



**DESIGN OPTIMIZATION OF KINETIC RECIPROCAL FRAME (KRF)
STRUCTURES AS AN ADAPTIVE FAÇADE MODEL FOR AIR TRAFFIC
CONTROL TOWERS: A CASE STUDY**

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IN ARCHITECTURE DEPARTMENT**

**GAZİ UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**

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DESIGN OPTIMIZATION OF KINETIC RECIPROCAL FRAME (KRF) STRUCTURES
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(M.Sc. Thesis)

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ABSTRACT

This research investigates the feasibility of using Kinetic Reciprocal Frame (KRF) structures as adaptive façade systems to solve environmental problems encountered in air traffic control (ATC) towers, such as lack of visual comfort, excessive daylight exposure, and loss of visibility due to glare and reflection. Antalya, Türkiye was chosen as the study area since the problems occur mostly in hot climate regions, and an ATC tower was created as a case study in accordance with ICAO (International Civil Aviation Organization) and FAA (Federal Aviation Administration) regulations. KRF-based adaptive façades were developed on the four most sunlit façades of the tower (southwest, south, southeast, and east), and the simulation and multi-objective optimization process were carried out with Rhinoceros 3D, Grasshopper, ClimateStudio, and Octopus software. The research focuses on three main performance criteria: annual sunlight exposure (ASE), useful daylight illuminance (UDI), and View-Out. In the baseline case, the ASE value was 100%, the UDI value was 6472.33 lux, and the view-out was 100%, resulting in severe glare and comfort losses. In the five best designs selected among 11,845 designs produced during the optimization process, the ASE value was reduced to 34.62%, the UDI value was stabilized in the range of 1894.48-2220.43 lux, and the outward visibility was maintained in the 85%-93.47% band. These results show that KRF adaptive façade systems are effective in improving both glare, reflectivity, and visual comfort. This study is valuable both in terms of examining the façade application performance of KRF structures and analyzing the daylighting and visual comfort standards of ATC towers.

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HAVA TRAFİK KONTROL KULELERİ İÇİN ADAPTİF BİR CEPHE MODELİ
OLARAK KİNETİK KARŞILIKLI/KİLİTLİ ÇERÇEVE YAPILARIN TASARIM
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ÖZET

Bu çalışma, hava trafik kontrol (ATC) kulelerinde karşılaşılan görsel konfor yetersizliği, aşırı güneş ışığı maruziyeti, yansıma ve kamaşma kaynaklı görüş kaybı gibi çevresel sorunlara çözüm üretmek amacıyla, kinetik karşılıklı/kilitli çerçeve (KRF) yapılarının adaptif cephe sistemleri olarak kullanılabilirliğini araştırmaktadır. Sorunların en çok sıcak iklim bölgelerinde ortaya çıkmasından ötürü çalışma alanı olarak Antalya, Türkiye seçilmiş ve vaka çalışması olarak ile ICAO (Uluslararası Sivil Havacılık Örgütü) ve FAA (Federal Havacılık İdaresi) yönetmeliklerine uygun bir ATC kulesi oluşturulmuştur. Kulenin en çok güneş alan dört cephesinde de (güneybatı, güney, güneydoğu ve doğu) KRF tabanlı adaptif cepheler geliştirilmiş; simülasyon ve çok amaçlı optimizasyon süreci Rhinoceros 3D, Grasshopper, ClimateStudio ve Octopus yazılımları ile gerçekleştirilmiştir. Çalışma, üç ana performans kriterine odaklanmıştır: yıllık güneş ışığı maruziyeti (ASE), kullanışlı güneş ışığı aydınlığı (UDI) ve görüş değeri (View-Out). Başlangıç durumunda ASE değeri %100, UDI değeri 6472,33 lüks ve dışa görüş değeri %100 olarak ölçülmüş; bu durum, ciddi parlama ve konfor kayıplarına yol açmıştır. Optimizasyon sürecinde üretilen 11.845 tasarım arasından seçilen en iyi beş tasarımda ASE değeri %34,62'ye kadar düşürülmüş, UDI değeri 1894,48–2220,43 lüks aralığında stabilize edilmiş ve görüş değeri %85-%93,47 bandında korunmuştur. Bu sonuçlar, KRF adaptif cephe sistemlerinin hem parlama, yansıtma hem de görsel konforu artırmada etkili olduğunu göstermektedir. Bu çalışma hem KRF yapılarının cephe uygulama performansının incelenmesi hem de ATC kulelerinin gün ışığı ve görsel konfor standartlarının analizi açısından değerlidir.

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Anahtar Kelimeler : Kinetik karşılıklı/kilitli çerçeve (KRF) yapılar, hava trafik kontrol kulesi (ATCT), çok amaçlı optimizasyon, gün ışığı performans analizi
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SYMBOLS AND ABBREVIATIONS

The symbols and abbreviations used in this study are presented below, along with their explanations.

Symbols

Explanations

cm	Centimeter
H	Hours
kW	Kilowatt
lx	Lux
L	Number of independent loops
m	Meter
M	Mobility
m²	Square meters
%	Percentage
°	Degree

Abbreviations

Explanations

A.D.	Anno Domini (After Christ)
ACC	Area Control Center
AF	Adaptive Façade
APP	Approach Control Unit
ASE	Annual Sunlight Exposure
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
B.C.	Before Christ
BIPV	Building-Integrated Photovoltaics
CAD	Computer-Aided Design
DGCA	Directorate General of Civil Aviation
DHMI	State Airports Authority of Türkiye
EPW	EnergyPlus Weather
FAA	Federal Aviation Administration

Abbreviations**Explanations**

HVAC	Heating, Ventilation and Air Conditioning
ICAO	International Civil Aviation Organization
KRF	Kinetic Reciprocal Frame
PV	Photovoltaic
RF	Reciprocal Frame
TWR	Aerodrome Control Tower
LEED	Leadership in Energy and Environmental Design
UDI	Useful Daylight Illuminance



1. INTRODUCTION

Historical background of aviation

Throughout history, humanity has had the desire to fly, which has been the passion that has pushed people's imagination and pushed them to make discoveries and develop new technologies. So much so that many cultures and civilizations have included flying elements in their mythologies and legends. In the 8th century B.C., the Greek mythology of Icarus and Daidalos included flying with wings made of wax and feathers, emulating birds. When Chinese classical texts are analyzed, it can be said that in texts such as Shan Hai Jing of the 4th century B.C. and 2nd century B.C., the Wind God Fei Lian gave aviation a military identity by commanding kites for attack. The fact that the ability to fly is unattainable for humans has been attributed to sacred beings in mythologies. For example, in Indian Mythology, in the Mahabharata Epic dated 400 B.C., Garuda is a semi-divine mount as a bird. Tulpar, whose figures appear on the Scythian Gold Plates in the 7th century BC (Alizade, 2019; Kim, 2002) and in the oral narratives of Turkish Mythology, is a winged horse. The sanctity of the horse, a big part of daily life for Turks, is expressed in this way. In Sumerian Mythology, this figure is depicted as a flying lion-headed eagle named Anzu (Verderame, 2021).

Humans have made many sketches and developed models to realize the dream of flight. Archytas, an ancient Greek philosopher, developed a steam-powered model he called "The Dove" in about 400 BC, and this is considered one of the first attempts at man-made flight vehicles. Names such as Abbas Ibn Firnas and Eilmer of Malmesbury are known to have developed glider-derived designs and flight trials in the Middle Ages (Jamsari et al., 2013). Leonardo da Vinci's flight machine sketches (see Figure 1.1), made in the 15th century, are one of the studies on the necessity of flight using aerodynamic designs. In the 17th century, Hezarfen Ahmet Çelebi, a Turkish scholar, studied the aerodynamic structure of wings, produced his wings, and flew over the Galata Tower in Istanbul, making a successful flight of about 3 kilometers. In the same century, Lagari Hasan Çelebi launched himself into the air with a rocket-like mechanism filled with gunpowder and made a soft landing on the sea (Uluslan, 2021).

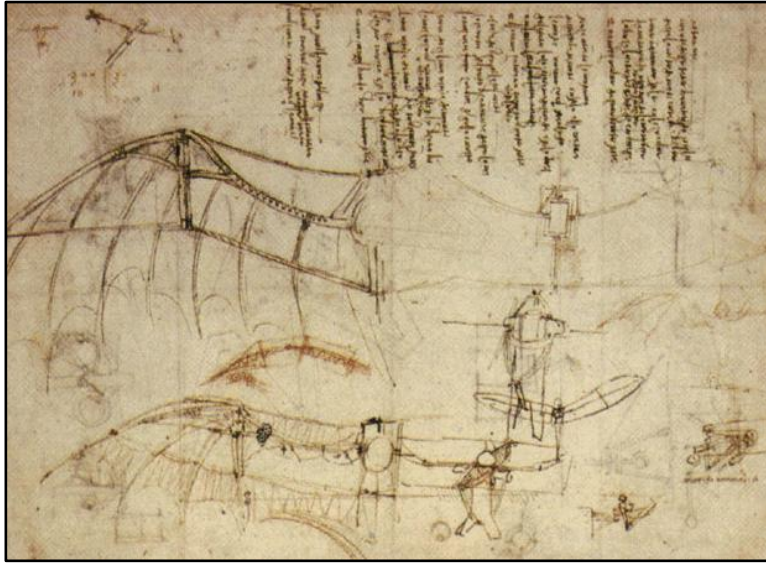


Figure 1.1. Leonardo da Vinci's flying machine.

The systematic scientific studies of flight actually began in the 18th century with the Montgolfier Brothers' hot air balloons and accelerated with George Cayley defining the modern aerodynamic principles (Petrescu et al., 2017). By the end of the 19th century and the beginning of the 20th century, the dream of powered flight became a reality with the Wright Brothers and their historic flight (see Figure 1.2) in 1903, the advent of modern aviation (Anderson and Bowden, 2005). The desire to fly has led to the creation of many other industries such as engineering material and aerodynamics. The rapid evolution of aircraft during the World Wars stressed the importance of air power which resulted in accelerated development of flying technology in the civil and military areas (Bilstein, 2001).

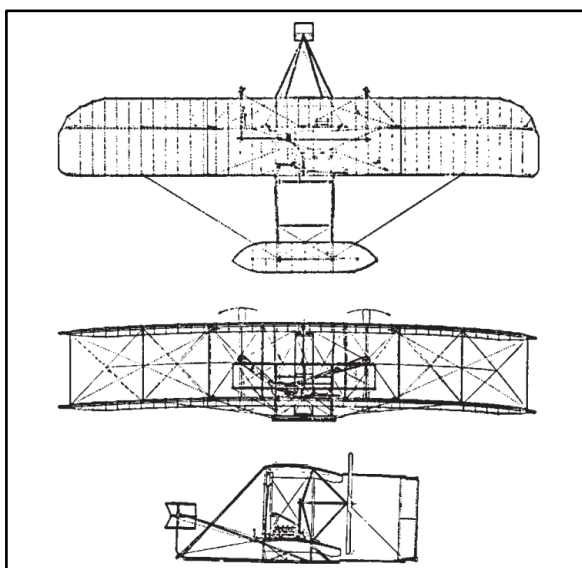


Figure 1.2. Sketches of the Wright Flyer 1 (Anderson and Bowden, 2005, 2).

