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Using KRF Structures As An Adaptive Facade And Evaluation of Daylight Performance Based on Geometry: A Case Study in Ankara

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ABSTRACT

Adaptive facades are widely used today because they are energy efficient and sustainable. It is expected that kinetic facades will become more common in the future and new geometries are constantly sought. Kinetic Reciprocal Frame (KRF) structures are also one of the innovative and sustainable approaches. In this study, KRF structures are used as adaptive facades and are analyzed in two stages. As a test model, a standard high-rise office building in Ankara, Turkey is created and simulations are made on the south facade. In the first stage, the modules' applicability in different geometries is examined and the differences within the geometries are revealed. KRF modules are examined for cost-effectiveness and mobility. In the second stage, analyzes are made on the daylight performance of the geometries. Modules are evaluated based on spatial daylight autonomy (sDA), annual sunlight exposure (ASE), and average lux. As a result, in terms of daylight performance, the hexagonal KRF module gives the best result by drawing the most homogeneous values due to its high mobility. However, it is noticed that the daylight performance of the triangle KRF module is weak compared to other modules, the ASE values cannot be controlled and it is more difficult to implement because it is not effective in terms of cost per module. The fact that hexagonal modules give good results in terms of cost is found to be good in support of it. This study is also valuable study in terms of the application performance of KRF structures on the facade.

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1. Introduction

Adaptive facades, also known as kinetic or active facades, are building facades that have the ability to change their functions, features, or behavior over time in response to transient performance requirements and boundary conditions, with the aim of improving the overall building performance (Loonen et al., 2015). They use automated systems such as sensors, actuators, and control systems to adjust the properties of the facade in response to external conditions, like solar radiation, temperature, and weather patterns. These adjustments can improve energy efficiency, natural lighting, and thermal comfort, and can also reduce the urban heat island effect. The goal of adaptive facades is to improve the energy efficiency and comfort of buildings, while also reducing the need for mechanical systems such as heating and cooling. Today, adaptive facades are widely used and will become more common in the future with the increasing climate and energy crises because buildings account for around 30 percent of the world's total energy consumption and a similar percentage of the world's greenhouse gas emissions as the main cause of climate change (Hong et al., 2007). As can be seen, the role of buildings in the energy crisis is enormous. One of the best ways to reduce energy consumption in buildings is to carefully design their facades.

A well-designed facade can help to improve the energy efficiency of a building, reduce its environmental impact, and improve the comfort of the building's occupants. Such as the use of sustainable materials such as locally sourced, renewable, or recycled materials help to reduce the environmental impact of the building over its life cycle. Incorporating adaptive facades, living walls or other vegetated elements on the facade can also help to improve the building's overall sustainability by reducing rainwater runoff, improving air quality, and providing a habitat for natural life.

This sustainable, environmentally friendly, and energy-efficient facade concept has been tried on static facades before kinetic facades. On static facades, Lim et al. (2012) measured the effect of sunshade systems on the space and compared the designs within themselves. Martokusumo et al. (2017) in addition to this study, algae panels are used, which is a sustainable approach, on the facade and measured its efficiency. Algae panels gave better results than vertical and sunshade static systems. Hachem & Elsayed (2016) investigated the energy production with photovoltaic panels by differentiating these folding movements and changing the repetitions in the number of modules.

Current literature research shows that there are experiments of environmentally friendly green facades on static facades, as well as studies that seek energy efficiency through geometric searches. As an example, Etman et al. (2013) made these sunshade elements with Mashrabiya geometries and analyzed their effect on space. Polat & İlerisoy (2020) examined the Voronoi geometry in terms of cost and symmetrical balance. Goharian et al. (2022) added thickness parameters to these facades and evaluated their effects on the space through solar radiance values. Rezakhani & Kim (2020) designed the Persian patterns, with a different geometric quest, as sunshades and made a concept study by experiencing them in virtual reality.

As can be seen, since the energy efficiency of buildings will gain more importance in the future, new geometries are constantly sought in facade designs, and in these geometries, kinetic systems come to the fore more than static systems. Thus, it has been revealed that kinetic facades are more economical in terms of energy consumption than fixed ones (Kim et al., 2015). In that case, adaptive facades are becoming increasingly popular in the design and construction of new buildings and are expected to play an important role in the future of sustainable architecture.

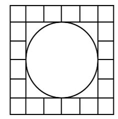
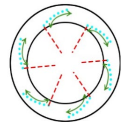
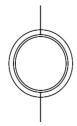
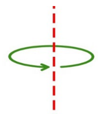
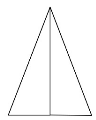
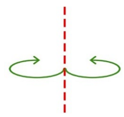
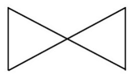
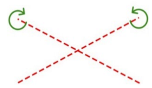
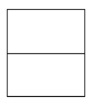
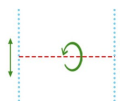
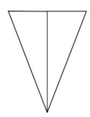
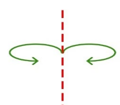
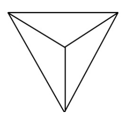
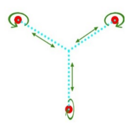
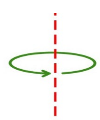
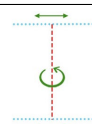
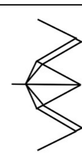
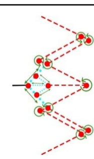
Each type of adaptive facade has its unique properties and functions and can be used in different ways to achieve specific goals. Fox & Kemp (2009) divided kinetic systems into three different categories. These are deployable, dynamic, and embedded systems. Embedded systems are systems that work permanently in a fixed place and maintain this position during operation. Deployable systems are systems that need a place temporarily and can be easily dismantled and transferred to another place after their mission. Dynamic systems are systems that can operate independently of the main architectural system. Kinetic facade systems belong to the embedded systems category among these systems.

There are different methods and movements in kinetic facade systems. Mahmoud & Elghazi (2016) classified the movements of kinetic facade systems as translation, rotation, and scaling as three basic movements. The movement of a facade, on the other hand, can include one of these movements, and it can also create complex movements with their combination. In that work, the author says that rolling motion is formed by the combination of translation and rotation movements. However, a basic movement can also become complicated on its own. For example, while the folding movement is a simple rotation movement, the rotational movement of SLE (Scissors Like Elements) will also bring about a translation movement, which in turn will create a scaling movement in a coating material attached to it.

