tessellation in Islamic Architecture

Islamic religion, culture, art and architecture spread across the continents. As a result of this, distinct characteristics of Islamic architecture were used by the masters in many buildings constructed in different regions. Since the human and natural figures are not used in Islamic architecture, geometric figures and patterns became more dominant representing the unity and the universe. Even though very complex geometries are seen in Islamic architecture, they are derived from regular polygons and simple grids. Various geometric patterns have been used in Islamic architecture such as radial and periodic patterns. The radial patterns revolve around the center point whereas the periodic patterns are created by translation and symmetry in two independent directions (Tennant, 2009). Girih and star patterns are two types of the periodic pattern which are based on equilateral triangles, squares and hexagons forming the regular tessellation. In most patterns, squares are used since they form a lattice system. However, hexagonal and triangular shapes also provide advantages of ease of fabrication and iteration as they are dual of each other. There is a study showing the compass-straight edged structures of the patterns step by step composed of square and hexagon (Broug, 2008). When the patterns used in Islamic architecture are examined, it is seen that most of them consist of the intersection of regular pentagons (Sarhangi, 2012).

3.4.1. Girih Patterns

Girih pattern can be defined as an ornamentation style used in Islamic architecture which is based on a set of five striped tiles. This set consists of a regular decagon, a rhombus, a regular pentagon and a bowtie-like shape (Figure 3.10). The sides of each polygon are equal, and the lines emerging from the midpoints of both sides intersect with each other at 72 and 108 degrees (Lu & Shephard, 1987).

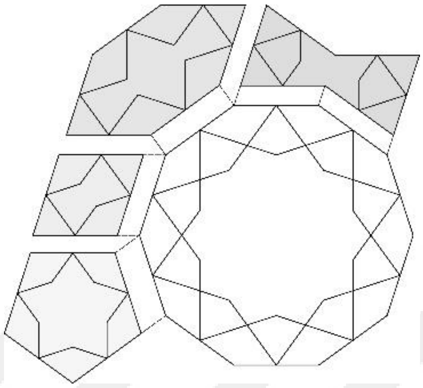


Figure 3.10. Girih Pattern

The date when Girih pattern was first used in architecture is still unknown (Lu & Shephard, 1987), but it is known that this pattern was used in the buildings of Seljuk and Ilkhanians. It was also used in decorative arts in the 14th century. One of the well-known examples of this pattern can be found in *Ottoman Green Mosque* in Bursa, Turkey (Figure 3.11). Another example is *Abbasid Al-Mustansiriya Madrasah* (Figure 3.12) that is one of the standing buildings in Baghdad demonstrating the development of geometric ornaments (Tabbaa, 2001). The main entrance of the building consists of three conical arches, star and polygon figures. Other entrances are decorated with zigzag geometric patterns and square patterns.

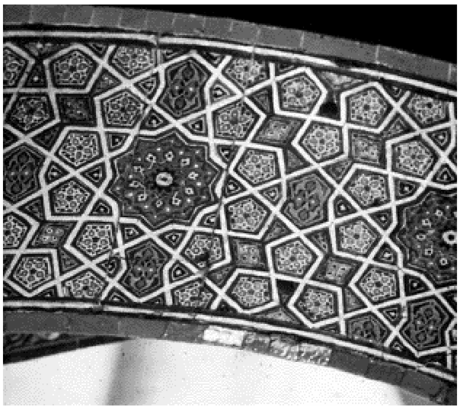


Figure 3.11. Ottoman Green Mosque

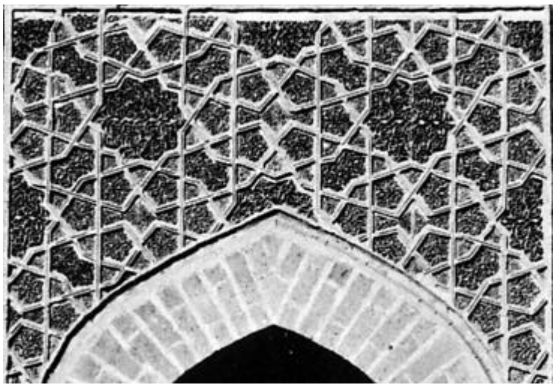


Figure 3.12. Abbasid Al-Mustansiriya Madrasah

3.4.2. Star Patterns

Star patterns are one of the complex patterns used in Islamic architecture, and little is known about how they originated and designed. In Islamic architecture, the use of circle is a way of representing the unity, the God and the qibla that is the direction towards the Kaaba (Critchlow, 1976; Akkach, 2012).

Most Islamic geometric patterns (IGPs) are based on regular polygons such as hexagons and octagons. Stars, the basic geometry of these IGPs, are formed by the combination of the vertices of these regular polygons. There is a group used to create star geometry ranging from hexagons, which are considered the simplest of all polygons, to much more complex polygons. Rosettes are formed from these stars (Figure 3.13).

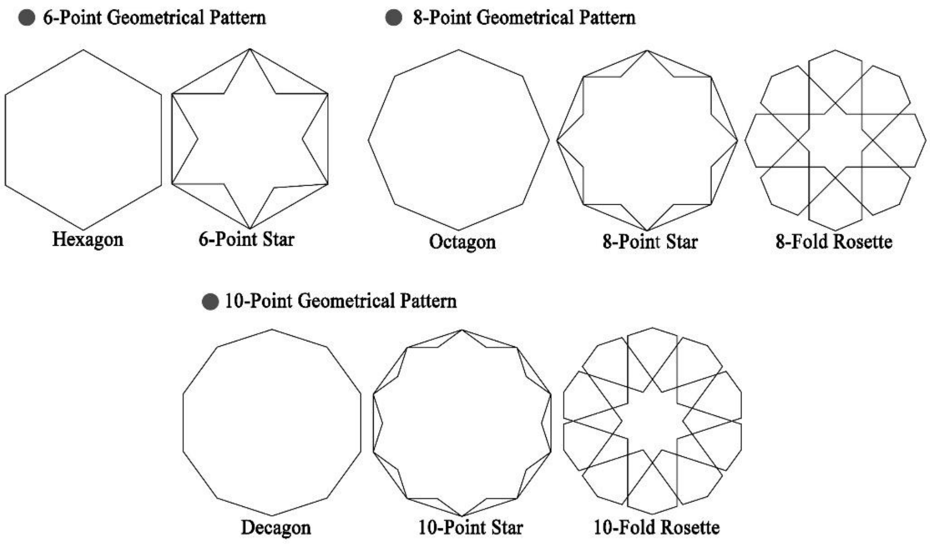


Figure 3.13. Evolution of the Star Pattern

An example of the use of star pattern can be seen in the Abbasid Palace in Baghdad which strongly represents the architectural features of the late Abbasid and early Seljuk periods (Abdullahi & Embi, 2013). The building has geometric patterns made of carved brick and terracotta, and some of the earliest examples of the rosettes attached to 8- and 12-point star patterns were used (Figure 3.14). Another example is the Sultan Hassan Complex located in Cairo (Figure 3.15). Although there are many different patterns in the structure, the most striking ones are the 6-, 8-, 10- and 12-star patterns and rosettes. The 16-star patterns found on the panels of the wooden pulpit are surprisingly intricate (Abdullahi & Embi, 2013).

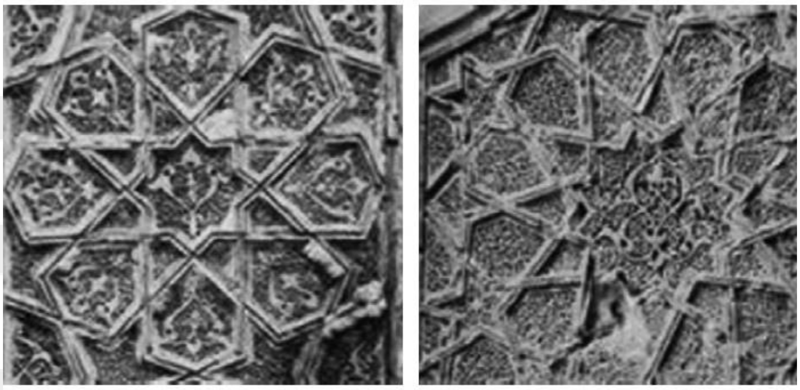


Figure 3.14. Abbasid Palace

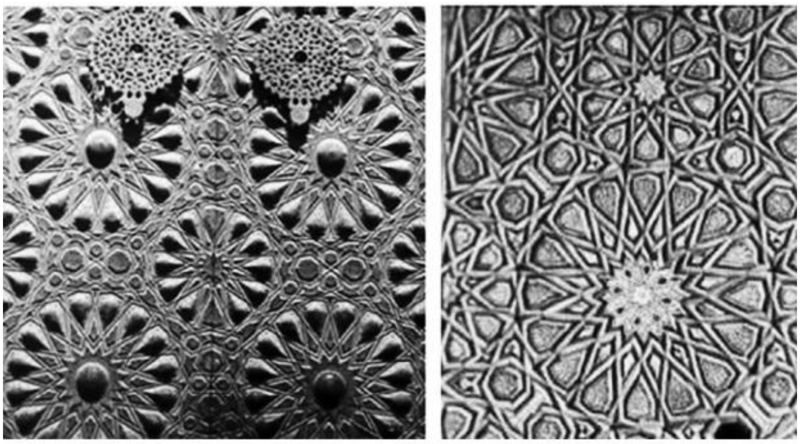


Figure 3.15. Sultan Hassan Complex

3.5. Tessellation in Contemporary Architecture

It is possible to see the examples of simple or complex tessellations in contemporary architecture. One of the two-dimensional examples of tessellation applied on a flat surface is seen on the ceiling of the *Yale Art Gallery* building designed by Louis Khan in 1953 (Figure 3.16). The waffle slab was created using regular tessellation made of equilateral triangles. Unlike previous example, a structural system called diagrid is used in the *London Swiss-Re* building designed by Norman Foster in 2004, which is an example of structural application of tessellation (Figure 3.17). A regular triangular tessellation pattern is used to cover the building facade.