Aviation is integral to global connectivity today, allowing more than 4 billion passengers to fly every year (IATA, 2023). Moreover, aviation allows for the fastest and most efficient form of transport in international trade. On a daily basis, over 130,000 commercial flights are managed globally by air traffic control (Flightradar24, 2025). Every day, more than 45,000 flights in the United States are controlled by the Air Traffic Control (ATC) system. In Europe, 30,000 flights are handled every day (Eurocontrol, 2024a). These huge numbers show how important advanced ATC technologies and infrastructures are for safety, efficiency, and seamless operation. The air traffic control towers, which serve as the nerve center of this system, organize the movements of the aircraft in airports and airspace. As global demand rises, automation within the aviation industry will be necessary to ensure the construction and supply of new aircraft and airport infrastructure. However, investment will also be necessary in sustainable aviation to alleviate congestion and climatic effects.

Challenges in modern aviation infrastructure

Aviation is one of the most connected and dynamic global systems and is likely to face challenges due to increasing air traffic, increased technological demands, and changes on a global scale like climate change. The air traffic control towers are not exempt from these pressures as they are central to the safe and efficient management of airspace. Tower control systems are vital parts of airport infrastructure and must adapt to the demands of modern aviation while responding to developing global challenges.

The world's air traffic is increasing at an exponential rate and is one of the greatest strains on an ATC tower. As more planes fly yearly, managing flight operations becomes more complex. ATC towers are facing difficulties in meeting the rising demand as they were built several years ago and do not have any recent systems incorporated (Kahne and Frolow, 1996). As a result of the requirement for advanced automation, improved communications, and real-time data, with more pressure on existing infrastructure. Newer towers come with new systems, while many regions remain not so able or standard, so the technology in use is not constant.

ATC tower operations are further complicated due to climate change. Aviation operations are being impacted directly by global temperatures, the number of extreme weather events, and wind changes. In other words, the large amount of intense weather is modified by climate

change, which is adversely affecting aviation operations. The control towers must adapt to these conditions to make them more resilient and adopt designs that will withstand extreme conditions and remain operational under fickle weather (FAA, 2023a). Dynamic and adaptive façade (AF) systems that optimize thermal performance and reduce energy demand are essential tools for mitigating the impacts of changing environmental conditions. However, adoption is still not widespread, especially when resources are limited or sustainability is not a priority.

ATC towers are under environmental stress, but more attention needs to be paid to sustainable energy. Airports rank among the largest consumers of energy in urban areas, and ATC towers significantly add to the carbon footprint. The lighting, climate control, and other systems in towers consume a lot of energy, so they have to incorporate technology to reduce usage. Adaptive systems are solutions that can respond to the stimulation of their environment, for example, solar radiation or wind loads. These systems can help mitigate energy consumption (Romano, 2021, 499-509). The use of these systems is still limited; hence, more investments need to be made in sustainable design.

It remains a challenge for ATC towers to keep ergonomically and safe for the user. Air traffic controllers must work in high-stress environments for long periods and remain focused for a long time. Ineffective workspace design, with inadequate lighting, ventilation, and acoustics, hastens fatigue and lowers performance. Working in these conditions for a long time could result in health issues such as musculoskeletal disorders, chronic fatigue, and reduced cognitive functioning (DeLucia et al., 2009). Although retrofitting existing towers for compliance with ergonomic standards has been undertaken, work environments are not optimal for the controllers in many facilities.

There are no worldwide designs for ATC towers, which makes things even more difficult. While advanced principles have been adopted for tower design in developed regions such as North America and Europe, many countries still follow an ad hoc approach without adequate consideration of site-specific operational or environmental factors (Kazda and Caves, 2010). This creates inefficiencies and lost opportunities for more resilient and adaptable designs, especially in rapidly growing aviation regions.

It is extremely important to develop innovative, sustainable, and adaptable infrastructure for the aviation industry as it keeps evolving. ATC towers must keep up with time and counter global challenges like climate change and energy sustainability as global challenges mainly global warming increasing population and changing climatic patterns create demand on limited earth's atmosphere which directly reduces the productivity of ATC. By solving this problem holistically, ATC towers can fulfill the requests concerning modern aviation and create a more resilient and sustainable future for aviation authorities.

Problem definition

Air traffic control towers are an essential component of aviation infrastructure. However, they are subjected to many challenges because their designs are outdated they face environmental pressures, and lack a unified global approach. The above challenges not only affect the operational efficiency of air traffic control towers but also impact their sustainability and the well-being of the users.

Many existing ATC towers were constructed decades ago when air traffic volumes and technological requirements were drastically lower than today. These towers are based on outdated systems, which do not allow for the installation of advanced technology like the latest radar systems automated communication devices, or real-time data systems. As air traffic volumes keep on going where many aviation hubs are rapidly developing, these limitations cause inefficiencies and increased operational risks (Kahne and Frolow, 1996). Moreover, their static structures are poorly equipped to adapt to the dynamic nature of modern aviation, further compounding operational challenges.

Although some newly constructed towers incorporate technological improvements, their designs generally fail to adequately meet criteria that are becoming increasingly important on a global scale, such as energy efficiency, climate compatibility, and user ergonomics. The absence of standardized global guidelines for ATC tower design leads to significant disparities in how these structures are conceptualized and executed. In certain regions, design practices are followed on an ad hoc basis, disregarding local climatic conditions, sustainability objectives, and ergonomics. This inconsistency limits the potential for innovative, resilient, and adaptable designs that could better align with global aviation demands (Kazda and Caves, 2010).

Environmental factors further complicate this issue. High solar radiation, particularly in hot climates, significantly increases the heat load and energy consumption within the tower. The uncontrolled use of glass-dominated façades causes glare, reflections, and loss of visual comfort. Common designs don't always include adaptive systems that can react to things changing in the environment, like the strength of solar radiation or wind. An example of this is the application of dynamic façades that respond to external climate conditions which can significantly improve thermal performance as well as lower energy consumption but it is not yet well adopted in ATC towers (FAA, 2023a; Romano, 2021, 499-509). Without adopting such sustainable practices, ATC towers risk becoming even larger contributors to the environmental footprint of aviation infrastructure.

The working environment of air traffic controllers is a fundamental issue that is often overlooked in tower designs but has a direct impact on operational efficiency. These professionals perform tasks that require long periods of high concentration, and it is therefore crucial that their workspaces are ergonomically, visually, and environmentally supportive. However, a significant portion of existing control cabins are characterized by issues such as inadequate daylight control, thermal discomfort, high noise levels, and static façade systems. In particular, intense sunlight reflections and glare from glass surfaces can cause significant visual discomfort indoors, leading to impaired external visibility, reduced operational awareness, and increased eye strain. The study noted that physically and psychologically harmful effects can be caused due to such surroundings as musculoskeletal disorders, chronic fatigue syndrome, and cognitive decline (Chellappa et al., 2011). Although awareness of such problems is growing, many ATC towers still lack ergonomic and user-centered design. The ATC tower design should find innovative solutions given high-tech issues with substandard architecture, design standards, environment, and working conditions on the one hand and significant growth on the other.

Scope and objectives of the study

This study aims to produce architectural solutions to environmental and ergonomic problems encountered in air traffic control (ATC) towers. In this regard, the potential use of kinetic reciprocal frame (KRF) structures as adaptive façade systems is being investigated. KRF systems possess the flexibility to respond to changing environmental and operational conditions, and are considered an innovative solution that can be integrated into ATC towers

in regions with varying climatic conditions due to these characteristics. In this study, the effects of these systems on visual comfort and daylight comfort were examined through a case study conducted on a major-capacity model tower in Antalya, a city with a hot climate in Türkiye.

Within the scope of the research, a numerical simulation infrastructure was developed using advanced parametric modeling tools such as Rhino and Grasshopper to test the performance of façade systems against variations in environmental conditions. The primary objective of the study is to achieve an adaptive façade design that balances conflicting design parameters to reduce glare and reflection, enhance daylight performance, improve user comfort, and maximize exterior view. To this end, multi-objective optimization methods were employed.

The specific objectives of the study are as follows:

- a. To identify and analyze daylight comfort and visual comfort issues encountered in ATC towers.
- b. To assess KRF structures' performance as adaptable façades for ATC towers that can respond to climate and tower operational needs effectively.
- c. To develop and optimize a parametric model that demonstrates the performance of KRF systems in improving daylight performance, view and user comfort in the major capacity ATC towers in hot climates context.
- d. Contribute to the development of standardized design guidelines that enable the integration of kinetic and adaptive systems in future ATC tower projects.
- e. Contribute to sustainable aviation infrastructure by proposing innovative design solutions that reduce environmental impact while enhancing operational efficiency.

The findings of this study are aimed at evaluating the developed parametric model in terms of architectural and technical criteria such as visual comfort, daylight performance, and external view. The solution designs obtained through simulation and multi-objective optimization will determine how successful the use of kinetic reciprocal frame structures as adaptive façades on ATC tower façades will be and to what extent they will solve problems. All of these analyses, optimizations, and recommendations are intended to serve as a guiding resource for improving the façade performance of air traffic control towers in hot climates.

Limitations of the study

Although this study is based on a structured and data-driven methodology, it has some limitations that affect the scope and depth of the research. The most significant limitations include data access and legal barriers, gaps in international regulations, and limited academic literature on ATC towers and KRF systems.

Access to architectural and operational data related to ATC towers was highly restricted; control room layouts and detailed plans are not publicly available for security reasons. As a result, some design assumptions were based on visual and indirect sources. Some of the data used in the study was obtained with the permission of the State Airports Authority of Türkiye (DHMI), while some was obtained from publicly available regulations and standards.

The absence of internationally binding architectural standards is also a significant shortcoming. While organizations such as ICAO (International Civil Aviation Organization), FAA (Federal Aviation Administration), and EASA (European Union Aviation Safety Agency) provide operational technical guidance, there are no standards regarding architectural requirements. Criteria such as tower height, daylight quantity, façade design, and viewing angles need to be standardized.

The study primarily examined daylight comfort, particularly in hot climates, but did not address issues such as different climate scenarios, energy efficiency, heating and cooling loads, noise, façade durability, and wind loads. These areas could be explored in detail in the future.

Studies on KRF systems are generally limited to structural and geometric analyses; as architectural applications increase, more optimal designs can be developed. The architectural literature on ATC towers, on the other hand, has mostly focused on operational regulations and is limited in terms of environmental performance and design strategies. This study offers unique contributions in terms of the architectural potential of KRF systems and the environmental requirements of ATC towers.