Based on these basic movements, different adaptive facade designs have emerged. Mahmoud & Elghazi (2016) analyzed the illumination levels in the space by making a hexagonal facade module perform three basic movements, translation, rotating, and scaling. Associating the folding movement with origami, Lee & Leounis (2011) has revealed designs that differentiate these folding movements. Pesenti et al. (2015) and Elghazi & Mahmoud (2016) tried this origami-inspired design on the facade, and the daylight performance of this kinetic facade design is analyzed. Kim et al. (2015) compared a static facade design and a responsive kinetic facade design in terms of heating and cooling loads. The kinetic facade design controls the sun by opening and closing the panels according to the incidence angle of the sun vectors on the facade panels. Thus, it has been revealed that a building with a kinetic facade design is more sustainable and economical than a building with a static facade design. Studies on green facades are carried out on kinetic facades as well as on static facades. Globa et al. (2021) kinetic facades evaluated the concept of sustainability through green architecture. It has designed and prototyped a sustainable green facade module. The research aimed to grow plants in these modules and to benefit from solar energy in this way. These modules can rotate and make maximum use of sunlight.

The purpose and performance of adaptive facades consist of many parameters. With these parameters, adaptive facades can give different performances. Seyrek et al. (2021) revealed the parameters that make all kinetic facade designs energy efficient and evaluated the tools that analyze these parameters. The research classified the performance of the facades as daylight performance, thermal performance, acoustic performance, and resistance to decay. The performance of the facade is related to many parameters such as the location of the building, climatic conditions, and the purpose of use of the building. In Table 1, different kinetic facades are analyzed through building function, panel shape, kinetic module form, movement axis, material, movement type, facade function, and scale of kinetic module parameters. Although the facade function and building function are similar to each other, it is seen that there are new searches and tries in the geometry of the panels and the types of movements.

Table 1 Adaptive Facades and Analysis of Parameters

	Building Function	Panel Shape	Kinetic Module Form	Movement Axis	Kinetic Module Material	Movement Type	Façade Function	Scale of Kinetic Module
Instştude du Monde Arabe (IMA, 2016)	Office and museum	Rectangular, Circular			Stainless Steel	Aperture	Daylight Performance	Full-Storey High
RMIT Design Hub (RMIT Design Hub, 2013)	Research and post graduate education	Circular			Steel, Glass	Pivot	Enery Production	Multiple Number within Full-Storey High
ThysesenKrupp Quarter Essen Q1 Building (Q1, ThyssenKrupp Quarter Essen / JSWD Architekten + Chaix & Morel et Associés, 2013)	Office	Triangular			Stainless Steel	Folding	Daylight Performance	Full-Storey High
DOHA Tower (Karakuş, 2016)	Office	Butterfly			Alüminium	Retracting	Aesthetic	Multiple Number within Full-Storey High
Kiefer Showroom (Kiefer Technic Showroom / Ernst Giselbrecht + Partner, 2010)	Office and Showroom	Rectangular			EIFS Panels	Folding, Sliding	Energy Effiency	Half-Storey High
South Denmark University Campus (University of Southern Denmark – Campus Kolding, 2022)	University	Triangular			Perforated Steel	Folding	Daylight Performance	Full-Storey High
Al Bahar Towers (Attia, 2017)	Office	Triangular			PTFE Panels	Folding	Daylight Performance	Multiple Number within Full-Storey High
India Expo 2020 Pavilion (Nagesh, 2022)	Pavilion	Rectangular			Rycled Industrial Aluminium	Pivot	Daylight Performans and Digital Show	Multiple Number within Full-Storey High
Apple Dubai Mall (Apple Dubai Mall/Foster+Partners, 2017)	Shopping Center	Rectangular			Lightweight Carbon Fibre	Folding, Sliding	Daylight Performance	Multiple Storey High
CJ R&D Center (Krymsky, 2011)	Research and Development Center	Triangular			Steel and Fabric Membrane	Folding	Daylight Performance	Half-Storey High

It is seen in the literature review that different movements and new geometry searches for different purposes in adaptable facades attract attention. KRF structures stand out with their potential at this point. It both contains new geometries within itself and has a different movement system. However, there are no reciprocal frame (RF) or kinetic reciprocal frame (KRF) structures in these kinetic facade systems. In addition, research on the architectural application of KRF structures is scarce and its application is very difficult. With the application of these KRF geometries as a facade system, a new solution will be found and these solutions need to be evaluated. This study aims to introduce KRF modules and evaluate their geometry and daylight performance by applying them on a facade. Therefore, it differs from other studies in that it discusses, researches and evaluates the applicability of KRF structures.

1.2 KRF Structures

Reciprocal frame structures are a type of structure that is made up of a combination of diagonal and vertical members that work together to provide strength and stability. Bavbrel & Olivier (2000) named each module that makes up this system a 'fan' and defined each element that makes up the fans as a 'nexor'. The book mathematically revealed the relationship between the elements of RF structures with each other. Asefi & Bahremandi-Tolou (2019), explained the process from the production to the use of these systems. The study is about the fabrication process, shared the connection details, and did a static analysis of several existing designs. Then determined which elements in this system had more stress.

Many static projects with Reciprocal Frame (RF) structures have been designed and studied without using columns such as sunshade pavilions, and circular houses (Pugnale & Sassone 2014; Popovic Larsen 2014; Chilton 2010). However, although these systems have kinetic potential in themselves, the number of studies on their applications is very limited or briefly mentioned at the end of the studies. RF structures, typically comprising interconnected elements that can move, change shape, and gain volume by rising in the z-axis, are constructed using a series of reciprocal bars or tubes, enabling a high degree of flexibility and movement. Such systems are called Kinetic Reciprocal Frame (KRF) structures.

KRF structures have low construction and maintenance costs as they can be used with sustainable materials, have high buckling resistance, replace damaged elements, offer design freedom as they can be produced with digital fabrication tools, and are lightweight Asefi & Bahremandi-Tolou (2019). In addition, since the system is integrally interconnected, even in complex designs, a small number of actuators can move the whole system. This reduces the energy consumption cost and construction cost of the system. Therefore, KRF structures can become an ideal solution for sustainable kinetic facade systems.

Chilton & Choo (1995) mentions a retractable roof design with the rotational motion of a roof formed with RF structures. This describes a design of KRF structures. These and many similar examples of KRF design remained at the conceptual stage and could not be elaborated. Nazarzadeh & Asefi (2022) discusses the movement mechanism of KRF structures in more detail and diversified and complicated the designs. By changing the support points of these designs, different types of movements have been achieved. It aims to increase structural performance by evaluating the movement mechanism.

The kinematic analysis of KRF structures is highly mathematical. A few input data determine all the remaining data. When the number of sides, element length, and thickness of the polygon are entered, many data such as the amount of elevation and the amount of translation at the joints are generated. Figure 1 shows the areas created by the KRF module moving. Data B describes the area of the polygonum, and data A describes the area created by the fans themselves. A=0 when the module is fully closed and A=B when it is fully opened. In order to make all these calculations easy, the fan thickness is assumed to be zero, but in a real model, the element thickness cannot be zero. That's why it is made by producing an algorithm for calculations.