Figure 3.16. Yale Art Gallery

Figure 3.17. London Swiss re Building

Another two-dimensional application of the tessellation is seen in the façade of the *Melbourne Federation Square* building designed by Lab Architecture (Figure 3.18). Contrary to previous examples, the façade does not consist of regular tessellation. Rather, it is composed of nonidentical triangular panels that do not repeat on the surface. On the other hand, the two-dimensional tessellation inspired by versatile floral patterns is used in the *Ravensbourne College* designed by Foreign Office Architects (Figure 3.19). The facade features a pattern of two irregular pentagons and rhombuses. Due to the rotational symmetry of the tessellation, different sizes of openings can be created in different locations on the facade.

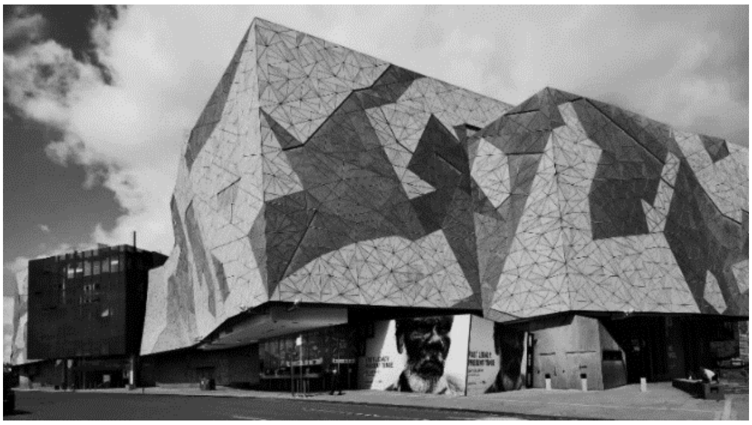


Figure 3.18. Federation Square Building

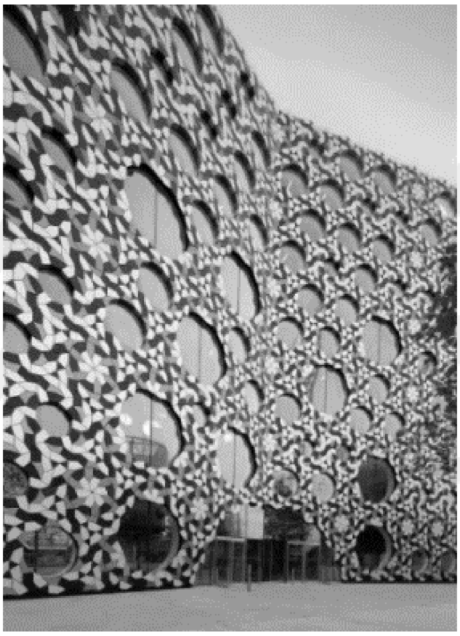


Figure 3.19. Ravensbourne Collage

One of the most important examples of three-dimensional tessellation can be seen in the roof of the *British Museum* in London designed by Foster and Partners (Figure 3.20). Formed of triangular tessellation, the roof geometry was generated using a mathematical model in which the side lengths of the triangles were optimized based on an algorithm (Kolarevic, 2004). The tessellated patterns can be generated using both regular or irregular geometries. For instance, the façade of the *Storey Hall* in Melbourne has a three-dimensional irregular tessellation (Figure 3.21). The most striking feature of this building is that the rhombus pattern continues from exterior surface to the interior walls and ceiling.

Figure 3.20. British Museum

Figure 3.21. Storey Hall

Apart from the static examples of the tessellation, it is also possible to see the impressive examples designed kinetically. For instance, the façade of the *Latvia Pavilion* (Figure 3.22) has a regular square tessellation which consists of 100.000 colored and transparent plastic elements positioned to represent nature (Jordana, 2020). The façade elements are free to move independently in reaction to wind movement as creating an oscillating motion. On the other hand, in the *Dancing Pavilion* built in Brazil, there are 345 round mirror elements that make full rotation in the horizontal direction (Figure 3.23). Inside the building, there are sensors that capture the music and movement of the people dancing. The data collected by the sensors activate the motors and the mirrors on the façade accordingly. Since this building was in temporary use, the façade does not have a functional purpose such as temperature control or daylight control.

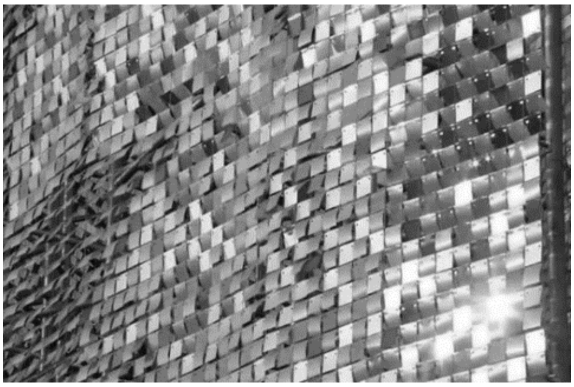


Figure 3.22. Latvia Pavilion

Figure 3.23. Dancing Pavilion

More complex façade systems have been proposed and implemented in the last decades. One of the well-known facades is the *Al-Bahr Towers* that has 1049 umbrella-like components organized into hexagonal units (Figure 3.24). Based on regular triangular tessellation, the responsive façade is controlled by a central building management system (BMS) (Cilento, 2020). Performing a folding movement, the system works in real time and provides mainly daylight and thermal control. There is also a facade system with hybrid movements such as rotation and translation in a much more complex way than the previous example (Figure 3.25). Inspired by *Mashrabiya,* which is based on the Islamic star and rosette patterns, the south façade of the *Institute Du Monde Arabe* has a regular square tessellation consisting of camera-like diaphragms. At low altitude levels, the diaphragms open by means of a photoelectric cell and close in the opposite direction when the sun is brighter. The expansion and contraction mechanism of these lens-like apertures is regulated by sliders to automatically control the amount of light entering the building (Schumacher, 2019).

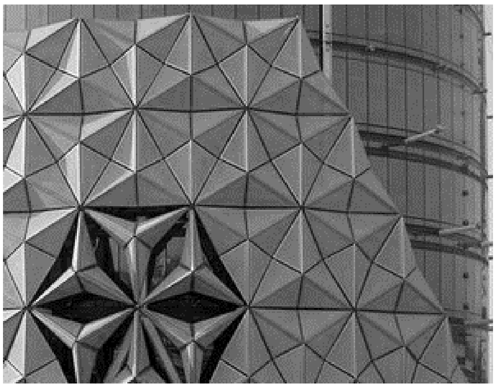


Figure 3.24. Al-Bahr Towers

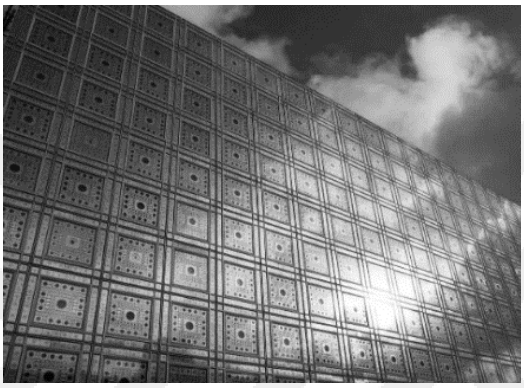


Figure 3.25. Institute Du Monde Arabe

CHAPTER 4
DESIGN OF RESPONSIVE FACADE SYSTEM

The design phase is crucial for the responsive facades to achieve the intended goals. In this multi-step design phase that includes geometric design, kinematics and performance analysis, right decisions should be made for the system to work effectively. However, the simultaneous progression of the design stages is a complex process in which each step should be considered at the same time. The façade design generated at the end of this process should be simple, flexible, feasible and running smoothly.

In this study, the design process of the proposed facade has started with the morphology of the modules forming the façade system. For this purpose, first, triangular and hexagonal shapes have been chosen since they are dual of each other and form regular, semi-regular and demi-regular tessellation patterns. Then, the triangular and hexagonal modules have been created and iterated on the surface to cover the façade. Because it has been aimed that the modules used in the responsive facade have rotational movement, a proper system allowing the rotation of the panels has been proposed. Afterwards, a parametric study has been carried out not only to investigate different patterns but also to create façade alternatives to perform the daylight analyses.