2. ADAPTIVE FAÇADES

According to a biological viewpoint, adaptation is described as your organism's practice of evolutionary enhancement of the capability to survive and to the environment (Darwin, 1968). Adaptive façades, often referred to as kinetic or active façades, are innovative building envelopes designed to dynamically alter their properties, functions, or behaviors in response to changing environmental conditions. These systems use automation technology to modify transparency, insulation, geometry, and shading using sensors, actuators, and control systems. By changing due to external stimuli like solar radiation, temperature, and wind, adaptive façades seek to improve energy efficiency, thermal comfort, and daylight use whilst simultaneously minimizing the dependency on mechanical systems of the building such as heating, cooling, and artificial lighting (Loonen et al., 2015).

Buildings are vital since they are responsible for most of the world's energy use and greenhouse gas emissions. The United Nations Environment Programme (UNEP) informs that the building and construction sector contributes around 34% of global energy demand and 37% of energy and process-related carbon dioxide (CO₂) emissions of this global energy demand (UNEP, 2022). Adaptive façades are one of the most promising ways to reduce this impact through better energy use and diminished need for mechanical systems used for heating, cooling, and lighting. By dynamically responding to environmental conditions, such as solar radiation and temperature, these systems enhance thermal comfort and daylight utilization while significantly lowering energy consumption.

2.1. The Background of Adaptive Façades

Adaptive façades are an evolving innovation in architecture. They change according to environmental conditions and show potential for greater energy efficiency and comfort. Rather than using a static building envelope, adaptive façades are designed to adjust in real time to issues involving thermal conditions, daylight, and visual comfort. This development is a response to modern architecture which needs to combine sustainable and functional design.

The idea of adaptive façades is based on the restrictions of traditional static façades, which dominated for centuries. These static systems were functional, but they struggled to achieve energy efficiency, aesthetic appeal, and occupant comfort. Over time, the emergence of advanced materials, automation technologies, and sustainable design principles paved the way for adaptive systems capable of addressing these shortcomings.

2.1.1. The emergence of static façades

Static façades, which served as the primary architectural solution for centuries, were initially designed to provide basic shelter and protection against external environmental factors. When the first examples of static façades are examined, it is seen that civilizations used façades as a protective and limiting element. Looking at the examples of Gobekliitepe (9500 B.C.) in Figure 2.1 and the pyramid of Djoser (2650 B.C.) in Figure 2.2, walls existed as the main element that protected the interior from external factors (difficult meteorological conditions, light, predators, or humans). At other times, static façades, like cave walls (see Figure 2.3) or Roman Entrance Arches, have been the message-giving elements. Needs have constantly changed and façades have continued to evolve in line with these needs.

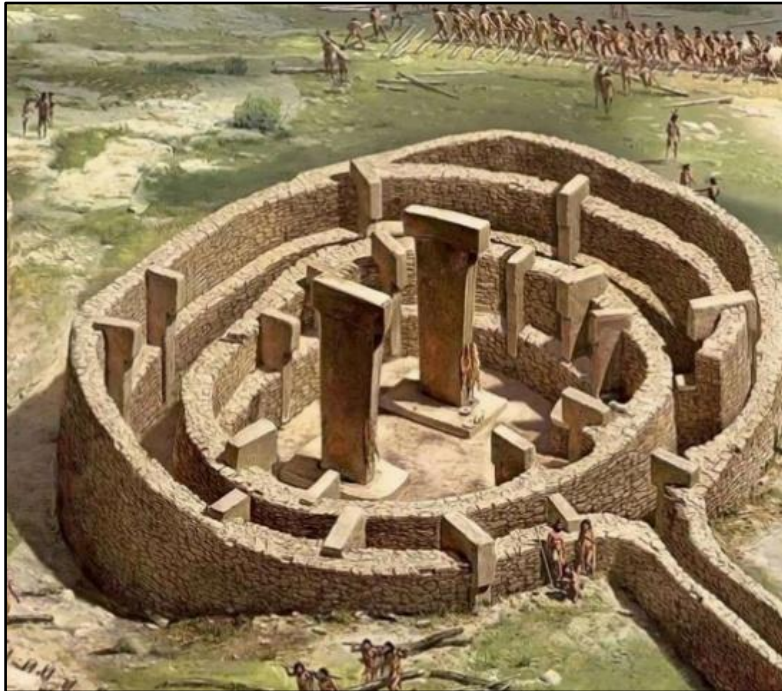


Figure 2.1. Illustration of Gobekliitepe, Türkiye (Karataş, 2020).



Figure 2.2. Pyramid of Djoser, Egypt (Sharp, 2007).



Figure 2.3. Cave Paintings (Günay, 2021; Juaristi and Monge-Barrio, 2016).

Static façades have had to adapt to different climatic conditions, reflecting the environmental challenges and cultural preferences of the regions in which they were developed. In hot dry climates, for example, façade design often makes use of shading elements to minimize heat gain while allowing natural ventilation. One of the most iconic examples of such adaptations is the Mashrabiya, a traditional element of Islamic architecture (see Figure 2.4). Mashrabiya screens, typically made from intricately carved wood or latticework, were used to regulate sunlight, provide ventilation, and maintain privacy, all while adding a decorative aspect to the building's exterior (Fathy, 1986).



Figure 2.4. Mashrabiya view from inside (Mohamed and Ali, 2014).

The Mashrabiya highlights how traditional architecture ingeniously responded to environmental challenges. By allowing cool air to circulate while blocking harsh sunlight, Mashrabiya contributed to passive cooling, reducing the need for mechanical systems (see Figure 2.5). This idea corresponds with current sustainable design which attempts to deal with passive events or energy consumption. Mediterranean architecture also adopts similar strategies where windows are set deep and with thick walls to give shade and insulation to the walls so that the inside temperature can be controlled (Bianca, 2000).

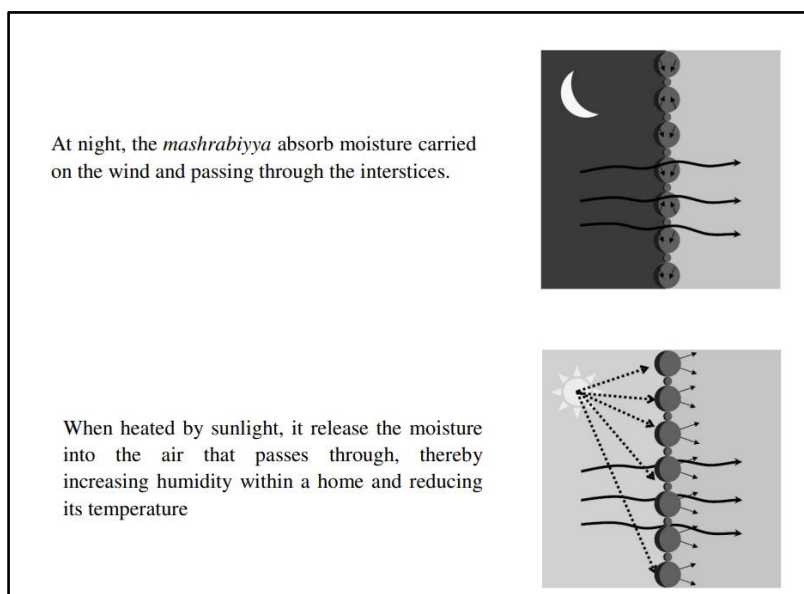


Figure 2.5. Mashrabiya's cooling process (Mohamed and Ali, 2014; Popovic Larsen, 1996).

In colder climates, static façades are adapted to prioritize insulation and heat retention. As seen in Figure 2.6, traditional Scandinavian architecture had compact building forms and thick timber walls to reduce heat loss (Donnelly, 1992, p. 26), and the use of smaller windows reduced the impact of cold winds. These regional adaptations demonstrate how static façades evolved to meet the climatic demands of their environments, balancing functionality with cultural expression.

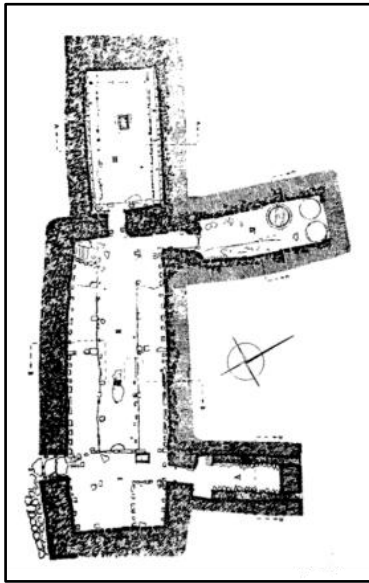


Figure 2.6. Thick Scandinavian building wall (Donnelly, 1992, p. 26).

The Industrial Revolution was an important turning point in façade design where many new materials and construction techniques became available. Around the 19th and 20th centuries, the employment of steel and glass enabled the development of curtain walls. Curtain walls became the staple of modern architecture. Architects like Ludwig Mies van der Rohe and Le Corbusier advocated for the reflection of objects through the use of large glazed surfaces so that a good visual quality and aesthetic appearance can register on the views. However, these designs often demonstrated excessive energy inefficiencies with large windows that caused a large gain of heat in summer and a large loss of heat in winter (Addington and Schodek, 2005).

Despite these innovations, static façades inherently lacked the ability to adapt to changing environmental conditions. Because they are fixed in nature, it was built mechanically such as heating, ventilation, and air conditioning to ensure thermal comfort in buildings. As energy demands increased, especially after the war, the inadequacies of static façades

became evident during rapid urbanization. The emergence of large-scale urban developments and high-rise buildings necessitated the need for more responsive and energy-efficient building envelopes (Giedion, 2009).

The energy crises of the 1970s and growing awareness of climate change shifted architectural priorities. Researchers began looking at other ways of façade design to lessen the impact on mechanical systems and enhance energy efficiency. Initial attempts to fix these problems included shading devices and double-glazing through passive designs. While these solutions were somewhat effective, they remained fixed and hence, did not have the necessary responsiveness to meet the complicated requirements of modern architecture. This growing recognition of the limitations of static façades set the stage for the development of kinetic and adaptive façade systems, which could dynamically respond to environmental stimuli.

2.1.2. Studies on static façades

Static façades have long been proven structurally stable and protect against the environment. These essential architectural elements have come in handy to the architect since ancient history. Traditionally, they would form the outer skin of the building to create a barrier against external conditions while shaping architecture. However, due to increasing demands for energy efficiency and sustainable development, the static façade has changed from a mere architectural component to a major parameter of environmental performance. The advancement has spurred research extensively on improving their thermal behavior, daylighting performance, and material efficiency as well as their limitations in meeting the latest sustainability targets.