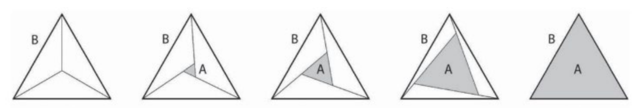
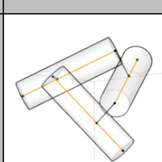
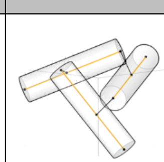
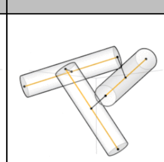
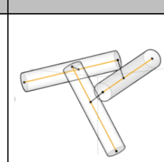
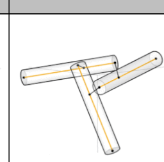
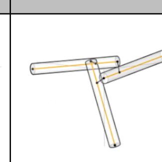
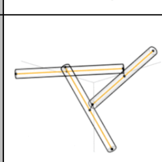
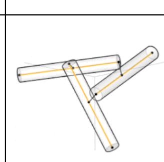
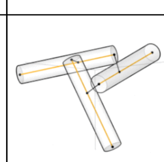
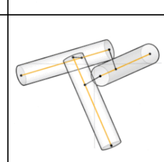
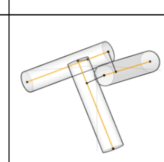
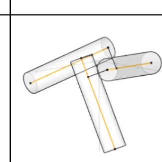
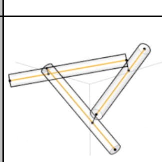
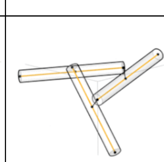
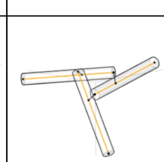
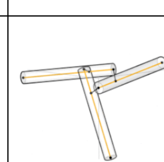
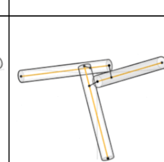
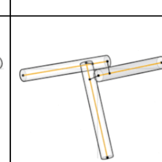


Figure 1 Openness and Closure Rates Created by the KRF mechanism (Nazarzadeh & Asefi, 2022)

Table 2 Movement Types of KRF Modules, (Vestartas & Petras, 2023) algorith is used to examine the action potential of reciprocal systems. Images are produced with this algorithm. For KRF modules new algorithm are produced.

	0.0	0.2	0.4	0.6	0.8	1.0
Moving Joints / Variable Thickness						
Fixed Joints/ Variable Thickness						
Moving Joints/ Fixed Thickness						

In order to make the application, calculations, and simulations correct, many algorithms are created by analyzing the KRF movements. Three movements can be made so that the ends of the elements can stay exactly on each other. These movements, as seen in Table 2, are divided into 6 different stages, as open 0.0 and closed 1.0, and examined. In the first part, the thickness of the elements should increase as the joints move. Otherwise, the system cannot be installed because there will be gaps between the fans. When the joints are fixed, the thickness of the elements must increase again in order for the ends of the fans to stay on each other. Else ways, the element length will be insufficient for closing and opening movement and the system will not be constructed. However, it is difficult to use an element with varying thicknesses in systems. When the fan thickness is kept constant, the joints must move to ensure that the ends of the fans stay on each other. Otherwise, the fans have to overflow over each other.

The fact that the joints move and the thickness and length of the fans change makes the applicability of these modules very difficult. Therefore, it is necessary to create a module where both the joints remain constant and the thickness and length of the fans do not change. In Figure 2, there are the stages of formation of a KRF module created using curvilinear fans instead of using flat fans. In this design, movement is made possible without changing the corners, element lengths, and thicknesses. Fans take a form in the curvature of the route drawn by the rotation movement from a corner point to the center point. Thus, a fourth type of movement is made possible.

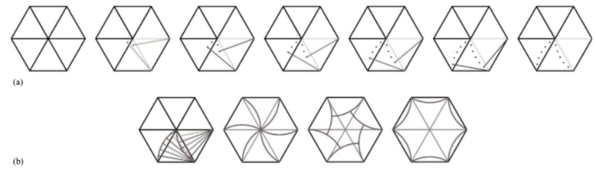
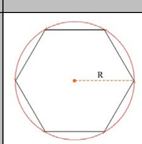
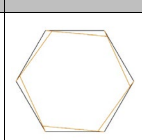
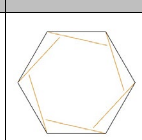
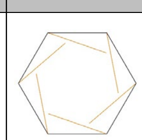
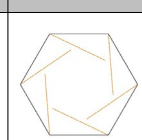
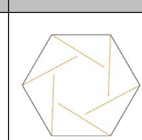
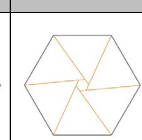
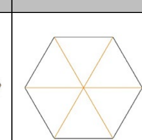
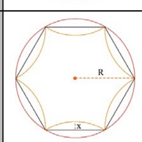
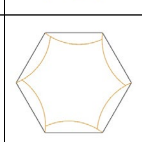
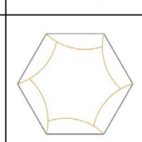
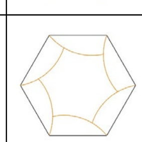
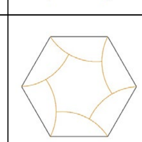
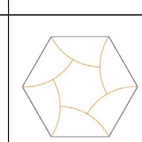
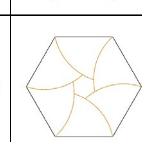
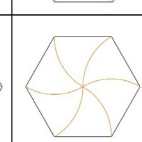
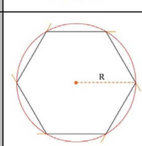
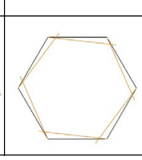
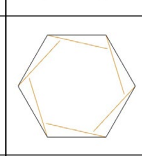
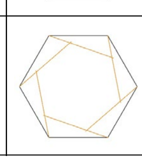
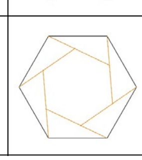
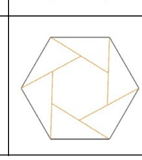
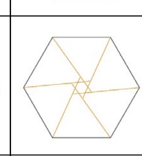
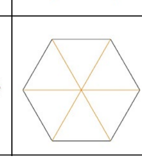


Figure 2 KRF Module with Curved Elements (Nazarzadeh & Asefi, 2022)

In Table 3, three different alternatives of the fourth movement type are compared from different angles and evaluated among each other. Since the radius of polygons is considered to be 2 meters, the length of a hexagon side is 2 meters. When curvilinear fans suitable for this geometry are used, one edge length increases to 2.1 meters. Module 1 is a KRF module with the same edge length but with flat elements. With this module type, the fans can move over each other at 0° to 5.4°, the system cannot be established between 5.4° and 54°, and the system can move again by overflowing over each other fans between 54° and 60°. As can be seen, the mobility of this module system is very limited.