In this study, four different façade systems have been developed using the proposed modules. The proposed façade systems can change their geometric configurations based on the movement of the sun and allow optimum daylight to enter the building during the day. The basic principles considered while designing the façade systems are as follows:

- easy iteration and reproduction of the selected shapes and modular system
- ability to create different patterns and configurations on the facade according to needs
- movement of the modules without blocking the others

- avoiding gaps and overlaps while covering the facade
- applicability to any facade at different sizes
- operability with a simple mechanism to reduce overall and maintenance costs
- controlling daylight and preventing unwanted heat gain

This section basically consists of four sections. The first section deals with the geometric design of modules and panels. The second section explains the movement principle of the created modules. The third section focuses on the parametric design approach of the modules and the facade design created using selected patterns. In the last section, the necessary mechanism design for this system is introduced.

4.1. Morphology of the Modules

Equilateral triangular and hexagonal shapes have been used to design the responsive façade system. First, each shape has been divided into sub equilateral triangles as shown in Figure 4.1. For the triangular shape, the midpoints of the sides have been found and then connected to each other by drawing lines parallel to its sides to form the sub four equilateral triangles. On the other hand, the hexagon has been subdivided into six sub-equilateral triangles by drawing lines from the vertices to the center point.

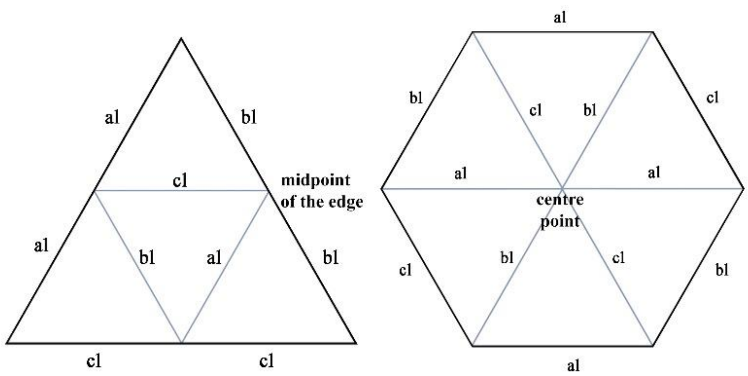


Figure 4.1. Division of Triangle and Hexagon

Second, the frame structures have been created for both triangular and hexagonal shapes based on the subdivision (Figure 5a). Then, the panels have been placed on the frame structures, which can be used at different sizes (Figure 5b). To prevent the panels from overlapping and not to block the intended rotational movement during the folding process, a distance between the panels and the frame structures have been left.

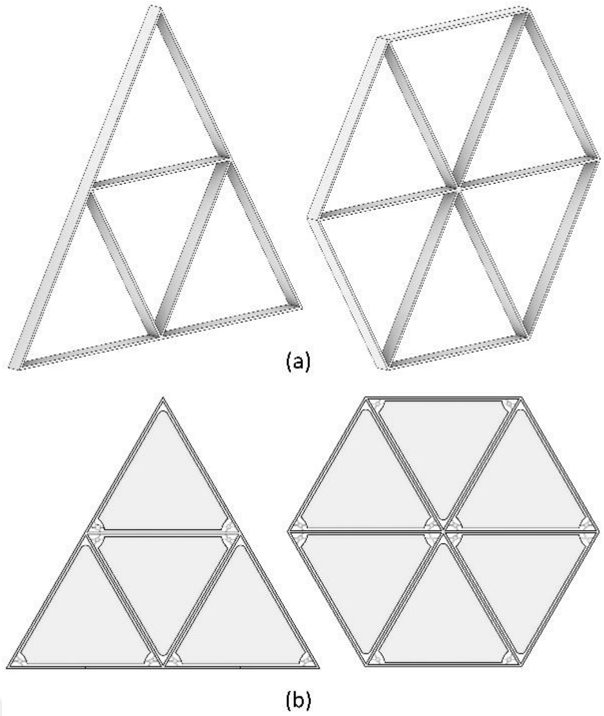


Figure 4.2. a) Frame Structures; b) Placement of the Triangular Panels

After the panels are connected to the frame, the modules can be iterated on the surface. As well as generating regular patterns using the proposed modules, it is also possible to create different configurations by changing the number of triangular or hexagonal modules and the tessellation type used on the surface (Figure 4.3). Since the triangular and hexagonal modules allow flexibility in shape generation, the patterns created on the facade can be modified and transformed into various different facade systems with configurations that grow, shrink, divide and integrate. While creating these configurations, the frames can be placed horizontally, vertically or at an angle (Figure 4.4). Hence, new alternatives can be created according to the functional needs. When necessary, gaps can be opened to customize the facade to the interior.

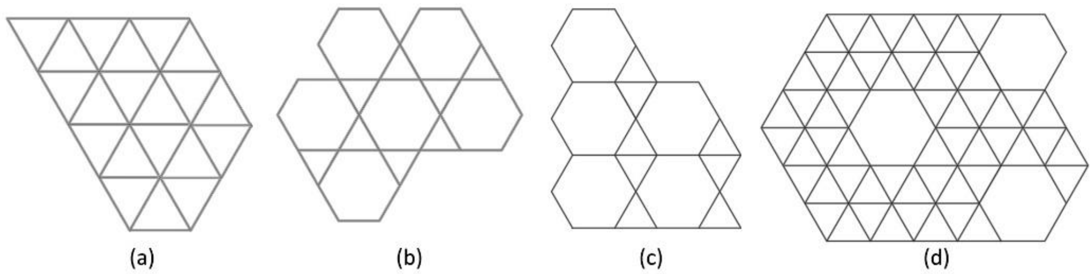


Figure 4.3. Semi-Regular and Demi-Regular Tessellated Patterns

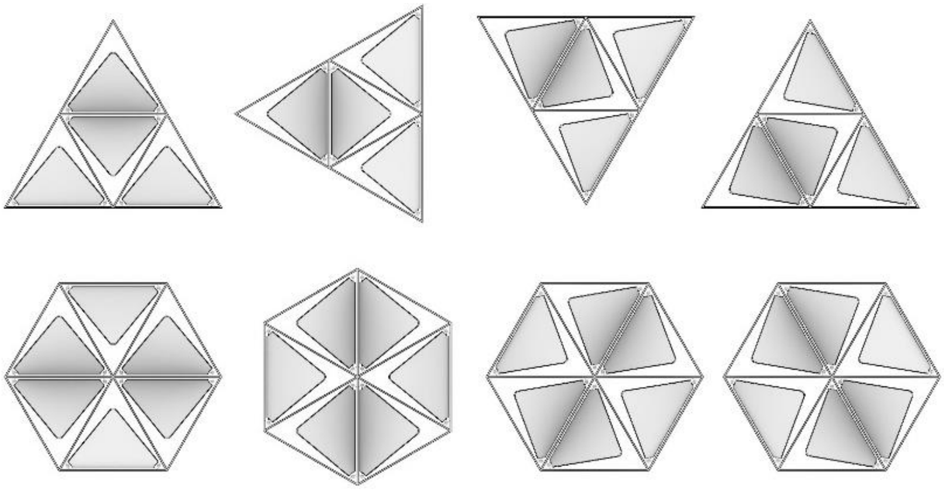


Figure 4.4. Alternative Placements of the Triangular and Hexagonal Modules

Even though the patterns composed of triangle and hexagon do not fully cover a square or rectangular surface, the parts at the edges of the surface can be subdivided into triangles as in the modules. That means the whole surface can be covered with identical or non-identical triangular panels. The panels that are identical with the façade module can be movable whereas the others can be fixed. As demonstrated in Figure 4.5 and 4.6, the parts represented by light blue color can be covered with either half modules or identical triangular plates. On the other hand, the dark blue parts can be covered by fixed plates.

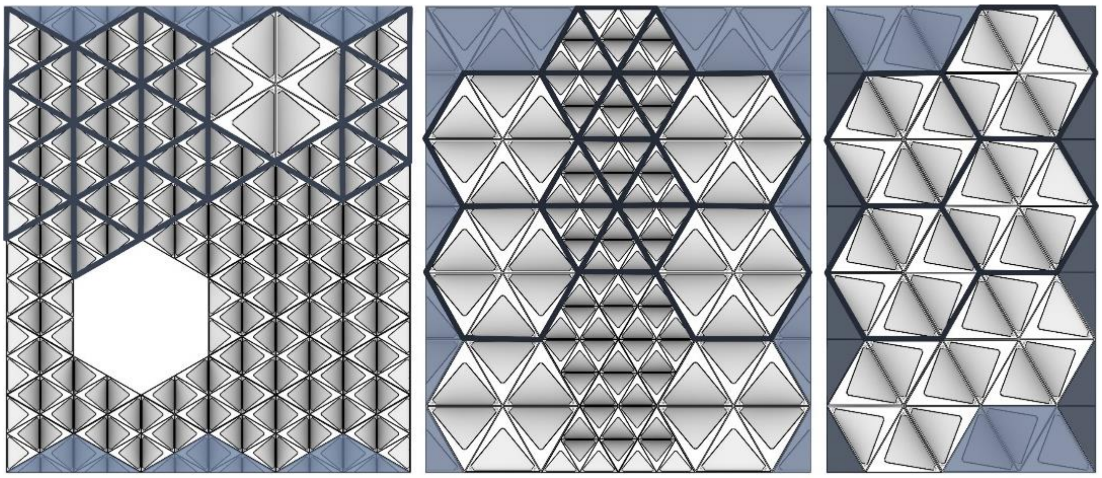


Figure 4.5. Gaps of the Tessellation on a Rectangular Façade (Light blue color represents gaps to be covered by half panels/half modules, Dark blue color represents gaps to be covered by static panels)