Static façades, known for their fixed design configurations, have been extensively studied for their ability to optimize energy performance through innovative geometries and sustainable materials. For instance, Etman et al. (2013) explored the potential of mashrabiya geometries, traditional perforated screens used in Middle Eastern architecture, as sun shading elements in modern façades. The study shows that these geometries can reduce solar gain and maintain indoor daylight levels making it a solution that balances energy efficiency and richness. This research gave a framework to include culturally relevant patterns in high-performance façade systems.

Polat and İlerisoy (2020) have examined the use of a mathematical pattern in façade design that takes inspiration from a cell structure known as Voronoi geometry. They showed that these Voronoi patterns are aesthetic and also a good way to reduce material use while maintaining structural integrity. According to their research, they also showed how computational geometry can help reconcile the goals of sustainability with those of aesthetics. Similarly, Goharian et al. (2022) included another dimension to the static façade studies by introducing variations of thicknesses into façade panels. Their work evaluated the impact of these variations on solar radiation transmission, revealing that thicker panels can significantly enhance thermal performance while maintaining daylighting benefits.

Rezakhani and Kim (2020) took a cultural approach utilizing Persian patterns to design the sunshades. They evaluated the efficacy of these designs in the regulation of solar exposure and improvement of occupant comfort using virtual reality simulations. Their study showed that patterns inspired by culture could be used in new façade systems to achieve functional and aesthetic goals.

Due to the increase in global priority for energy efficiency, geometric exploration in static façades is gaining momentum. Lim et al. (2012) explored static sunshade systems' impact on energy consumption and their capacity to reduce cooling loads in hot climates. Their research showed the need to optimize shading angles and the locations of the panels for energy savings. Martokusumo et al. (2017) built upon this concept by implementing algae panels within façades, paving the way for sustainable alternatives to typical vertical shading systems. Research showed that algae panels help consume less energy and sequester carbon, showcasing a great tool for reaching goals of energy efficiency. Hachem and Elsayed (2016) researched how folding photovoltaic panels can be integrated into static façades. It was shown how the modular changes in their configurations can improve energy production.

The intersection of geometry, parametric design, and simulation has further propelled research in façade design. Sharaidin et al. (2012) used simulation tools and parametric design techniques to develop a daylighting optimization of kinetic façades. Their study revealed that integrating dynamic movement into façade designs could significantly improve indoor light distribution while reducing glare. Glassman and Reinhart (2013) took this one step further by using future climate scenarios for parametric design. The researchers showed how geometric and material choices for façades can be made for long-term climate change

impacts to ensure energy efficiency and occupant comfort. Hosseini et al. (2019) further investigated static façades in morphological approaches, showing that complex geometric configurations can enhance thermal and visual comfort. Their analysis showed how optimizing static systems using advanced tools, would allow them to acquire some effects of dynamic façades without any mechanical movement. Likewise, Tabadkani et al. (2019) used parametric tools for adaptive façades, proving the ability of the former to modify suitably for optimal visual comfort.

Adaptive façades, also known as kinetic or responsive façades, go beyond the fixed capabilities of static designs by dynamically adjusting to environmental changes. Loonen et al. (2015) describe adaptive façades as a system of sensors, actuators, and automatic control that enables the building performance to adapt to solar radiation, temperature, or wind. They emphasized that these systems could significantly reduce energy consumption while enhancing occupant comfort. Panya et al. (2020) designed interactive motion façades that respond to changes in the environment using parametric strategies for more flexibility and aesthetics. Also, Hinkle et al. (2022) demonstrated the strong energy-saving potential of an adaptive façade typology in achieving thermal and visual comfort, especially at early design stages.

Even though adaptive systems offer many advantages static façades are still very important due to their simplicity and cost-effectiveness.. Seyrek et al. (2021) studied kinetic green façades in comparative assessment with static systems and observed that although kinetic systems allow for much more adaptability, maintenance of static systems is easier and less complicated than economic means. To better understand this comparison, Dastoum et al. (2024) explore geometric optimization in static façades, emphasizing its potential to enhance daylighting and thermal performance without the complexity or cost of kinetic systems.

Kim et al. (2015) highlighted the economic advantages of kinetic façades, demonstrating that their ability to adapt to changing conditions reduces overall energy costs over a building's lifecycle. Seyrek et al. (2021) further supported this view, static and kinetic façades have their advantages, but static systems are more economically affordable and stable in the long term.

Both the façade types become more sustainable with the combination of renewable energy systems. Athienitis et al. (2018) studied Building-Integrated Photovoltaics (BIPV) in façades that can provide considerable energy savings. Adaptive façades with photovoltaic capabilities, as studied by Hachem and Elsayed (2016), reinforced these findings by showcasing how foldable photovoltaic systems in adaptive designs could optimize energy production while maintaining functional and aesthetic balance.

The future of sustainable architecture is a blend between static and adaptive façades. Designs that combine the fixed geometry of static structures with the kinetic adaptability of dynamic skins will probably dominate buildings in the future. Hong et al. (2007) there is an urgent need for this kind of innovation as buildings consume almost 30% of energy and greenhouse gas emissions globally. By integrating sustainable materials and advanced technologies, both façade types can contribute significantly to reducing the environmental footprint of the built environment.

2.1.3. Transition from static to adaptive façades

Historically, building envelopes have mostly been solved via static façades which provide protection, privacy, and aesthetics. But they cannot adapt easily according to changing environments. This is increasingly becoming a problem considering the energy demands and climate change. Traditional static façades rely on a fixed configuration, which could cause inefficiency in the area of thermal performance, daylight control, and overall building efficiency. Due to the above constraints, they are in search of more responsive systems to meet architectural requirements.

Static façades primarily have the challenge of not being able to dynamically control solar heat gain, ventilation, and thermal comfort. As a result, the energy needs and emission of greenhouse gases are increased as there is a high reliance on heating, ventilation, and air conditioning (HVAC) ports and artificial lighting. As sustainability goals become more pressing globally, the architectural community is exploring options like kinetic façades. These systems provide flexibility and enhancement by reacting in real time to environmental changes.

The growth of kinetic façades is driven by advances in material science, automation, and computing technology. New kinetic products consist of moving parts with sensors and devices. Moreover, they enable performance optimization of a given building due to solar radiation, wind, and temperature. For instance, studies indicate that kinetic façades can reduce cooling loads by as much as 40%, contributing significantly to energy efficiency (Hinkle et al., 2022). The availability of parametric design tools, like Rhino and Grasshopper, enhances the architect's ability to design and evaluate these complex systems by conforming to functional performance and innovative aesthetics.

In the last two decades, a lot of academic and industrial research has focused on kinetic façades. According to data from the Web of Science (WOS) database, in the last 3 years, the number of research on façades has decreased by approximately 25%, while the number of citations has increased by approximately 44%, while research on kinetic façades has increased by approximately 18% and citations by approximately 55% (see Figure 2.7). Similarly, the global façade market has also increased, for example, the global façade market is estimated to grow at a compound annual growth rate (CAGR) of 6.3% from 2023 to 2030 due to the development of energy-efficient technologies and an increasing awareness about sustainability (IDE, 2022). This increase is especially remarkable in areas with difficult climate conditions such as the Middle East and Southern Europe, where kinetic systems can effectively meet tight environmental criteria and extreme weather conditions.

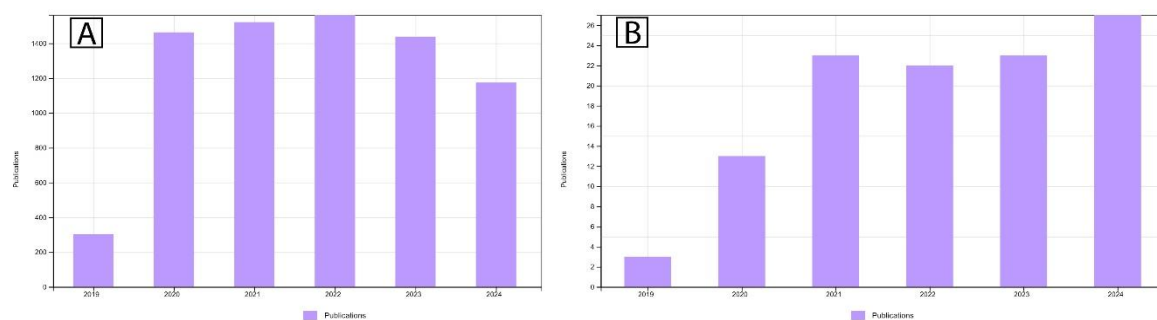


Figure 2.7. Number of articles published on WOS database between 2019-2024 a) on façades, b) on kinetic façades.

Adaptive façades demonstrate how technology has advanced in building façades through adaptation. Studies by Kolarevic and Parlac (2015) show significant improvements in energy performance and occupant comfort through adaptive systems with 30% improvement in daylight response, and a 20% reduction in glare as compared to fixed systems. The metrics of kinetic façades speak volumes of their efficiency.

Architectural projects show that it is possible to enhance design practices with kinetic façades. We can see applications of kinetic façades in many places around the world. For example, Dynamic shading systems help the Al Bahar Towers in Abu Dhabi to respond to the intensity of solar energy. This reduces solar gain but preserves the aesthetic quality of the towers. Similarly, the Institute du Monde Arabe in Paris features kinetic openings that control light infiltration, offering a hybrid performance that expresses culture and optimizes the environment. These and many other examples show how kinetic façades help to increase sustainability and at the same time provide opportunities for creative expression for the architect.

As urbanization accelerates and climate challenges increase, kinetic façades represent a significant shift in architectural priorities. Kinetic façades respond to new demands for sustainability by overcoming the limitations of static systems and taking advantage of technological advances. As seen in Table 2.1, both types of façade have their advantages and disadvantages. Therefore, the building types addressed by both façade types differ. However, regardless of the façade system, it is possible to say that more sustainable façade systems stand out. However, the increasing use of kinetic façades in both research and practice points to their importance in the development of more durable, sensitive, and aesthetic architecture in the future.

Table 2.1. Static façade and adaptive façade comparison (source: Author).

	ADAPTABILITY	ENERGY EFFICIENCY	INITIAL COST	MAINTENANCE	AESTHETIC APPEAL	DURABILITY
STATIC FACADES	Fixed and rigid, unable to respond to changing environmental conditions.	Relies on passive insulation and fixed shading, leading to higher energy consumption in dynamic climates.	Generally lower due to simpler construction and fewer components.	Minimal, with lower operational costs and fewer moving parts.	Limited to static visual impact, which may lack dynamism.	High durability due to fewer movable parts and simpler construction.
ADAPTIVE FACADES	Dynamic and responsive, capable of adjusting to real-time environmental stimuli (e.g., sunlight, wind).	Reduces heating and cooling loads by optimizing natural lighting, shading, and ventilation.	Higher due to advanced technology, specialized materials, and customization.	Requires regular maintenance of moving components, sensors, and mechanical systems.	Offers visually dynamic designs that can transform based on environmental changes or user needs.	Potentially lower durability; mechanical parts and sensors are subject to wear and tear.