Module 2 is an optimum module in which the fan length can be kept at a minimum level without overflowing with curvilinear fans. The mobility of this module is quite high and easy to be applied. Module 3 is a module formed with flat fans and has high mobility. However, in this module, the system closes properly only at 32°, and at all other angles, the fans overlap each other. While the element length is 2.1 m in the curvilinear module, it increases to 2.3 meters in this module. As the geometries change, the lengths of these elements increase, and the thickness of the fans in the real modulus will also affect the movement and may cause problems in the case of full closing and opening.

Table 2 Difference of Modules Created with Flat Elements and Curved Elements

	0° Rotated	5,4° Rotated	12,8° Rotated	19,2° Rotated	25,6° Rotated	32° Rotated	54° Rotated	60° Rotated	Module Info
Module 1									R = 2 meters Elements Length = 2.1 meters
Module 2									R = 2 meters Elements Length = 2.1 meters x = 0.28 m
Module 3									R = 2 meters Elements Length = 2.3 meters

2. Methodology

As seen in Figure 3, this study is analyzed in two stages. In the first stage, a geometric analysis of the KRF modules is performed. Using the Rhinoceros 3D/Grasshopper program, which is a parametric design tool, the algorithm of the kinematics of the KRF module is created, and then modules with different geometries are derived with this algorithm. Then these geometries are analyzed over cost, mobility, and geometry parameters. In the second stage, the daylight performance of KRF modules produced in different

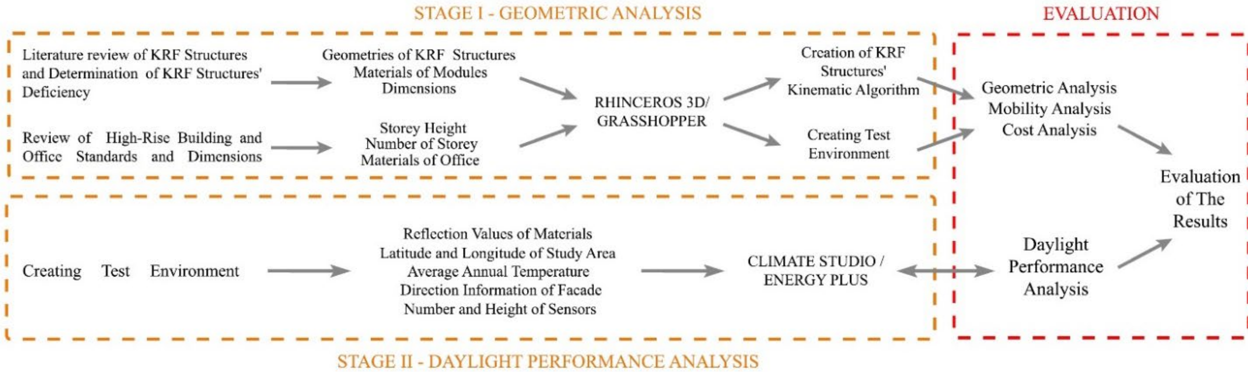


Figure 3 Workflow Chart

geometries is analyzed. For this evaluation, the south facade of a high-rise office building is selected as the test environment in Ankara, Turkey. Climate Studio, a fast and accurate simulation plugin created on EnergyPlus, is used for this analysis. With the results obtained here, the effect of KRF modules on the space is examined over spatial daylight autonomy (sDA), annual sunlight exposure (ASE), and average lux (avg. lux). Finally, by evaluating all these results together, it is aimed to find the most optimum one among the KRF modules in terms of use on the facade.

2.1 Case Study

The fans in the KRF modules are connected to each other with a single freedom sliding joint, allowing the fans to move over each other. Since one of the fans moving will move the other fans, the number of actuators required for the system has not changed from geometry to geometry, so it is not accounted for in the analysis. To define the open and closed surfaces on the module, a flexible fabric is attached to the gaps between the fans. Thus, the fans can change the open and closed surface ratios by stretching or relaxing the fabric while moving. The fact that the open and closed surface ratios can be controlled with the fan movements means that the modules can have control over the daylight.

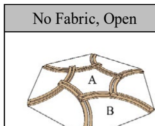
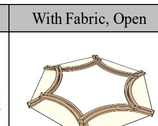
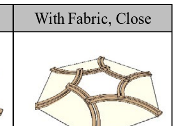
As the geometries of the modules change, many parameters such as fans lengths, areas of fabrics, sliding joints' lengths, mobility in unit rotation angle, closed area per angle, facade tesselation, and amount of elevation also change. It will not be fair and accurate to compare KRF modules with different geometries with these parameters. Therefore, an open and closed state will be defined for the modules over the ratios of their open and closed surfaces, and the stages between those definitions will be evaluated. The region marked with "A" in Table 4 and the area in the center of the modules represents the open area. "B" represents the entire area of the polygon in which the module is formed. In short, closed areas can be expressed as B-A. In other words, each module will act according to the size of its geometry and the evaluation will be made with these parameters.

The movement limit for all modules is set to 5A=B. In other words, the modules will continue to close until the open surface area is one-fifth of the entire polygon area. This ratio is determined by the fact that the light is not desired to be completely blocked, visual permeability, and the limited mobility of the octagonal module.

Table 5 shows all open and closed stages of the KRF facade modules in triangular, rectangular, pentagonal, hexagonal, and octagonal geometries. Since the story height is 4 meters for a standard office building, the diameter determined for the polygons is 4 meters. Each module is one story high. 20 cm wide and 5 cm thick wooden elements are preferred for the fans that make up the modules. A circular construction is created from pipe profiles with a diameter of 10 cm to carry the KRF modules. Since all polygons are derived from this circle, they can be supported in the construction regardless of the geometries.

The curvatures of the KRF modules are such that the fans that can form the module have the shortest length. As the number of elements of the KRF modules increases, the curvature of the fans increases, but the length of the fans decreases. This curvature value is constant for each geometry and depends on the diameter of the polygon, the thickness of the fans, and the amount of rise. However, no matter how short the curvatures are, all modules except the hexagonal module seem to overhang each other at least once during the opening and closing phases. While this curvature works perfectly in the hexagonal module, it becomes a limiting factor in polygons with more sides. The octagonal module at stage 1.0 in Table 5 cannot pass the ratio 5A=B. This is because the system locks itself at that stage and wants to get out of the sliding joint.