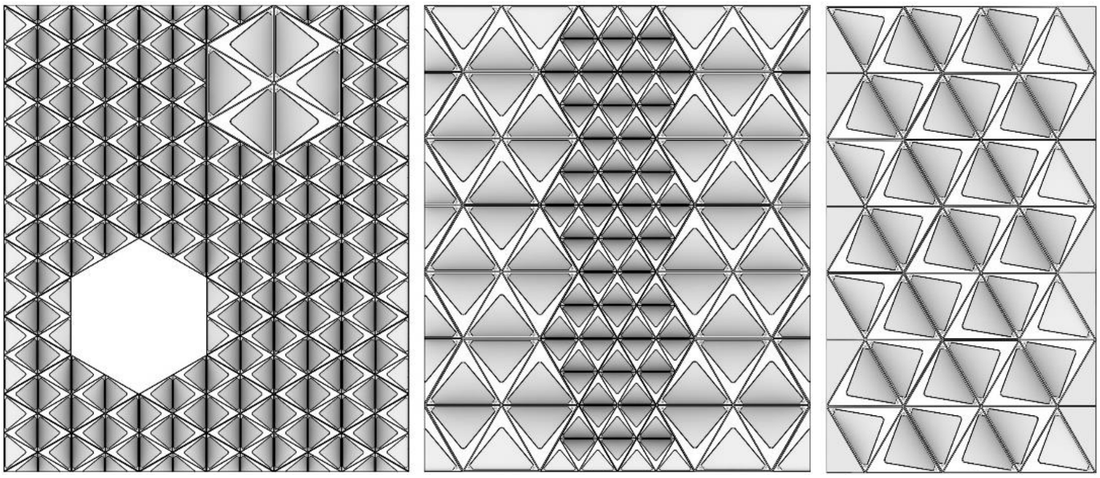


Figure 4.6. Tessellation Design in a Rectangular Façade

4.2. Movement Capabilities of the Proposed Modules

In the façade design, it has been aimed that the modules can move individually and allow creating different configurations. In order to facilitate the movement of the panels, a suitable mechanism has been proposed. Holes have been opened at certain points of the frame structures where the connectors are placed (Figure 4.7). Four-ended fasteners placed in those holes have been connected to the frame structure. While three ends of the connector have been fixed to the frame, the other allows rotational movement of the panel by means of a rotary motor (Figure 4.8).

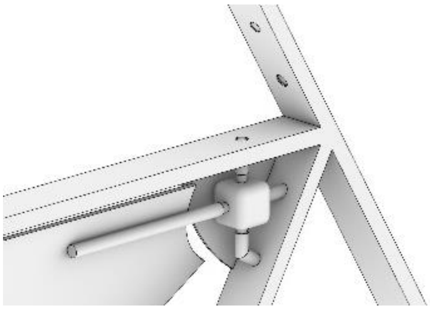


Figure 4.7. Connection Detail

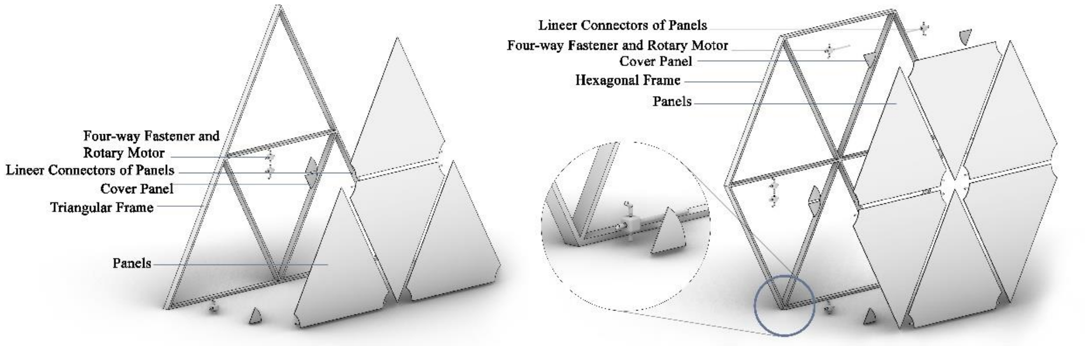


Figure 4.8. Exploded Diagrams of the Modules

The triangular frames positioned inside the proposed modules define the boundaries of the panels on which they move. The panels perform rotational movements about the horizontal axis during the folding process. Each panel can fold from 0^0 to 90^0 to the outside (Figure 4.9).

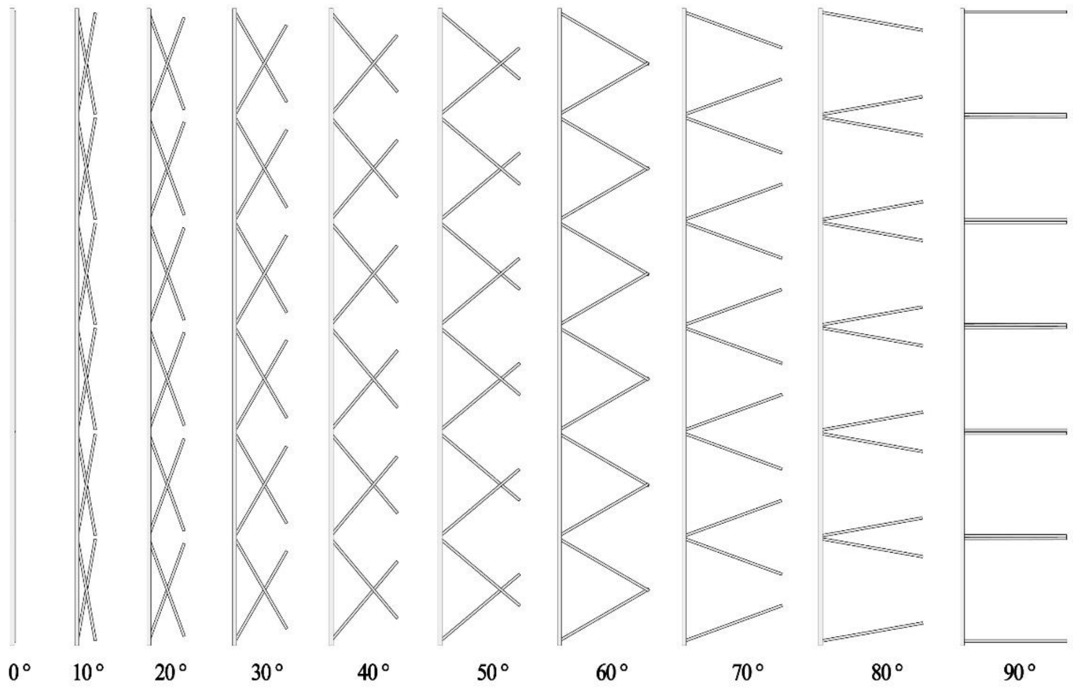


Figure 4.9. Folding Stages of the Panels

4.3. Parametric Model of the Façade Modules

Parametric design is a process based on algorithmic thinking that defines the set of rules and key parameters required to find optimal solution to the design problem. Using the parametric design in architecture, the design of complex geometries, form-finding, optimizations and advanced designs can be facilitated. In this study, Rhinoceros® (3D CAD modeling software) and Grasshopper® (graphical algorithm editor) have been used to generate the parametric models.

Based on the proposed façade modules, the parametric models of the façade systems have been created in Grasshopper®. The patterns in Figure 4.3 have been used in the parametric models to generate the façade systems. The models have been formed in two main steps. In the first step, triangular and hexagonal modules have been defined in Grasshopper®. The sides of the sub equilateral triangles in the triangular module have been determined as 50cm; thus, the side lengths of the module have been 1m (Figure 4.10a). Likewise, the side lengths of the regular hexagon have been determined as 1m to create the hexagonal module (Figure 4.10b). On the other hand, the side lengths of the panels in the triangular module are 45cm while they equal to 90cm in the hexagonal module. The respective edges of the panels on the horizontal axis have been designated as the rotation axis in the models. The panels have been defined in the parametric models as to be moved between 0^0 and 90^0 without blocking the movements of the other panels (Figure 4.11).