2.2. Classification of Adaptive Façades

Adaptive façades exhibit diverse parameters and serve various purposes, making their classification complex. Many studies classify and evaluate these façades according to their different characteristics. Recent literature identifies terms such as “active façades”, (Diarce et al., 2013; Elguezal et al., 2019; Giovanardi et al., 2024), “advanced façades” (Ayçam and Ceylan, 2017; Taveres-Cachat et al., 2017), “biomimetic or bio-inspired façades” (Avinç et al., 2024; Hosseini et al., 2024; Webb et al., 2018), “bio-active” (Metwally and Ibrahim, 2024), “kinetic façades” (Alakavuk and Sarisayin, 2024; Sadeghi and Maden, 2024; F. Wagiri et al., 2024), “dynamic façades” (Gong et al., 2024), “intelligent façades” (Habibi et al., 2022), “interactive façades” (Apriliawan et al., 2024), “movable façades” (Kim et al., 2024), “responsive façades” (Ibrahim and Fayed, 2024), “smart façades” (Jafari and Alipour, 2021), “switchable façades” (Platzer, 2003), “transformable façades” (Jung et al., 2015; Matheou et al., 2020). The increasing number of studies on such different characteristics of adaptive façades in recent years is a result of the new searches on façades. As new studies emerge, new classifications emerge. In addition, this diversity in studies reveals the necessity of the classification of adaptive façades.

Façades can often fall under multiple classification systems simultaneously, as they are dynamic elements with multifaceted characteristics. For instance, a façade can simultaneously exhibit features of being embedded, folding, and contributing to both optic and thermal comfort. This chapter provides an in-depth exploration of adaptive façades by synthesizing various complementary perspectives. In this context, the system’s mobility, operational mechanisms, mechanical dynamics, and functional aspects are examined. Studies have employed different classification approaches, including mobility-based classifications (Elmokadem et al., 2018; Moloney, 2011), stem operation-based classifications (Athienitis et al., 2018), and movement-based classifications (Bedon et al., 2019; Güney and Arpacioğlu, 2024; Moloney, 2016; Velasco et al., 2015). Additionally, functionality-based classifications draw insights from research conducted by Romano et al. (2018), Attia et al. (2020), Loonen et al. (2015), and Schleicher et al. (2011).

2.2.1. System mobility-based classification

Although kinetic façade systems are façade systems that can move as the name suggests, the system has different mobility within itself. This mobility expresses the relationship of the façade system with the building. The system can be fully dependent on the building, partially dependent on the building, or independent of the building. Fox and Yeh (2000) evaluate these façade systems in 3 categories depending on their relationship with the building. As stated in Figure 2.8, they are classified in 3 different ways: embedded, deployable, and dynamic systems.

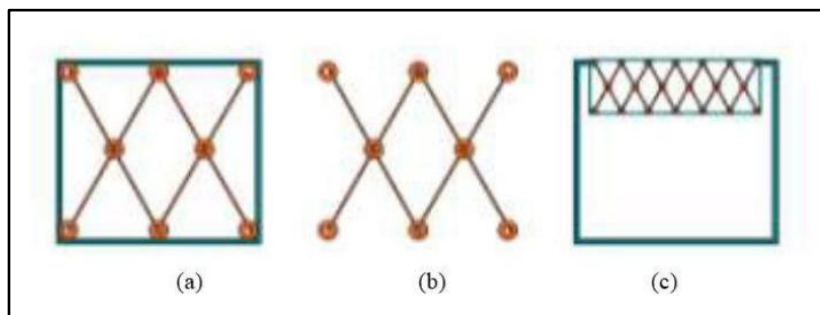


Figure 2.8. Embedded (a), deployable (b), and dynamic kinetic façade (c) S: (Elmokadem et al., 2018).

Embedded systems: These systems are built to stay put and operate as part of a more general part of the whole architecture. Their purpose is to respond to changes in orientation or environmental conditions while remaining fixed.

Deployable systems: Deployable systems are constructions or assembly that may be mobile. They can be easily assembled, dismantled and moved so they are ideal for portable exhibitions or self-assembly shelters. They have flexibility and easy to transport so as to serve short term.

Dynamic systems: The dynamic systems operate independently of the principal architecture, unlike the embedded and deployable systems. These are made in such a way to move by themselves without any control of the user. These systems are usually implemented into other elements, such as shutters, partitions, walls, or ceilings. Moloney (2011) analyzed these systems in 3 categories:

1. Mobile systems can be moved and redeployed in response to the requirements of varying structures, spaces, and contexts.
2. Transformable systems are the structures that change their geometry can adapt to new tasks or when space is limited. This makes them useful where flexibility and economical use of space are needed.
3. Incremental kinetic systems work on a principle of modularity; components can be added, removed, or modified depending on the needs of the building or the environment.

As Figure 2.9 shows, even the same module system has the potential to be implemented in different ways. It can be embedded and have partial control over environmental factors. Or it can be deployable and installed in the necessary places in a cost-effective way. Finally, if you design it in a dynamic structure independent of the building, you can increase your control over environmental conditions thanks to the mobility you achieve.



Figure 2.9. Embedded (a), deployable (b), and dynamic (c) façade types (source: Author).

2.2.2. Operational-based classification

Adaptive façades can be classified into types according to their responses to the environment. These include active, passive, and hybrid systems with their own benefits and design considerations. These systems address energy efficiency, occupant comfort, and sustainability objectives in varied contexts. Adaptive façade systems are unique in that they are able to respond to environmental change, automatically or semi-automatically, depending on the extent to which they rely on an external energy source or mechanism.

Passive façades utilize material properties and architectural strategies to respond to environmental conditions without requiring energy inputs. These systems are characterized by their simplicity, cost-effectiveness, and low maintenance. Examples include double-skin façades (DSFs), ventilated façades, and phase-change materials (PCMs), which facilitate natural ventilation and thermal regulation (Metwally and Ibrahim, 2024). The perforated mesh façades or insulation thermally insulated façades are examples of façades that we encounter in everyday life at the same time

Studies have shown that opaque façades and shading devices can reduce heat gains while maintaining visual comfort. Adaptive shading according to solar orientation is effective in mitigating solar heat gain in hot climates while still allowing sufficient daylight (Zhang et al., 2022). However, while passive systems are effective in static or moderately dynamic environments, they lack real-time responsiveness to rapid environmental fluctuations.

Active systems make use of mechanical components, sensors, and control algorithms to adjust in real-time to environmental stimuli. These systems use an energy source other than themselves but are accurate and can adapt in real-time. Popular examples are electrochromic glass, motorized shading devices, and kinetic façades, which can dynamically adjust solar radiation and daylight levels (Hafizi and Vural, 2022).

A study by Fernando et al. (2023) shows how kinetic façades have the ability to adapt their aperture size in real time, which greatly improves thermal comfort and daylight entry. Despite their benefits, the high implementation and running costs are restrictive meaning they're often only used in high-performance or specialized buildings.

As seen in Table 2.2, Hybrid adaptive façades combine the strengths of both passive and active systems, providing a balance between energy efficiency and real-time adaptability. These systems often integrate static shading devices with dynamic control mechanisms to achieve both sustainability and user comfort (Javanmard and Mangano, 2024). For example, hybrid façades may include photovoltaic-integrated shading systems, capable of both generating power and being adapted to sunlight.

In climates with high variability, hybrid systems work particularly well. Research by Mohtashami et al. (2022) shows that hybrid façades combining static thermal insulation with dynamic airflow systems can optimize energy performance while improving occupant well-being. Hybrid design is essential for the success of many sustainable façades today. Designing only a passive façade is inadequate, while designing only an active façade is costly and may not be sustainable. In this case, new searches and applications bring hybrid systems to the forefront.

Table 2.2. Passive, active, and hybrid system comparison (source: Author).

	ENERGY SOURCE	ADAPTABILITY	COST	MAINTENANCE	COMPLEXITY	EXAMPLES
PASSIVE SYSTEM	No external energy required; relies on natural material properties. □	Low; limited to static environmental responses. □	Low initial and operational costs. □	Minimal maintenance required. □	Simple; utilizes existing materials and structures. □	Double-skin façades, phase-change materials, ventilated façades. □
ACTIVE SYSTEM	Requires external energy for sensors, actuators, and control systems. □	High; responds dynamically to environmental changes in real-time. □	High initial and operational costs. □	Requires frequent maintenance of mechanical and electronic components. □	High; integrates advanced technology and automation. □	Electrochromic glass, motorized shading devices, kinetic façades. □
HYBRID SYSTEM	Combines natural properties with minimal external energy.	Moderate to high; balances static and dynamic adaptability.	Moderate; depends on the extent of active components.	Moderate; includes maintenance for both active and passive elements.	Moderate to high; integrates both active and passive technologies.	Photovoltaic-integrated shading, hybrid double-skin façades.

2.2.3. Movement based classification

Kinetic façade systems use different kinds of methods and movements. According to Mahmoud and Elghazi (2016), kinetic façade systems provide three main movements: translation, rotation, and scaling. A façade may move where just one motion occurs, or there may be combinations of these with a more complex dynamic result. The combining of a translation with a rotation gives rise to a rolling motion. Further, a simple basic motion may result in a complex dynamic action. For example, folding is fundamentally a rotation movement, yet in systems like Scissors-Like Elements (SLE), the rotational action inherently triggers a translational movement, which subsequently leads to scaling within the attached cladding material.

Başar (2014), while evaluating these movements, took these movements in spaces and user experiences as a basis and classified them as sliding, rotation, folding, expanding and contracting, opening and closing, and stretching. Although this classification was created for movements in buildings, it is also very suitable for classifying façade movements. In this section, the open and close movement is evaluated by including it in the rotation movement (see Figure 2.10).

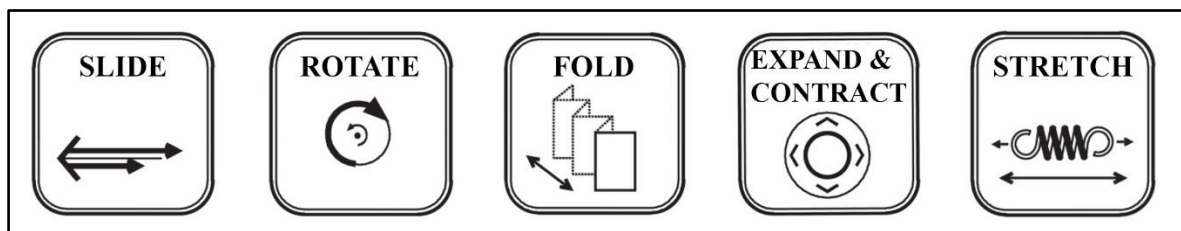


Figure 2.10. Movement variations in architectural structures (Reorganized and translated from (Başar, 2014).