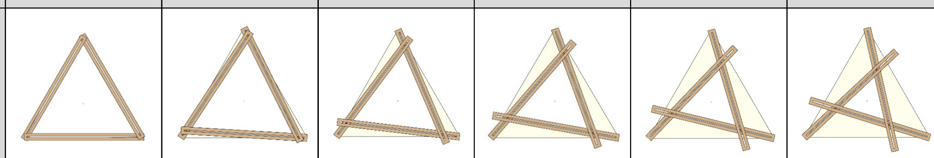
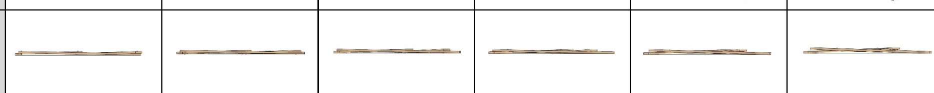
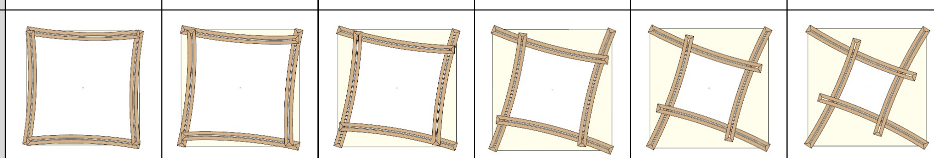
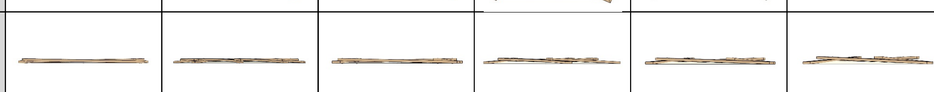
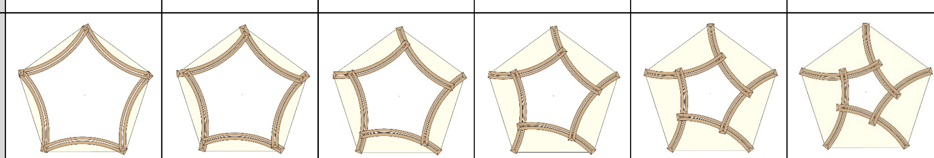
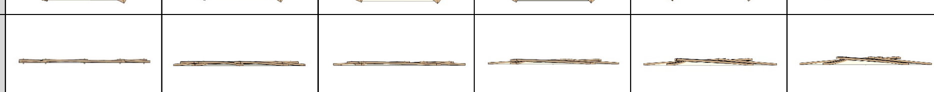
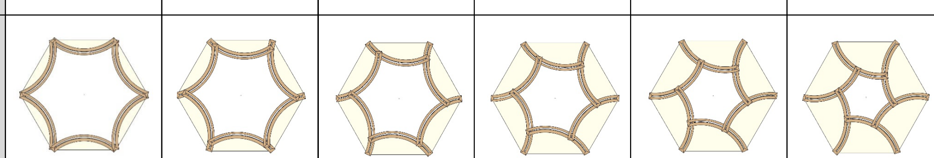
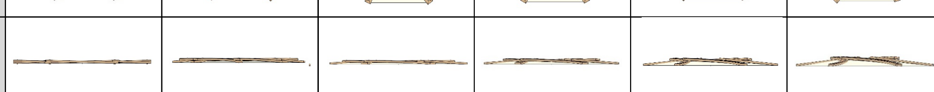
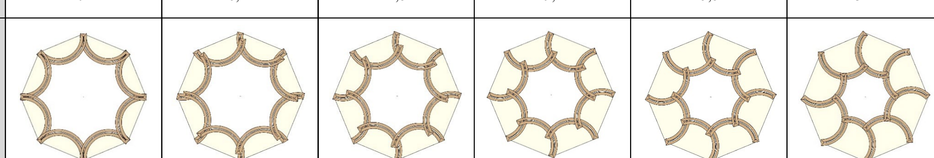
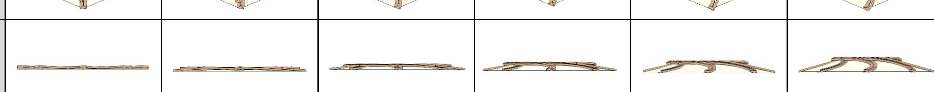
Table 3 KRF Modules' Open and Closed Stages

No Fabric, Open	With Fabric, Open	No Fabric, Close	With Fabric, Close
 A B			

While all parameters are constant, it is observed that as the number of sides of the polygons increases, the amount of elevation increases. While there is not much difference in elevation between the triangular module and the rectangular module, the rising rate increases greatly after the pentagon module. In addition, as the number of edges increases, the angles that the modules have to close, that is, the distance that the fans have to move increases. While the angle of rotation required to achieve the 5A=B ratio is

17.1° for the triangular KRF module, it increased approximately 2 times to 32° for the hexagonal module. The closed area per angle value describes how much the unit angle change affects the amount of modulus closure. Since many parameters such as the curvilinearity of the geometries and the volume gained in the third dimension affect this value, these values do not seem to be proportional to the number of sides of the polygons. Closed area per angle data is an average value since it is the total amount of closed area divided by the angle. The amount of increase in closed areas with changing angles is not homogeneous and varies from geometry to geometry

Table 4 KRF Module Geometries and Opening and Closing Stages

		0.0	0.2	0.4	0.6	0.8	1.0	Module Info
Triangle	Top View							Elements Length 3.46 m
	Side View							Amount of Rise 0.10 m - 0.16 m
	Rotation Angle	0°	3,4°	6,8°	10,2°	13,7°	17,1°	Closed Area Per Angle ~0,24 m²
Rectangle	Top View							Elements Length 2.84 m
	Side View							Amount of Rise 0.10 m - 0.17 m
	Rotation Angle	0°	4,9°	9,8°	14,2°	19,1°	24,5°	Closed Area Per Angle ~0,26 m²
Pentagon	Top View							Elements Length 2.45 m
	Side View							Amount of Rise 0.10 m - 0.24 m
	Rotation Angle	0°	5,5°	11°	16,4°	22°	27,4°	Closed Area Per Angle ~0,28 m²
Hexagon	Top View							Elements Length 2.19 m
	Side View							Amount of Rise 0.10 m - 0.27 m
	Rotation Angle	0°	6,4°	12,8°	19,2°	25,8°	32°	Closed Area Per Angle ~0,26 m²
Octagon	Top View							Elements Length 2.05 m
	Side View							Amount of Rise 0.10 m - 0.44 m
	Rotation Angle	0°	8,8°	17,6°	26,4°	35,2°	44°	Closed Area Per Angle ~0,2 m²

2.2 *Performance Parameters*

2.2.1 Study Area

Ankara, Turkey is a city where tall buildings are increasing in number and large glass facades appear without any control. The region is located at 39.925533 latitudes and 32.866287 longitudes. The location where the study is done is important because it affects the angle of incidence of the sun's rays, but parameters such as the direction of the facade and the height of the building or materials will not change the result since the evaluation is made between the modules themselves. In such harsh climates, energy consumption is higher and climate control becomes more important. The mobility of such facade designs makes them applicable on all facades. Table 6 shows the data obtained from the TMYx dataset for the region. TMYx dataset is data generated using the ISD (US NOAA's Integrated Surface Database) using the TMY/ISO 15927-4:2005 methodologies (Lawrie & Crawley, 2023).