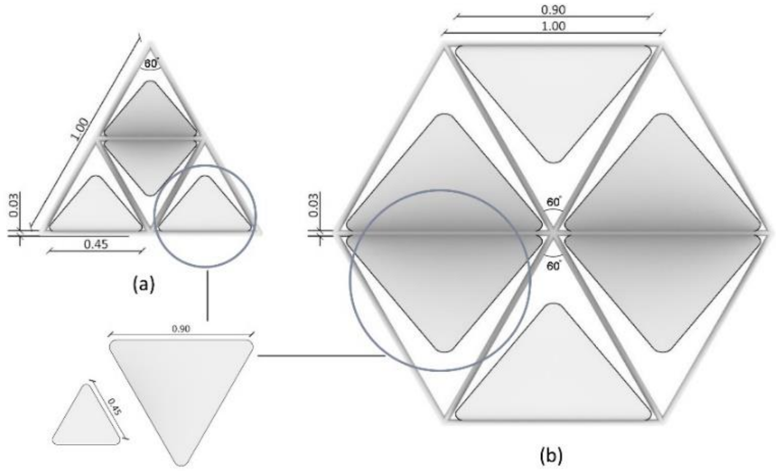


Figure 4.10. Dimensions of the Frames and Panels: a) Triangular Module; b) Hexagonal Module

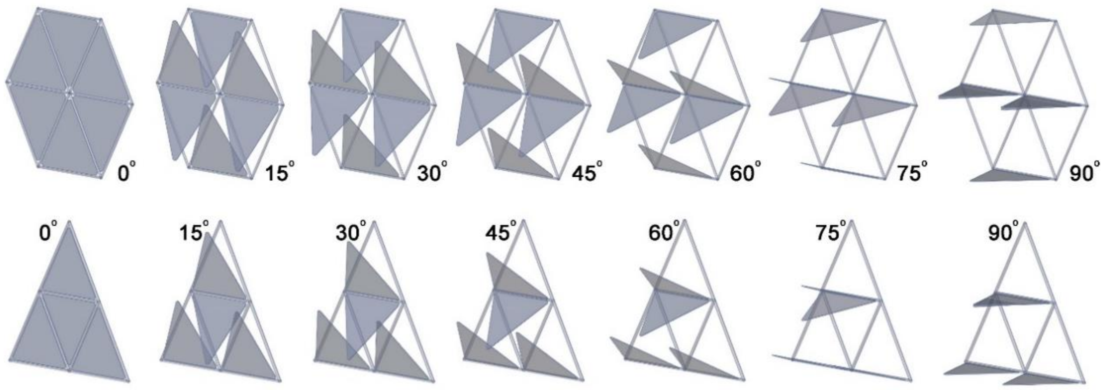


Figure 4.11. Movement Process of Hexagonal and Triangular Modules

In the second step, the modules have been iterated on the selected patterns horizontally and vertically to cover the façade. The half modules that are vertically half of the regular triangular and hexagonal modules have been created in this step to cover the gaps remaining at the edges. Aforementioned generation method and side lengths have been used to define the half modules (Figure 4.12). These half modules have been positioned to fit the edges on rectangular façade.

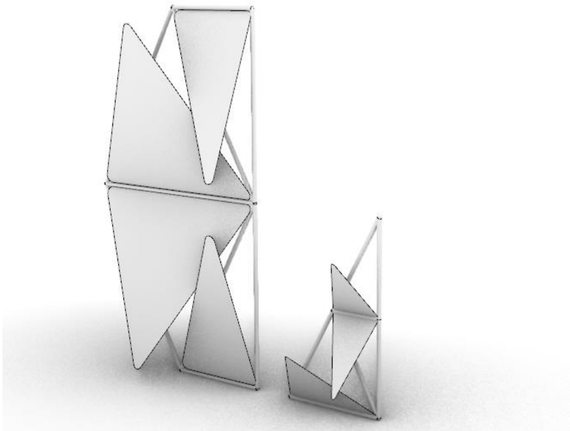


Figure 4.12. Half Modules

In order to place the modules on the façade, a generic model of 12x15x6.50m has been created. The rotation axes of the modules created in the façade systems have been defined horizontally, because the models are intended to be applied to the south façade. The input parameters have been determined as the number of vertical and horizontal repetitions of the modules and the rotation angle of the panels (Figure 4.13).

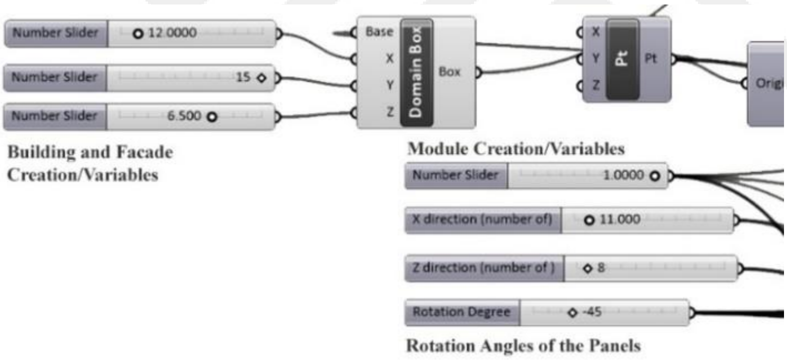


Figure 4.13. Determined Variables

After defining all required parameters, the first model has been created based on the regular tessellation of equilateral triangles (Figure 4.3a). The triangular modules have been repeated eight times vertically and eleven times horizontally based on the translation and glide reflection operations to cover the façade without any gaps (Figure 4.14a). Half-triangular modules have been used for the uncovered gaps formed on the right and left sides of the façade (Figure 4.14b).

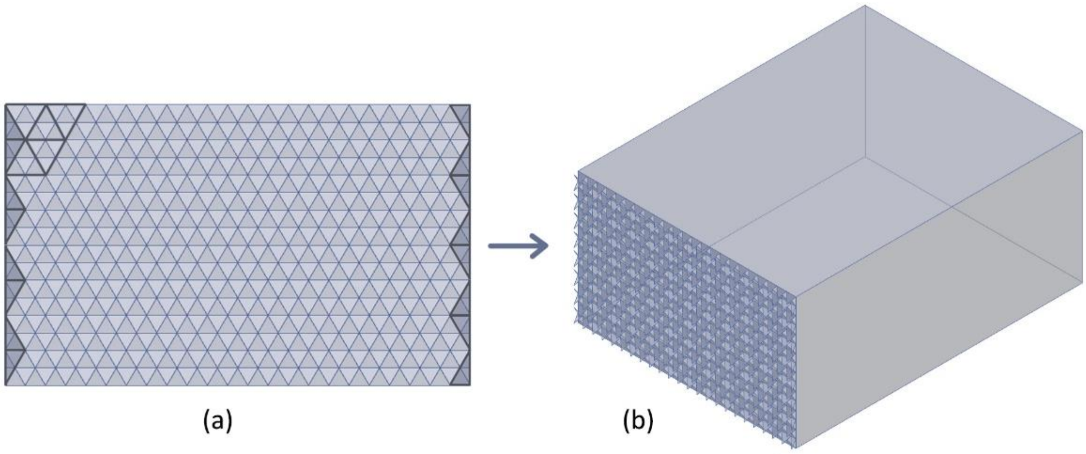


Figure 4.14. a) Regular Tessellated Pattern (dark blue color represents gaps to be covered by half panels/half modules); b) 3D Visual of the First Model

For the second model, semi-regular tessellation made of equilateral triangles and hexagons have been used (Figure 4.3b). The hexagons have been placed in four consecutive rows of 6-5-6-5 repetitions from top to bottom while the triangular modules have been placed in the spaces between the hexagonal modules (Figure 4.15). The half hexagonal and triangular modules have been used for the gaps formed at the edges.

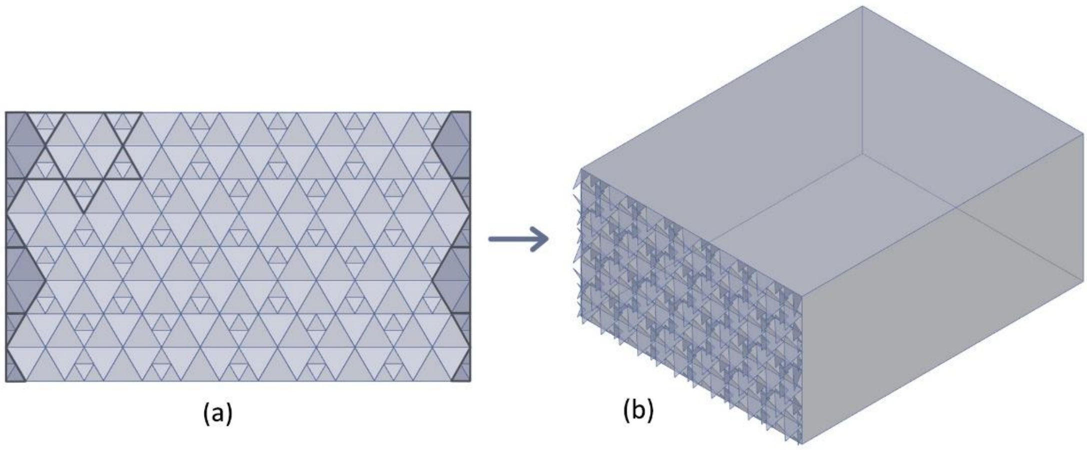


Figure 4.15. a) Semi-Regular Tessellated Pattern; b) 3D Visual of the Second Model

The third model consists of semi-regular tessellation made of equilateral triangles and hexagons as in the previous model but the pattern is different (Figure 4.3c). In this model, the hexagonal module has been duplicated four times vertically, with side-to-side connections. Then, this vertical row has been duplicated six times horizontally, with point-to-point connections between the hexagons. The triangular modules have been placed in the spaces between the hexagons (Figure 4.16). Unlike the previous model, only half-triangular modules have been used for the gaps formed at the edges.