Sliding façades

Sliding motions involve the linear movement of the façade components along one or several axes using tracks or guide rails. These movements can occur in horizontal, vertical, or diagonal directions, depending on the intended functionality. The sliding pathway may follow a straight, curved, or irregular trajectory, tailored to the architectural design and operational requirements. Başar (2014) states that this movement is usually seen as a horizontal or vertical shift in buildings.

Built-in 2017 in Shanghai, China, the Bund Finance Center offers users an aesthetic façade inspired by traditional Chinese weaving and utilizing the latest technology. Horizontally curvilinear slide tracks were created around the building. Bronze rods of different lengths are mounted on these slide tracks. In this way, a façade pattern was created in different layers on the façade (see Figure 2.11). Each layer has a different sliding movement within itself, resulting in a dynamic façade appearance.

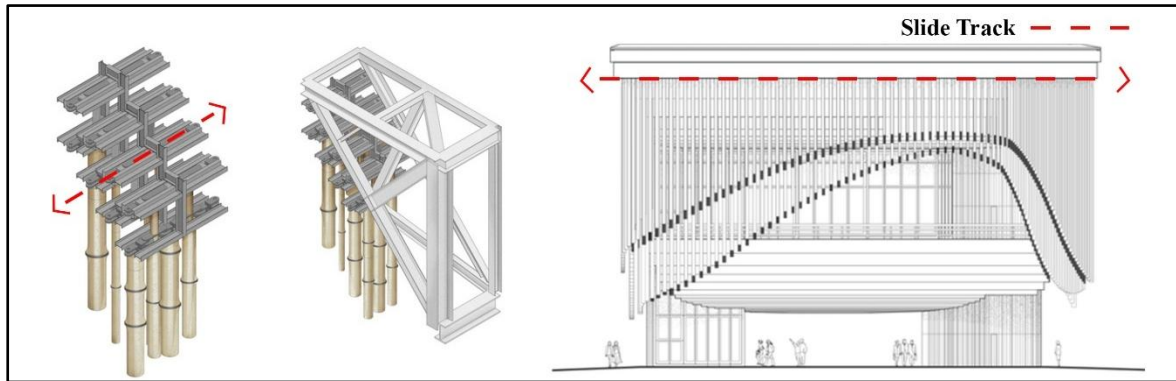


Figure 2.11. Bund Finance Center façade details and view (Reorganized from (Archdaily, 2017)).

Rotational movements

Rotating movements involve the pivoting of façade elements around fixed or variable axes. These systems can operate on single-axis, dual-axis, or multi-axis configurations, allowing precise control over solar shading, ventilation, or visibility. The rotational movement can range from partial rotations, such as louvers tilting at specific angles, to full 360-degree rotations for highly adaptable systems. Mobility is related to the mechanical design of the system, panel size, and geometry.



Figure 2.12. Hazza Bin Zayed Stadium façade details and view (Paech et al., 2014; Popovic)

Built-in 2014 in Abu Dhabi, UAE, Hazza bin Zayed Stadium is a semi-open stadium designed in a desert climate. The façade of the stadium features 612 PTFE/Glass membrane panels inspired by palm bole (Paech et al., 2014). These independent panels are mounted on a diagonal steel construction as seen in Figure 2.12. These panels, which do not obstruct the view from the inside, play an important role in the thermal comfort of the building and add aesthetic value to the stadium.

Folding movements

Başar (2014) defines folding as a movement in which the whole form changes without any deformation. Folding systems represent façade components designed to pivot or fold along specific hinges or axes, enabling them to open or close in a controlled manner. Basically, this movement around the axes creates changes in the geometry of the façade, allowing the amount of natural light for the interior space, the solar angle for photovoltaic panels, or the entrance volume for ventilation to be increased or decreased.

Built-in 2019 in Barcelona, Spain, Apartment Building for Four Friends is an example of a kinetic façade using the folding movement. It shows that this type of façade, which is usually used in expensive office buildings, can be used even in residential uses. Rectangular wooden façade panels are folded from the center axis to change the geometry of the façade (see Figure 2.13). Thus, they provide daylight performance and thermal comfort. It also gives the building an aesthetic appearance.



Figure 2.13. Apartment Building for Four Friends façade detail and view (Archdaily, 2019).

Expanding and contracting movements

The expansion and contraction movements involve changing a structure's volume so that it serves multiple purposes. This reversible motion creates changes across the whole form but without permanent deformation, making it flexible and reusable. The path of expanding or contracting may follow a linear, curve-like or irregular one for functional and aesthetic purposes. According to Başar (2014), example systems for this scope are truss systems, bar systems, systems sliding on one another in the plane, fan shaped systems.

Yazdani Studio has developed a kinetic façade proposal for the CJ Cheiljedang Research and Development Center building in Seoul, South Korea. Truss systems mounted on beam alignments can provide daylight control throughout the floor when opened (see Figure 2.14). This system is planned to be controlled by micro-linear actuators (Krymsky, 2011). Using perforated metal coatings on the truss system is aimed to provide shading for the spaces and to prevent visual communication with the outside.

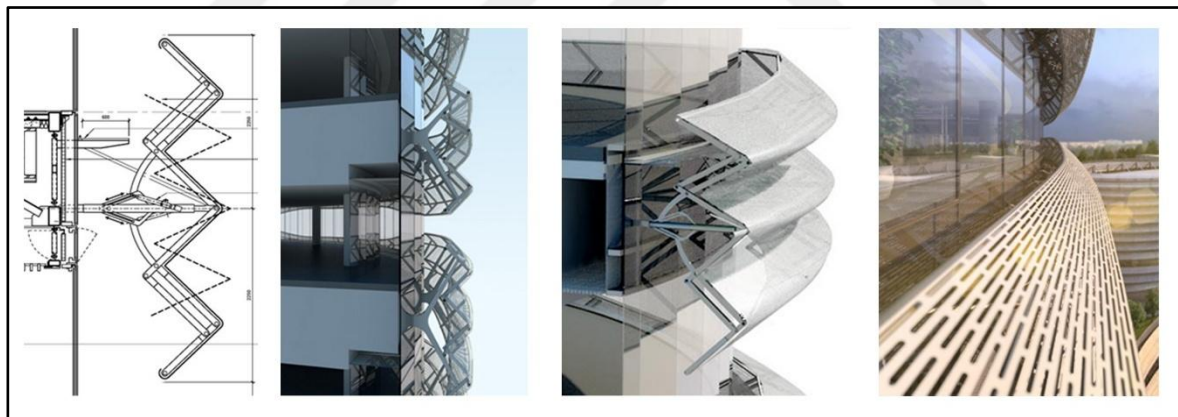


Figure 2.14. CJ RandD Center façade details (Michler, 2012).

Stretching movements

Stretch movements refer to the change of length of one or more façade elements in one or more directions. Usually, it is applied through flexible materials or tensioned mechanical systems. Stretching can help smooth the transition of façade lines and improve its energy performance by reducing thermal losses. A Elnawawy et al. (2023) have investigated the stretch potential of ETFE panels. The inner layer inside the panel is pushed by pneumatic systems to control the sun shading and opening and closing mechanism of the system (see

Figure 2.15). It states that the panels can increase the light received by the workspaces, reduce the temperature, and provide energy efficiency.

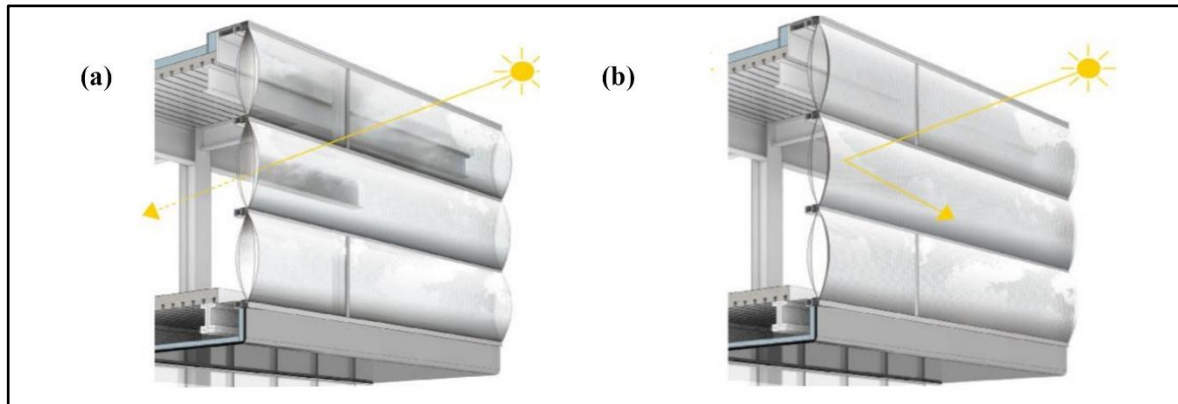


Figure 2.15. (a) Open mode of ETFE panels, (b) close mode of ETFE panels (A Elnawawy et al., 2023; Popovic Larsen, 1996).

2.2.4. Functionality-based classification

Functionality-based classification of adaptive façades categorizes them based on their operational goals, or functions. Adaptive façades are innovative mechanisms that help address environmental, energy, and comfort issues of building performance. This classification includes thermal regulation, daylight control, natural ventilation, energy generation, visual aesthetics, and acoustic performance.

Thermal regulation

The main goal of adaptive façades is thermal control which refers to maintaining the thermal comfort level inside while minimizing energy. These technologies can reflect solar heat and increase insulation according to external temperature. Most adaptive façade systems have thermal regulation as their main objective, in addition to daylight control or aesthetic appearance. To give an example of façades where thermal regulation is a main purpose, PCMs embedded in façades can store and release heat as the temperature of the façades changes, this reduces reliance on heating and cooling systems. Dynamic shading systems, such as louvers or blinds used to block sunlight at peak hours to manage solar heat gain but can allow passive heating at colder times.

Built in 2009 in Barcelona, Spain, the Media-TIC building is able to cope with the hot climatic conditions thanks to its adaptive façade. Ethylene tetrafluoroethylene (ETFE) panels are used on the façade. As seen in Figure 2.16, there are many of these panels on the façade and they are connected to a steel construction. ETFE panels are controlled by a pneumatic system. The panels gain volume by inflating and can return to their former form by deflating again.