Table 5 Study Area Climate Data (TMYx dataset)

Study Area Climate Data
Koeppen climate Zone: Temperate, Dry Warm Summer (Csb)
ASHRAE climate zone: Mixed (4)
Average annual temperature: 13 °C
Annual total solar radiation: 1,733 kWh/m2
Annual HDD for 18 °C is: 2,332
Annual CDD for 10 °C is: 2,052

2.2.2 Parametric Office Model

A standard high office building is preferred for the study. According to the Tall Building Council (CTBUH), a building with 14 floors or more than 50 meters is typically considered a tall structure. Since the floor height of an average office is 4 meters, the modules are designed with a diameter of 4 meters, and the dimensions are preferred as 4 and its multiples in order for the modulation to be smooth.

As seen in Figure 4 dimensions of the office space are 28 meters wide, 16 meters deep, and 4 meters high. The building has 15 floors and is 60 meters high. Only the south facade of the building is chosen as a glass facade, and the other facades are designed as closed. Although the facade designs change, the space dimensions remain the same. Thus, it is aimed to analyze the effect of facade designs on the space more clearly.

As for material preferences, it is aimed to choose standard materials that can be used in every office. Grey carpet material with 7,11% reflectance value is used for the floor, grey plaster material with 21,74% reflectance value is used for the wall material, IES LM-83 illuminated ceiling lm83 material with 70,00% reflectance value is used for the ceiling. The glass material is double-layered (from outside to inside, Solarban 70XL on Atlantica 6 mm, Krypton-EN673 12,7 mm, Clear Float Glass Clear 5.8mm) and has a U-value of 1,22 W/m².K, SHGC of 0,224. Galvanized steel with a value of 22.13% is used for the circular construction to be installed in front of the facade and to carry the panels. For the KRF modules, wood oak material, which is a sustainable material and has a reflectance value of 32.86%, is preferred. The membrane covering the modules is a white fabric material with 83.37% reflectance values.

2.2.3 Daylighting Simulations

For Daylighting simulations, LEED v4 design has been used as the standard and evaluations have been made according to these standards. According to IECC 2021 standards, the illuminance levels of office space should be between 300-500 lux. Evaluations are made by accepting 10 times these values as the limit so climate Studio parameters are set to measure between 500 lux and 5000 lux. Spatial daylight autonomy (sDA), annual sun exposure (ASE), and average lux (Avg. Lux) values are accepted as daylight performance measurement parameters.
Measurements are made on the first floor, eighth floor, and fifteenth floors (Figure 5). Sensors are placed on the floors decently 2 meters apart. A total of 135 sensors are used on every three floors. Annual measurements are made on these three floors while each module is at a different stage, and it is aimed to compare the performance of the facades by taking the average of these values. The office building is a closed system in itself with its glass facade. In these measurements, the KRF facade design plays the role of a parametric shading element. Since the construction required to carry KRF facade modules will change these values, the measurements are made without construction, with construction, and with facade modules.

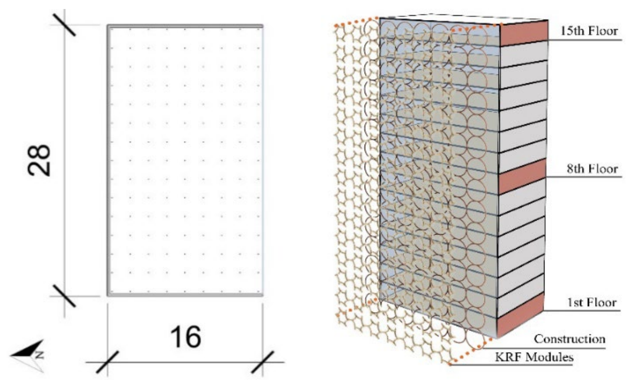


Figure 4 Sensor Placement on Test Model

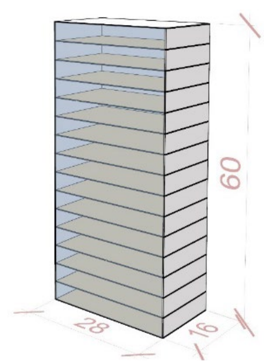


Figure 5 Test Model

3. Results

3.1 *Stage I - Geometric Analysis*

When the geometries of KRF modules change, their properties also change. As mentioned in the Case Study section, as the number of edges of the geometries increases, the modules get higher, and the shortening of the fans and their curvature increase. From the triangle to the hexagonal module, the mobility increases and improves, and after the hexagon, the mobility is restricted.

In Table 7, the costs of the facades created with different KRF modules have been analyzed and the construction cost has been ignored because the necessary sizes must be calculated with a static calculation. Current ministry unit price positions are used for the calculations, and the average of the values taken from several manufacturers is accepted for the data not included in these positions. Here, it reveals the relationship of the actual targeted prices with the geometries, independent of the original value.

Table 6 Cost Analysis of KRF Modules in Turkish Lira (TL)

	Waterproof Flexible White Fabric (200 ₺ for m²)	First Class Wood Elements	Metal Rail Joints (100 ₺ for metres)	Cost Per Module (₺)	Total Façade Cost (₺)
Triangle	834	888,8	1039,23	2762,03	290013,15
Rectangle	1296	969,21	1135,13	3400,34	357035,7
Pentagon	1640	1035,16	1222,69	3897,85	409274,25
Hexagon	1728	1088,63	1312,37	4129	433545
Octagon	1904	1371,78	1636,36	4912,14	515774,7

The cost analysis shows that the cost per fabric used for modules increases for triangular, quadrilateral, and pentagonal modules while it decreases for hexagonal and octagonal modules. This is related to the volume that the modules gain in the third dimension and the form that the fabric gains in line with this volume. The cost per wood used for modules decreases as the number of sides of the geometries increases. Therefore, the same can be said for the sliding joints (rail) installed on the fans. In terms of the total cost, the cost increases as the number of sides of the polygon increases. While the total cost of the facade for the triangular module is 290013 TL, the cost of the hexagonal module with twice as many elements did not double and cost 433545 TL.

Figure 6 shows the facade tessellations of the KRF modules. Although all geometries are derived from a circle, facade tessellations may not be smooth. When the modules are analyzed, the smoothest facade tessellation occurs in rectangular and octagonal modules. Since the joints do not touch each other in triangular, hexagonal, and pentagonal modules, irregular geometries appear in the gaps between the modules.