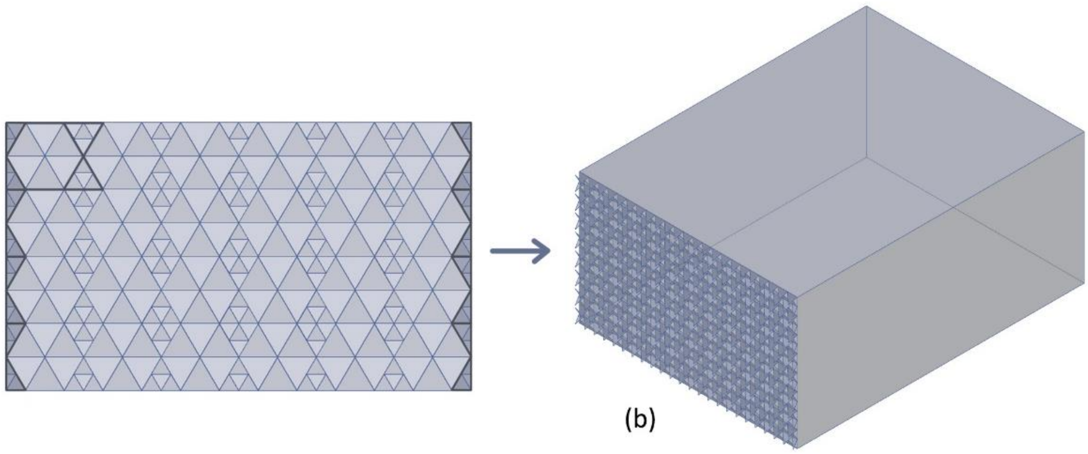


Figure 4.16. a) Demi-Regular Tessellated Pattern; b) 3D Visual of the Third Model

The forth model has a demi-regular tessellated pattern in which the hexagons have been repeated horizontally with a distance of 1m. Having translation symmetry, this row has been duplicated vertically by shifting (Figure 4.17). The hexagons have been surrounded by the triangular modules. The spaces remaining at the edges have been covered with the half triangular modules as in the previous models.

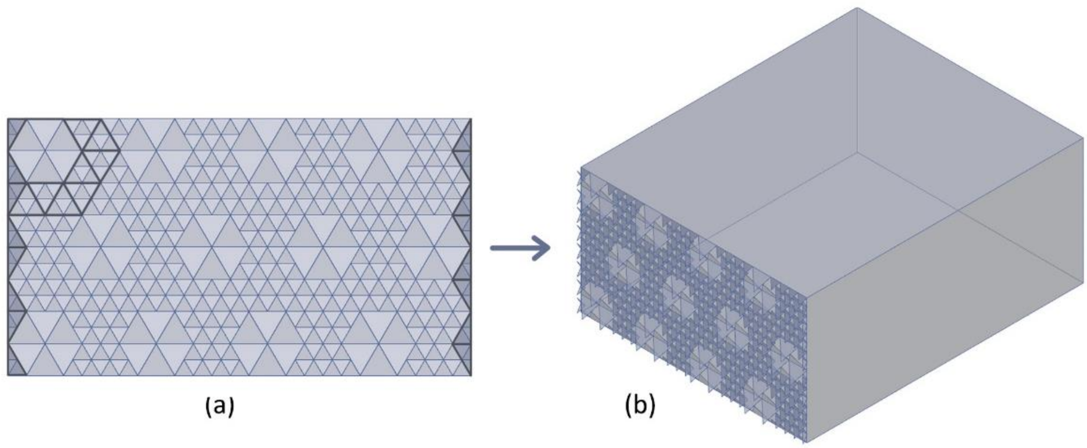


Figure 4.17. a) Demi-Regular Tessellated Pattern; b) 3D Visual of the Forth Model

CHAPTER 5
COMPUTATIONAL PERFORMANCE ANALYSIS

With the help of developing technology, the researchers, architects and engineers have started to use simulation programs to evaluate their proposed designs. By means of these programs, the decisions made on the design proposal can be easily revised or improved in the design process. Within the scope of this study, the proposed façade models generated in the Grasshopper® have ben simulated using DIVA plugin for the daylight analysis. Design variations have been tested at different configurations and the results are explained in detail.

5.1. Dynamic Daylight Assessment Methods

The design parameters such as the size, shape and orientation of the shading elements and the openings on the facade affect the natural light entering into the interior space. It is required to analyze the effect of those variables to create an accurate and efficient facade design or to improve its performance. For this purpose, dynamic daylight performance metrics such as daylight autonomy, continuous daylight autonomy, maximum daylight autonomy, useful daylight illuminance, spatial daylight autonomy, annual sunlight exposure have been developed as an alternative to the existing static daylight performance metrics (daylight factor, average daylight factor, average amount of illumination, illuminance level at a point and the ratio of vertical illuminance to horizontal illuminance) (Mardaljevic et al., 2009). Dynamic daylight performance metrics are the methods using natural and physical variables such as climate, location, direction and direct light from the sun that affect the amount of daylight (Kılıç, 2017). The dynamic daylight performance metrics are defined for monthly, seasonal or annual time intervals by including daylight diversity based on the annual climate data (Mardaljevic et al., 2009). Among these methods, spatial daylight autonomy (sDA) and useful daylight illuminance (UDI) are mostly used in the recent studies (Nabil & Mardaljevic, 2006; Verso et al., 2014; Galatioto & Beccali, 2016; Wagdy et al., 2016; Hu et al., 2014; Bayz et al., 2019;).

Proposed by IES (2013) as a new approach to evaluate the preferred indoor daylight in spaces such as classrooms, offices, libraries and meeting areas, the sDA is a yearly daylighting metric used to describe the percentage of floor area that receives sufficient daylight during the operating hours. The space should receive at least 300 lux for at least 50% of the annual operating hours. Ranging from 0 to 100% of the floor area, the sDA values between 55% and 74% indicate that the daylighting in the space 'nominally accepted' by the user while the values above 75% is defined as 'preferred' (Lee et al., 2019).

On the other hand, the UDI is a metric that describes annual illuminance percentage in the working plane in the chosen space (Reinhart et al., 2006). Instead of a specific illumination level taken as a threshold in daylight evaluations, a range that is deemed useful by users is specified to evaluate indoor daylight performance. There are three illumination levels for the UDI which are 0-100 lux, 100-2000 lux and above 2000 lux. If the illuminance level is between 100-300 lux, it can be accepted as sufficient but artificial lighting may be needed. If the UDI is in the range of 300-3000 lux, it can be considered as desirable (Mardaljevic et al, 2012). Low (< 100 lux) and high (> 2000 lux) daylight illuminance levels may cause visual discomfort (Nabil & Mardaljevic, 2005).

5.2. Computational Performance Analysis

Covering a floor area of 180m^2, the size of the generic model is 12m (width) x 15m (depth) x 6.5m (height). It has been assumed that the southern façade of the model has glazing where the proposed façade systems have been applied. New components have been added in the parametric model for the analysis as shown in Figure 5.1. Grids of 0.6m have been created to be used for the measurements on the floor. The results obtained are the arithmetic mean of the calculations. The daylight analyses have been conducted based on the annual weather data of İzmir, Turkey.

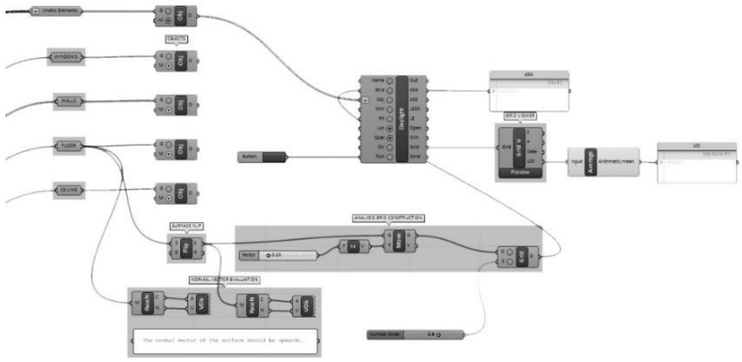


Figure 5.1. Grasshopper Definition of Sun Light Analysis

In order to compare the efficiencies of the proposed façade models, first of all, an analysis of the base model has been carried out without applying any responsive façade proposal. While the sDA value of the base model has been obtained as 99.6, the UDI value was calculated as 51.13% (Figure 5.2). Although the model has an acceptable sDA value, the percentage of the space receiving daylight remained at 51%. The main purpose is to increase the UDI value as much as possible without reducing the sDA value below 55%.

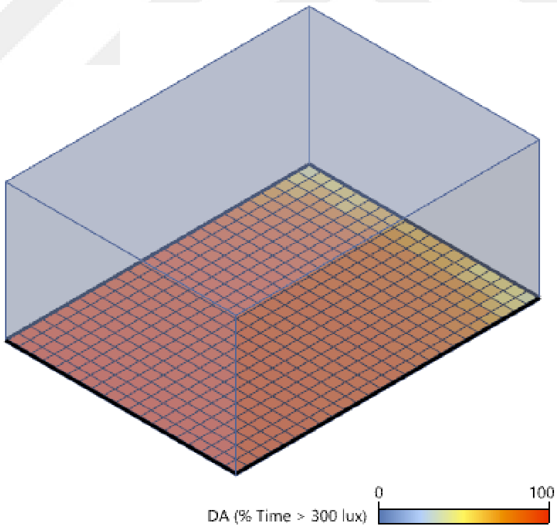


Figure 5.2. Simulation Visual of the Base Model

In the second stage, the proposed responsive façades have been applied to the base model. The façade systems have been tested at three different angles that are respectively 30^0, 45^0 and 60^0. Because. there are very few changes in the values obtained in the base model at the configuration of 90^0, it was not included. Since it can create completely dark spaces when closed, 0^0 configuration was not included as well.