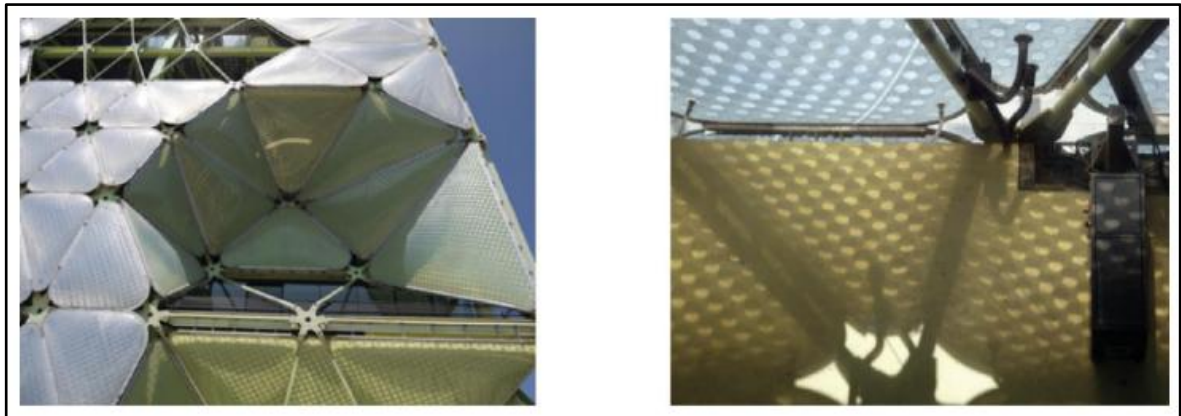


Figure 2.16. Appearance of the panels on the façade and technical connections (Juaristi and Monge-Barrio, 2016).

When the sun is detected, pneumatic systems fill the panels with nitrogen gas, causing them to inflate. At the same time, this gas gives these panels a thermal insulation function. These panels, which have a double-walled structure, can also control the sun thanks to their special texture when they inflate (see Figure 2.17).

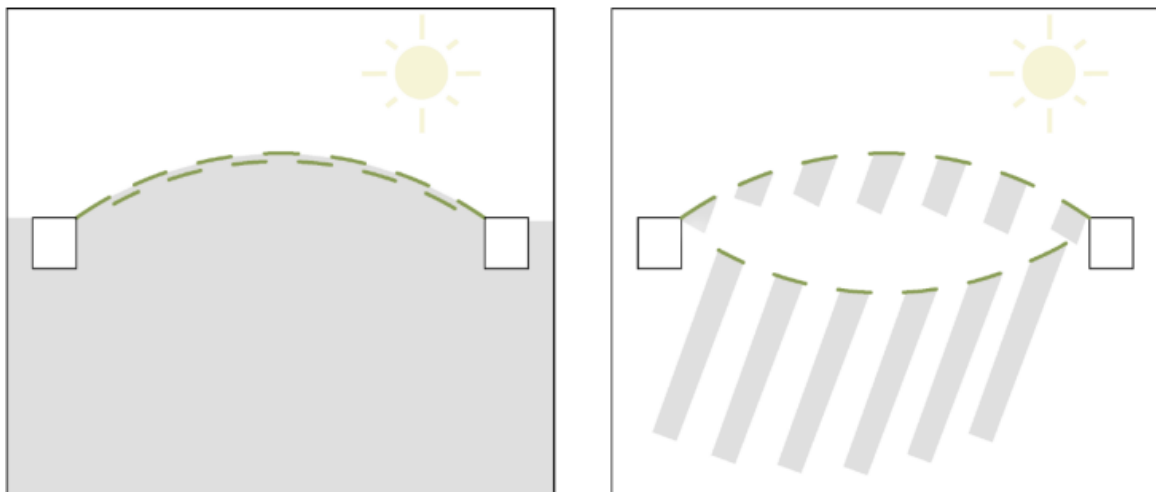


Figure 2.17. By interacting with the sun, the façade module swells and creates shading (Juaristi and Monge-Barrio, 2016).

Daylight performance

Daylight control systems are utilized to control the quantity and quality of natural light in a building and improve visual comfort while diminishing artificial lighting. Adaptive façades made for this purpose make use of technologies such as electrochromic glass, dynamic shading devices, or any light-redirecting systems. They improve occupant well-being, reducing glare, while at the same time optimizing energy efficiency. For example, light shelves can redirect sunlight deeper into interior spaces, reducing energy demands while maintaining consistent illumination.

Built in 2012 in Abu Dhabi, The United Arab Emirates (UAE) Al Bahar Towers is a glass-fronted office building in a desert climate. This building has adaptive features to both reduce heating and cooling loads, provide daylight control, and provide user comfort for indoor working environments. Except for the north façade, all façades have façade panels that detect the angle of the sun with smart sensors and can open and close in reaction to it (see Figure 2.18).

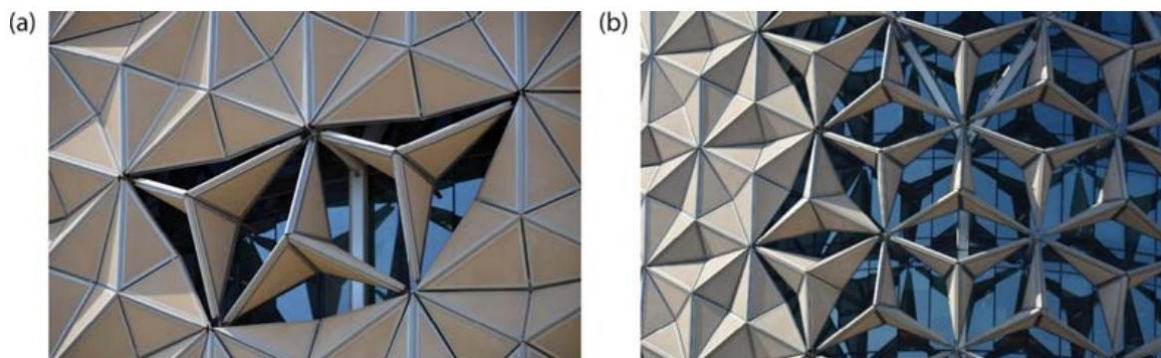


Figure 2.18. Closing the façade in response to the sun (a), balancing sunlight in the half-open position (b) s: (Attia, 2017) (photo courtesy: Terry Boake).

It can be closed to protect from excessive sun or to protect privacy when the sun is not shining. Likewise, it can be opened in order to benefit from the sun to the extent desired. One of the advantages of this type of façade is that there are no limitations such as open form or closed form as in other kinetic structures. Variable parameters such as the position of the sun change these façades instantaneously and the optimum form for that situation emerges. This situation eliminates the limitation of kinetic façades.

Natural ventilation

Ventilation adaptive façades are designed to guarantee better indoor air quality and thermal comfort by means of the exchange of air between the interior and exterior of the building. Operable windows, adjustable vents, or ventilated double-skin façades are usually provided for this purpose. Such systems are most effective in reducing the need for mechanical ventilation in mild climates, thus minimizing energy consumption. Real-time factors such as temperature, humidity, and air quality can be used by automated systems to control the ventilation to optimize performance.

Built in 2014 in Paris, France Breath Box Pavilion is one of the examples of natural ventilation on façades. Unlike other kinetic façades, a passive system is considered here. This building, which is very windy due to its location, has a façade design that interacts with the wind. The wind rotates the panels on the façades, entering the space and creating a dynamic image on the façade. In this way, natural ventilation is provided by a passive kinetic façade system (see Figure 2.19).



Figure 2.19. Breath Box Pavilion façade system (Archdaily, 2014) (photo courtesy: Paul Kozlowski).



Figure 2.20. Façade of Breath Box Pavilion (Archdaily, 2014) (photo courtesy: Paul Kozlowski).

Energy generation

Façades act as a shell separating the space from the external environment. Since this shell is in contact with external factors, it is the most important building element that can benefit from these factors. With these approaches on façades, it is aimed to reduce the energy consumption of the building and to develop sustainable approaches. While the electricity generated is used for the building's consumption, the façade design itself is used passively for daylight performance. Sureshkumar Jayakumari et al. (2024) tested this potential using building-integrated photovoltaic (BIPV) on kinetic façades (see Figure 2.21). The use of these panels reduced the total energy consumption of the building by 18%. This is an example of the passive effect. In addition, the energy production covered 26% of the building's energy needs (see Figure 2.22).

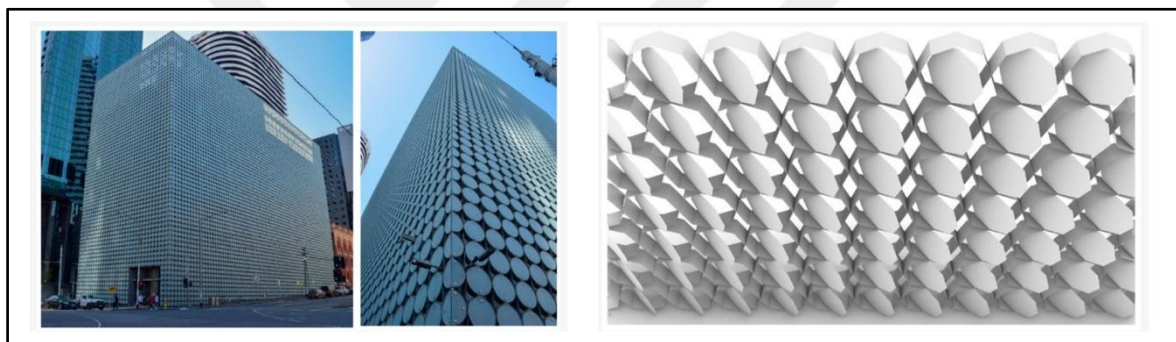


Figure 2.21. RMIT The Design Hub and parametric model (Sureshkumar Jayakumari et al., 2024).

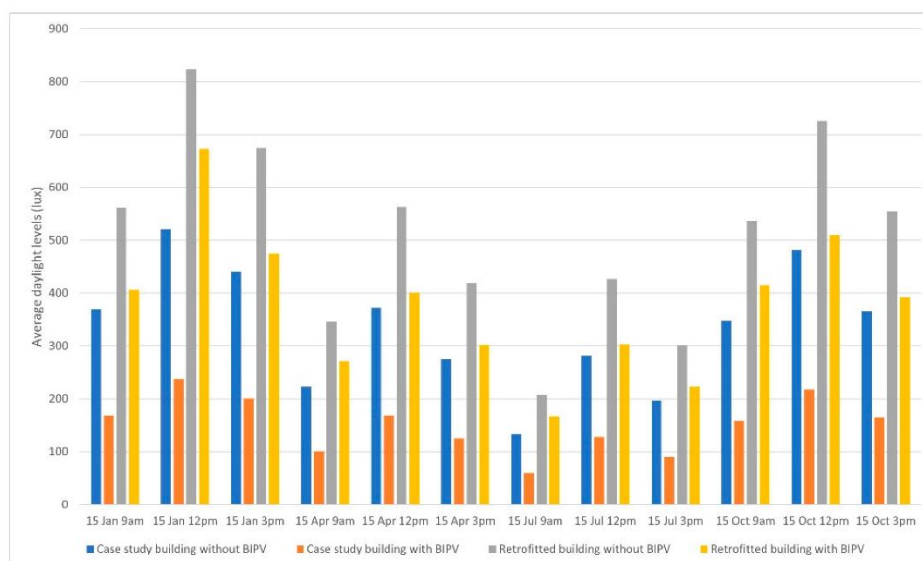


Figure 2.22. Daylight performance analysis (Sureshkumar Jayakumari et al., 2024).