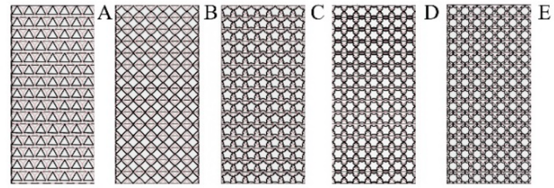


Figure 6 Facade Tessellations Triangle (A), Rectangle (B), Pentagon (C), Hexagon (D) and Octagon (E)

3.2 *Stage II - Daylight Performance Analysis*

The bare state of the facade is analyzed and then the one with the construction added is analyzed (Figure 7). In this way, by understanding the effect of the construction, clearer results are obtained regarding the effect of the KRF modules. The average lux value in figure 8A is 3098 lux, ASE is 33.3% and sDA is 84.9%. In figure 8B, the average lux value is 2617 lux, ASE is 33.3% and sDA is 76,8%. The added construction would not change the ASE value at all, it only slightly reduced the "over-lit" areas.

The values obtained as a result of the simulations are given graphically in Figure 8. In general, the triangular module and the pentagonal module draw very unstable graphs, while the other modules draw more balanced graphs. Whereas the triangular module does not show a significant change in the sDA and ASE values, the pentagonal module shows a significant but unbalanced change and the hexagonal module shows a similar change in a more balanced way.

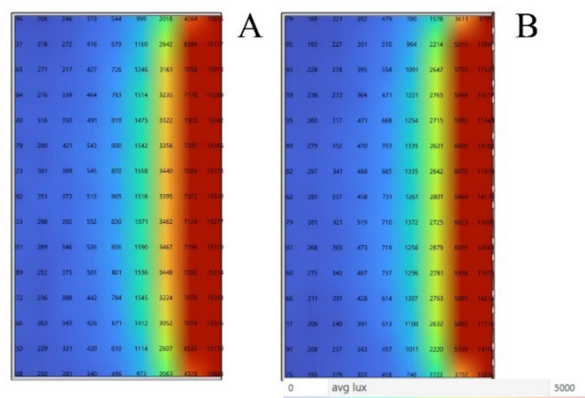


Figure 7 Average Lux Results Without Construction (A) and With Construction (B)

In Table 8, annual average lux values of six different phases between open and closed states of KRF modules with different geometries are given. Values are examined between 0 and 5000 lux, and values above 5000 lux are accepted as "over-lit" areas. As the values

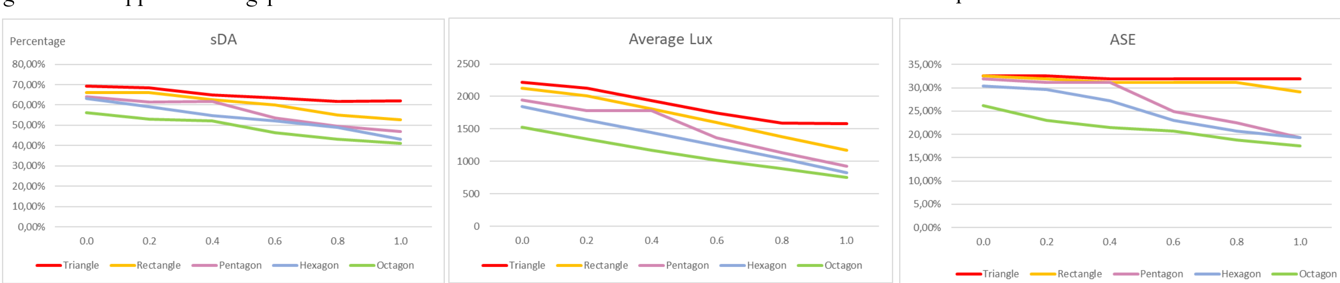


Figure 8 Spatial Daylight Autonomy (sDA), Average Lux (Avg Lux) and Annual Sunlight Exposure (ASE) Graphs by KRF Modules' Stages

approach 5000, the weight of the red color increases. The analysis of average values does not aim to measure whether the facade provides the necessary lighting for the office space but to analyze how much different geometries can control daylight. The 16-meter-deep office room is about 4 meters "over-lit" due to the light from the south facade. The triangular module is able to reduce this distance to about 3 meters when fully closed. All other modules are able to reduce the avg. lux value to below 5000 at stage 1.0 and provide the user comfort specified by the standards.

4. Evaluation Results

Without adding any facade to the design, all values are quite high and are far outside the comfort zone. The construction added before the KRF modules slightly change the values. While the ASE value is 33,3% and sDA is 84,9%, it is seen that the circular module construction designed to carry KRF modules does not change the ASE value, only reduces the sDA value by 8,1%. In other words, the areas that daylight can reach in the office space have decreased, but while doing this, their average lux value has decreased by 481 lux. Although these values seem to comply with IECC 2021 standards because the selected office building is very large, one-third of the space is outside the standards. It is understood from