In the first model based on the regular triangular tessellation (3.3.3.3.3.3), there are 16 half modules and 176 triangular modules that are used in 8 rows. The system has a total of 752 panels. These panels have been positioned at an angle of 30^0 to the plane of the façade to perform the analysis. As a result of the analysis, the sDA value has been found as 35.8% while the UDI remained at 45.19%. Since the obtained values are below the target values, the same system has been re-analyzed with 45^0 panel angles. The result showed that both sDA and UDI values have increased to 52.8% and 61.67%, respectively. When the panels remaining at 60^0 were analyzed, it has been found that the sDA value is 72.1% and the UDI value is 71.41% (Figures 5.3-5.5).

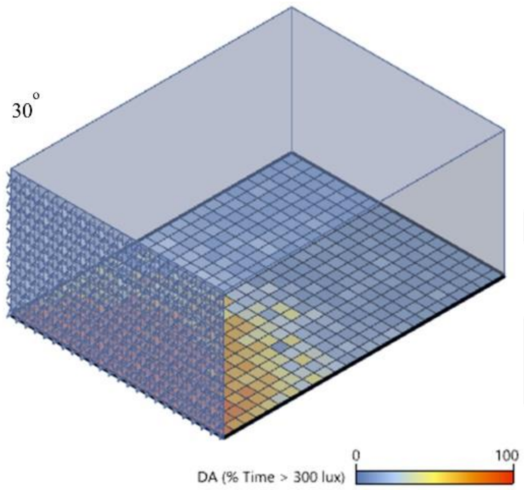


Figure 5.3. Simulation Result of the First Model (30 degree)

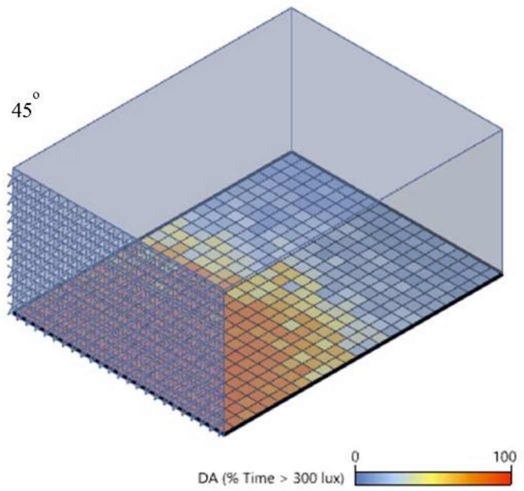


Figure 5.4. Simulation Result of the First Model (45 degree)

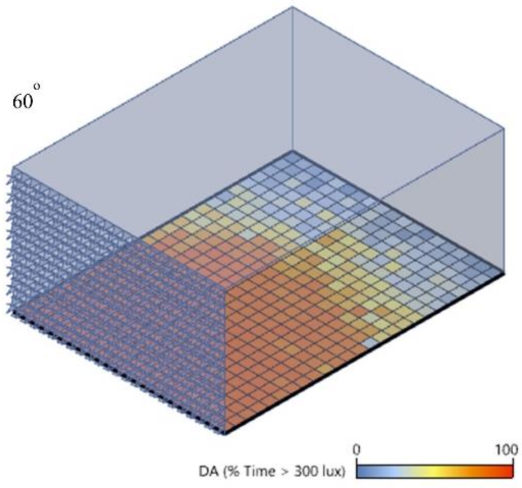


Figure 5.5. Simulation Result of the First Model (60 degree)

Having a semi-regular tessellation based on 3.6.3.6 pattern formed by hexagon and triangle, the second model has a total of 22 hexagonal modules and 66 triangular modules. In addition, 4 half hexagonal modules and 8 half triangular modules have been used for the gaps remaining at the edges. The façade system consists of 444 panels in total. As in the previous model, first an analysis has been carried out at an angle of 300. It has been found that the sDA value is 34.4% and the UDI value is 45.65%. To increase these values, new simulations have been performed with the configurations at 45^0 and 60^0. The results obtained from the analyses are respectively as follows: 54% for sDA and 61.97% for UDI at 45^0, and 72% for sDA and 70.62% for UDI (Figures 5.6-5.8).

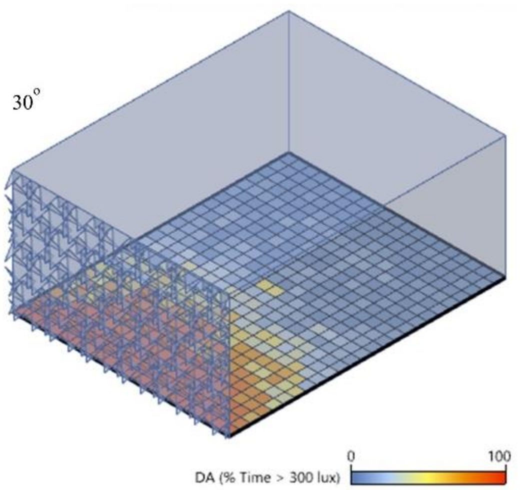


Figure 5.6. Simulation Result of the Second Model (30 degree)

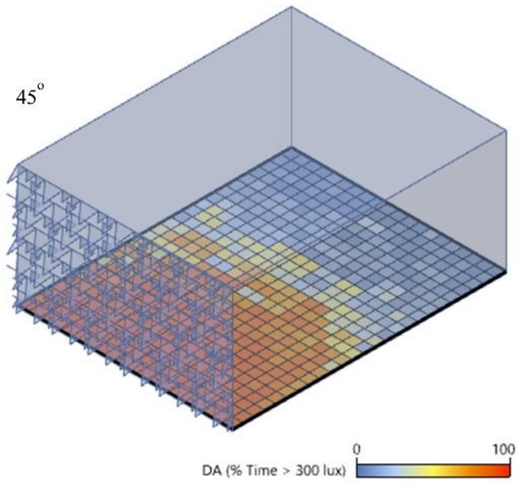


Figure 5.7. Simulation Result of the Second Model (45 degree)

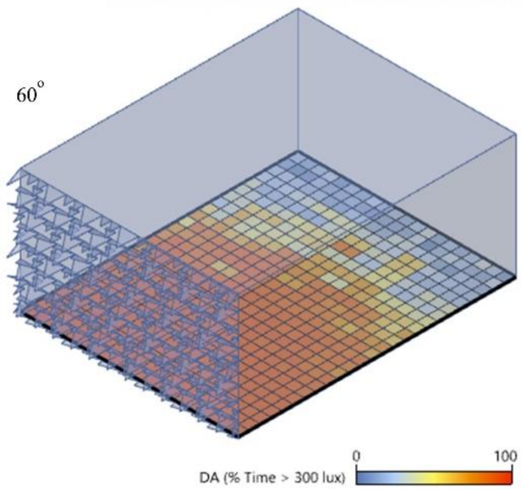


Figure 5.8. Simulation Result of the Second Model (60 degree)

Created based on demi-regular tessellation patterns, the remaining two models also consist of hexagonal and triangle modules. Containing 368 panels in total, the third model has a total of 24 hexagonal modules and 40 triangular modules. In addition, there are 16 half-triangular modules on the façade. In the case of remaining the panels at 30^0, the sDA value is 36.3% while the UDI value is 44.33%. However, they have increased at the configuration of 45^0. The values have been found as follows: 54.2% for sDA and 62.51% for UDI. Likewise, higher values have been obtained at the configuration of 60^0. The results are 74.0% for sDA value and 70.70% for UDI (Figures 5.9-5.11).

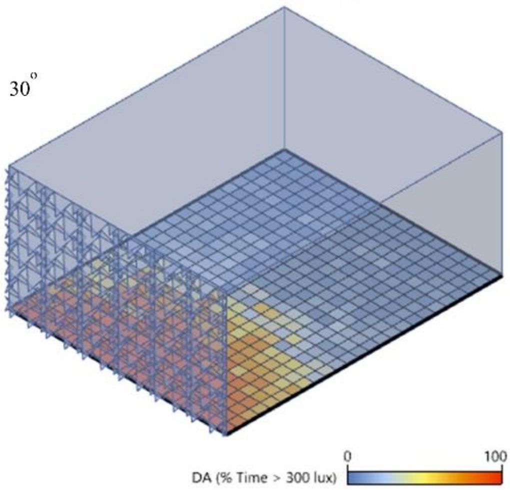


Figure 5.9. Simulation Result of the Third Model (30 degree)

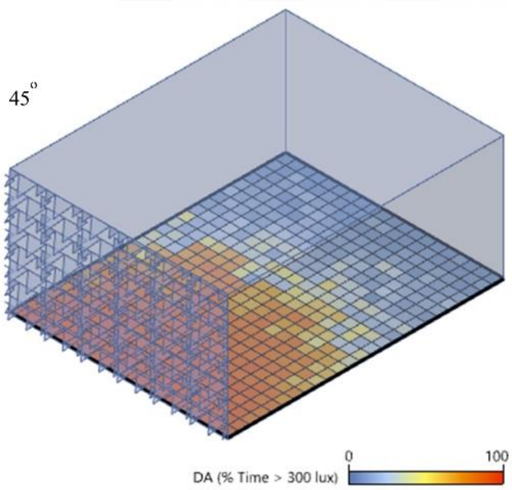


Figure 5.10. Simulation Result of the Third Model (45 degree)