Table 7 Daylight Analysis For KRF Modules

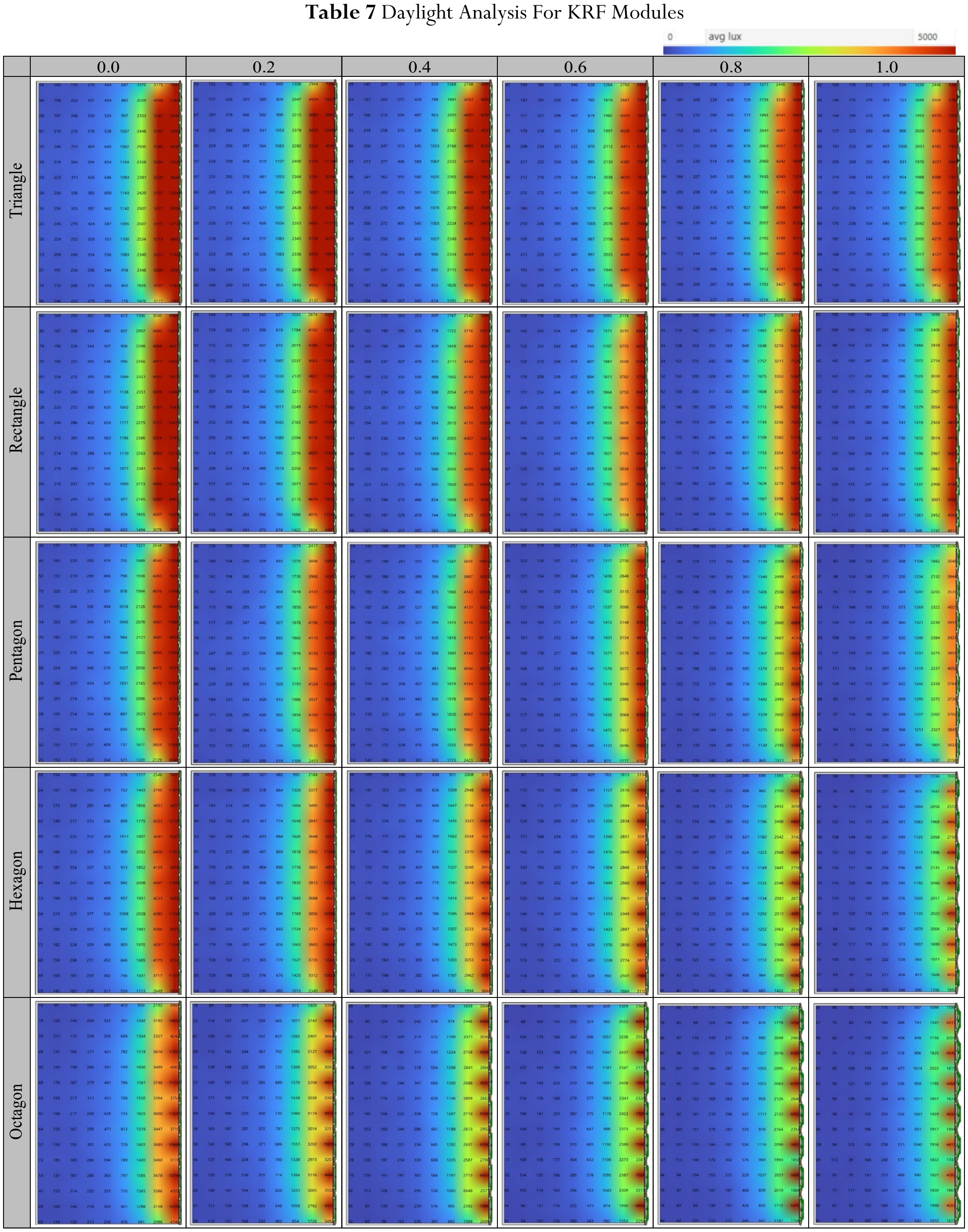


Table 8 that all KRF facade modules are effective in improving the visual environment and user comfort. Since the azimuth angle changes throughout the year, the facades need to gain volume in the third dimension to gain different angles for the control of these values. As seen in the values of the triangular KRF modules in Figure 7 it is seen that the greatest control is between the states of 0.2 and 0.8, and there is almost no difference between the stages of 0.8 and 1.0. It seems that there is almost no change in the ASE values. This shows that the triangular modules cannot provide sufficient solar control because they do not gain enough volume in the third dimension.

In rectangular modules, a homogeneous decrease is observed in the average lux value in direct proportion to the progress of the stages. However, despite this homogeneous decrease in lux value, a significant change in ASE values is seen only between 0.8 and 1.0 stages. The sDA values increased at the 0.2 stage and managed to stay above 60% until the 0.6 stage. Although rectangular modules provide better tessellation than triangular modules, there is almost no difference in the volume they gain in the third dimension. This explains the similarity of their graphics. Pentagonal KRF modules, on the other hand, can rise up to 14 cm from their existing height gain approximately 2 times more volume than triangular and rectangular modules. The most striking part of this module type is 0.4 to 0.6 phase. At this stage of transition, the ASE value decreased by 6,2% and the sDA value decreased by 8,1%. In the next stages, the values continue to decrease. As can be understood from here, the most effective form of pentagon modules is between 0.6 and 1.0 stages.

Hexagonal KRF modules draw homogeneous graphs at all values. Only 5.9% reduction is experienced in sDA value during the transition from 0.8 stage to 1.0 stage, the module closed itself and prevented the passage of sunlight to a large extent. The homogeneous decrease in all these values shows that the rising value and the ratio of open surface and closed surface are balanced, and this module type is ideal for climate control. When looking at the octagonal module in Figure 8, the octagonal module shows that the average lux value still draws a homogeneous graph, the sDA graph is irregular, and the ASE value does not change much after the 0.2 stage. In addition, in Table 8, it is seen that the system is good at blocking light, but it will have difficulties in getting light in winter months, which will create an increase in heating and cooling loads. It is seen that the average lux value is around 200 lux in December and January, even at the 0.0 stage, which is the clearest state (Figure 9). This shows that the system has problems receiving light.

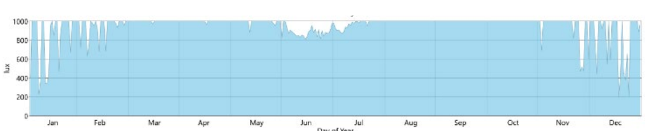


Figure 9 Average Lux Values of The Octagonal KRF Module At Stage 0.0 Throughout The Year

When the modules are evaluated in terms of cost-effectiveness, it is seen that the total cost increases as the number of edges of the geometries increases. Although the cost seems to increase as the number of sides of the polygon increases in Table 8, when the costs per element are considered, it seems that the costs decrease and reach a more optimum level. In this case, triangular KRF modules give the worst results in terms of both solar control and cost, hexagonal KRF modules are the most optimal module for solar control, and octagonal KRF modules are the most economical in terms of cost.

In terms of mobility and daylight performance, the hexagonal KRF module turned out to be the most optimum. This is evidenced by the fact that the system moves and rises sufficiently and thus can control the sun rays at different angles, then drawing more homogeneous graphics. In addition, the fact that it performs better than other modules in terms of cost-effectiveness supports this.

5. CONCLUSION

Although Reciprocal Frame (RF) structures are a system that is frequently used in architecture and a lot of research has been done about it, the applications of KRF structures in architecture are one of the points that have been overlooked. Each KRF module is energy efficient as it can move with a single actuator as it has its own kinematics compared to other kinetic systems. It has a strong potential for sustainable architecture as it has low construction and maintenance costs and can be used with sustainable materials. This study has produced kinetic facade modules based on the geometric analysis of existing KRF structures and aims to find the optimum one by comparing them among themselves in the simulation results. Although all KRF facade designs help in daylighting performance, triangular modules give the worst result among these designs, while hexagonal KRF modules give the most optimum result.

This study analyses the geometric and daylight performance ofKRF modules and evaluates them in terms of mobility, cost and visual comfort. In order to fully analyze the energy efficiency of KRF modules, the algorithm of the openness and closure ratios of the modules should be created in a way that changes depending on the sun. In addition, it is very difficult to analyze the energy consumption exactly as the fully closed modules will increase the use of artificial lighting. To improve this study, KRF modules can be used individually on the facade, as well as the entire facade can be designed as a KRF. Thus, a more holistic facade design can be achieved by getting rid of the uncontrolled blind spots caused by the tessellation of the modules.

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