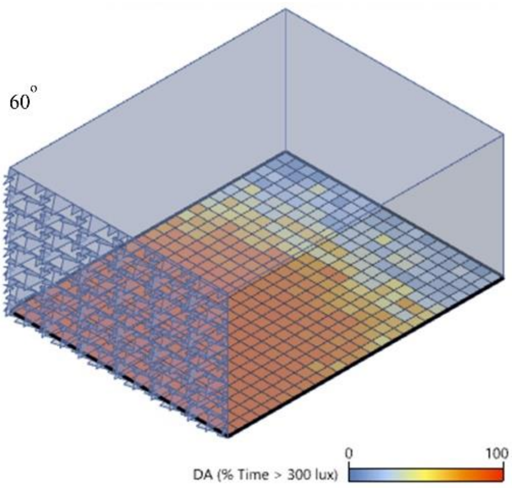


Figure 5.11. Simulation Result of the Third Model (60 degree)

The last model formed by 2 rows of triangular rows around the hexagons consists of 12 hexagonal modules, 120 triangular modules and 16 half-triangle modules. The façade system has 616 panels in total. The values obtained as a result of the first analysis tested with the panels at 30^0 are 34.2% for sDA and 44.24% for UDI. The simulation results of the second case with 45^0 panels shows that the values increase to 54.8% for sDA and 62.43 for UDI. In the last case of 60^0, the sDA and UDI values have been respectively found as 74.4% and 71.55% (Figures 5.12-5.14).

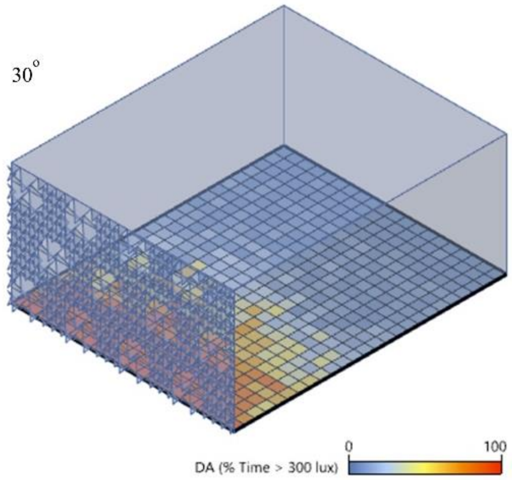


Figure 5.12. Simulation Result of the Fourth Model (30 degree)

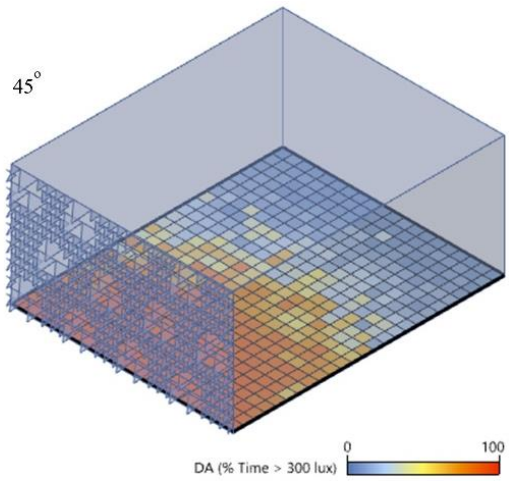


Figure 5.13. Simulation Result of the Fourth Model (45 degree)

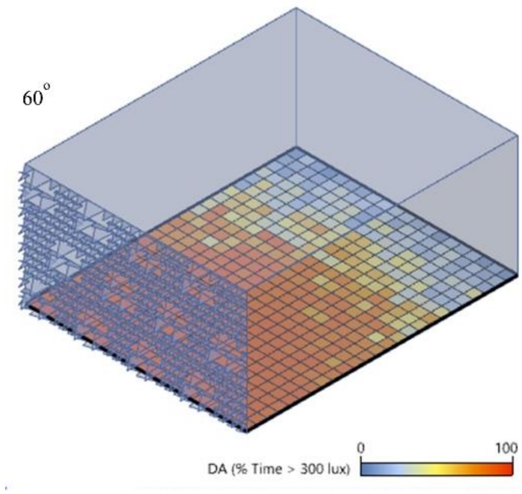


Figure 5.14. Simulation Result of the Fourth Model (60 degree)

5.3. Results

In this study, modular façade systems based on different tessellated patterns have been developed. These systems have been simulated to perform the daylight analyses according to the daylighting metrics. The results of the analyses carried out with the goal of increasing the UDI at optimum level without reducing the sDA value below 55% have been demonstrated in Table 5.1 to compare the cases.

Table 5. 1. Analysis Results

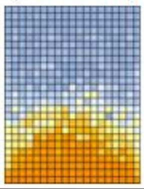
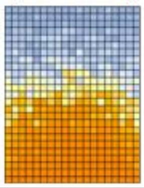
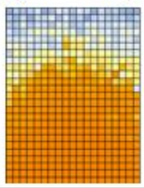
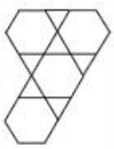
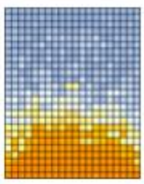
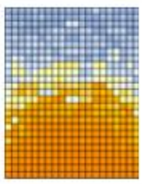
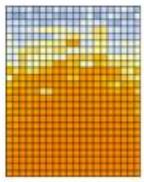
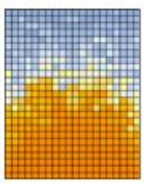
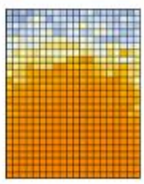
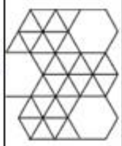
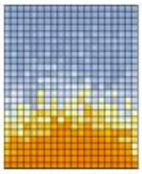
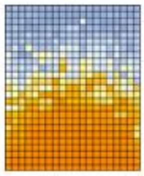
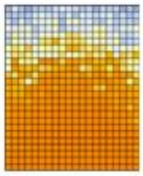
Cases	Pattern	Angle of the Panels	sDA Result	UDI Result	Analys Result (30 - Visual)	Analys Result (45 - Visual)	Analys Result (60 - Visual)
Model 1		30	35.8	45.19			
		45	52.8	61.67			
		60	72.1	71.41			
Model 2		30	34.4	45.65			
		45	54.0	61.97			
		60	72.0	70.62			
Model 3		30	36.3	44.33			
		45	54.2	62.51			
		60	74.0	70.70			

Table 5.1. (cont.)

Model 4		30	34.2	44.24			
		45	54.8	62.43			
		60	74.4	71.55			

Compared to the base model in which sDA and UDI values are respectively 99.6% and 51.13%, the proposed façade systems tested at different configurations demonstrate that the desired values have been found at the configuration of 450. However, the UDI value increasing at the desired level of sDA at 60^0 gave better results. The sDA values obtained at the configuration of 60^0 are respectively 72.1%, 72.0%, 74.0% and 74.4% while the UDI values are 71.41%, 70.62%, 70.70% and 71.55%. The panels can be fully closed according to the needs during the day or be opened when necessary.

This study contributes to the literature since the proposed façade systems based on tessellation improve the daylight performance compared to the conventional shading systems. It is clear that the proposed systems have positive effect on controlling the daylight, and 'preferable' conditions are obtained for the users. It is possible to apply the proposed systems to any facade in any location by changing only the direction of the modules in the system, because the proposed systems have a simple mechanism while most of the existing proposals in the literature have complex mechanisms.

CHAPTER 6
CONCLUSION

In this thesis, the development of a modular responsive facade system has been presented systematically. Within this context, the geometric design based on tessellation method, the parametric modeling built to generate different patterns, the mechanism used to obtain desired movements and the daylight analyses of four proposed façade patterns have been carried out. In this section, the achievements reached within the scope of the study and possible future studies have been presented.

6.1. Achievements

The main achievements of the study have been listed below.

- Based on the detailed review on the responsive facade systems, a systematic classification proposal using a simple classification matrix has been presented.
- The examples of the tessellation used throughout the history for different applications have been investigated not only to study its development process but also to explore its possible application to the building façade.
- The triangular and hexagonal tessellated patterns that have been used to design the responsive façade system provide form flexibility and meet the functional requirements as they move.
- The parametric models created for the simulations and climate-based daylight analyzes allows changing the design parameters according to the user preferences. They can be also used to increase the performance of the proposed façade system.
- Rather than using complex mechanical systems as in many responsive façade systems in the literature, simple façade systems have been proposed which have a simple mechanism and offer various geometric configurations. It can be applied to any facade in any location by simply changing its orientation.

6.2. Future Works

The studies that can be carried out in the future have been presented below.

- Since this study is limited to regular triangular and hexagonal tessellation patterns, other tessellations such as semi-regular and irregular patterns should be investigated.
- In this study, simulation programs have been used to evaluate the performance the façade system. However, the system movement should be tested by building a prototype.
- Although the proposed façade system reduces the need for artificial lighting and heating as well as increasing the efficiency of the use of daylight in the building, the energy consumed by the system should be also examined.
- The cost of the facade system can be investigated and new approaches can be developed to reduce its cost.

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