Visual aesthetics

Aesthetics, one of the architectural design parameters, applies to adaptive façades as it does to other building components. Adaptive façades push the design limits thanks to their movement and ability to interact with different parameters. They can offer a dynamic and unusual appearance instead of standard static views. Façade designs that react to the sun, wind, or people in the environment give the building an artistic identity and can serve as a landmark that attracts people's attention. Many adaptive façades have aesthetic purposes as well as other functions. In addition to these, some buildings may have the sole purpose of being aesthetic and attracting environmental interest, while others have aesthetics as their main purpose and can serve other purposes, such as daylight performance as a passive system.

Built in 2012 on the car park façade of Brisbane Airport in Brisbane, Australia, the main purpose of the façade design is visual aesthetics. This façade, which is integrated into the wind parameter, reflects the dynamic structure of the wind on the façade. As the wind changes, the panels on the façade rotate and become a focal point for people. As seen in Figure 2.23, a large number of aluminum panels in rectangular form are connected to the construction installed on more than one façade. Each of these panels can rotate independently from the system. In this way, each panel reflects the intensity of the wind in its amount and creates the dynamism of the façade. The hollow structures between these panels and the angle formed by the movements of the panels on the façade block the sunlight and shade the interior.

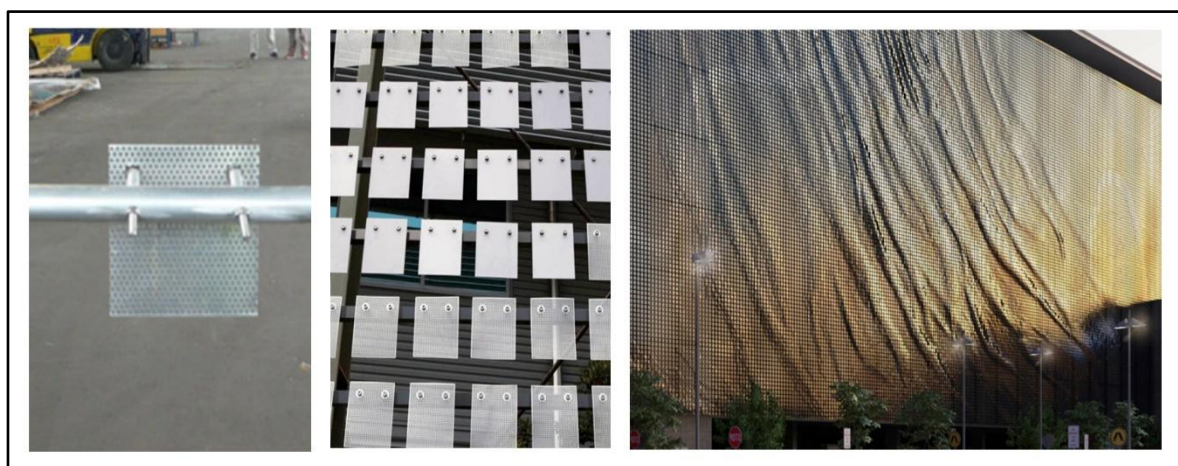


Figure 2.23. Façade details and view of Brisbane Airport (Designboom, 2012).

Acoustic performance

Studies on the acoustic performance of adaptive façades are quite limited. This situation is examined on different scales in the field of architecture. Studies in this field are evaluated on acoustic performance by changing the volume indoors or by using multi-layered panels, perforated surfaces, and dynamic acoustic barriers. For theater stages, this method has been used for centuries. In addition, from an urban scale, the sound is reflected or absorbed from façades and plays an important role in providing acoustic comfort for the city and the building environment (Balderrama et al., 2022). The material choices on the façades, the geometry of the façades, and the interaction of the façades with people also affect the acoustic comfort of people in spaces such as streets, squares, or courtyards outside the building.

At the building scale, studies are carried out on the effects of kinetic façades on acoustic comfort in the space. Secchi et al. (2022) analyze the acoustics and daylight comfort in a space by adding kinetic horizontal louvers. Although the research suggests that the kinetic horizontal louvers added in the first stage will negatively affect the acoustics of the space, it is seen that the use of sound-absorbing materials on these elements and changes in the angle of the façades are positive in reducing sound pressure. In addition to the acoustic benefits it provides, it has positive effects on daylight performance (see Figure 2.24).

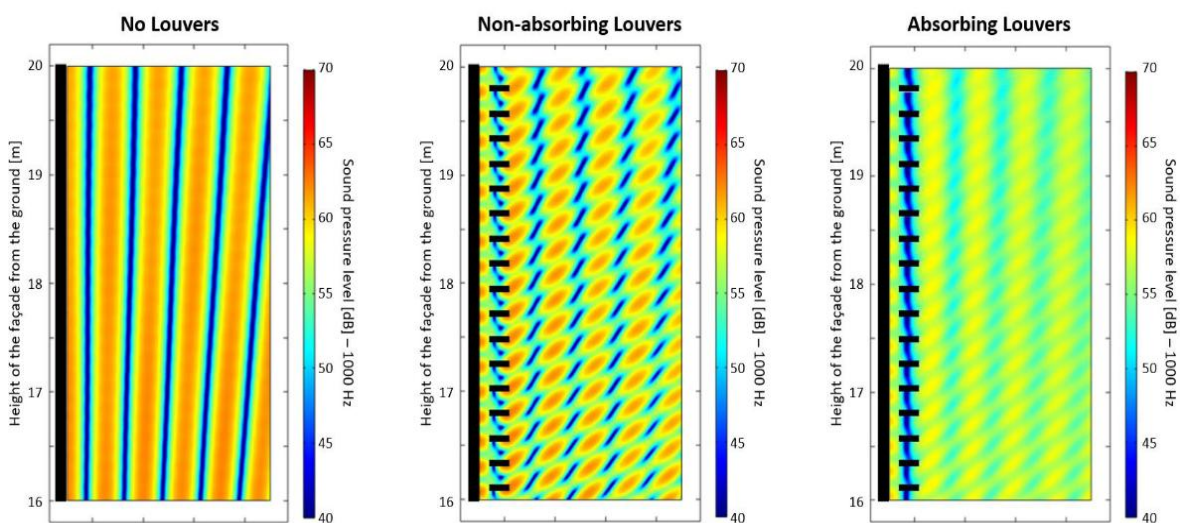


Figure 2.24. Sound pressure level simulation results. Left: without louvres. Center: non-absorbing louvres. Right: sound-absorbing louvres (Secchi et al., 2022).

As mentioned in the sections above, there are many academic studies on adaptive façades, and the number of buildings using these façades is increasing. In this context, these studies and buildings are analyzed. As seen in Table 2.3, the buildings and studies are analyzed in terms of the function of the building, the shape of the façade panel used, the axes of motion and type, and the function and size of the façade.

Table 2.3. Adaptive façade analysis and parameters (source: Author).

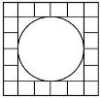
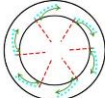
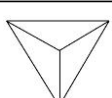
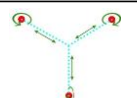
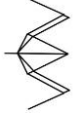
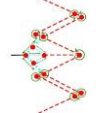
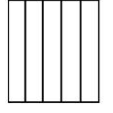
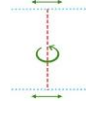
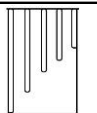
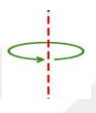
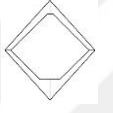
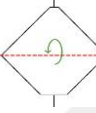
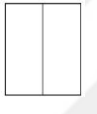
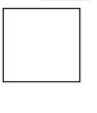
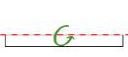
	Building Function	Panel Shape	Kinetic Module Form	Movement Axis	Kinetic Module Material	Movement Type	Façade Function	Scale of Kinetic Module
Institute du Monde Arabe (IMA, 2023)	Office and museum	Rectangular, Circular			Stainless Steel	Stretching	Daylight Performance	Full-Storey High
RMIT Design Hub	Research and post graduate education	Circular			Steel, Glass/BIPV	Rotating	Energy Generation	Multiple Number within Full-Storey High
ThyssenKrupp Quarter Essen Q1 Building	Office	Triangular			Stainless Steel	Folding	Daylight Performance	Full-Storey High
DOHA Tower (Karakuş, 2016)	Office	Butterfly			Aluminium	Expanding, Contracting	Visual Aesthetics	Multiple Number within Full-Storey High
Kiefer Showroom	Office and Showroom	Rectangular			EIFS Panels	Folding, Sliding	Energy Efficiency	Half-Storey High
South Denmark University Campus	University	Triangular			Perforated Steel	Folding	Daylight Control	Full-Storey High
Al Bahar Towers	Office	Triangular			PTFE Panels	Folding	Daylight Performance	Multiple Number within Full-Storey High
Media-TIC	Office	Triangular			ETFE	Stretching	Thermal Regulation	Multiple Number within Full-Storey High
India Expo 2020 Pavilion	Pavilion	Rectangular			Recycled Industrial Aluminium	Rotating	Daylight Performance and Visual Aesthetics	Multiple Number within Full-Storey High
Apple Dubai Mall	Shopping Center	Rectangular			Lightweight Carbon Fibre	Fold, Slide	Daylight Performance	Multiple Storey High

Table 2.3 (continued) Adaptive façade analysis and parameters (source: Author).

	Building Function	Panel Shape	Kinetic Module Form	Movement Axis	Kinetic Module Material	Movement Type	Façade Function	Scale of Kinetic Module
CJ R&D Center	Research and Development Center	Triangular			Steel and Fabric Membrane	Folding	Daylight Performance	Half-Storey High
Fünf Höfe	Shopping Center	Rectangular			Perforated Metal	Folding, Sliding	Daylight Performance	Full-Storey High
Bund Finance Centre	Mixed Use	Cylindrical			Magnesium Alloy Pipe	Sliding	Daylight Performance	Multiple Storey High
Algeahouse	Residential	Rectangular			Glass/Algae	Rotating	Daylight Performance	Full-Storey High
Hazza Bin Zayed Stadium	Stadium	Diamond			PTFE/Glass membrane panel	Rotating	Thermal Regulation and Visual Aesthetics	Multiple Number within Full-Storey High
Apartment Building for Four Friends	Residential	Rectangular			Wood	Folding	Daylight performance and thermal comfort	Full-Storey High
Breath Box Pavilion	Public Space	Rectangular			Glass/Mirror	Rotating	Natural Ventilation	Multiple Number within Full-Storey High
Brisbane Airport	Airport	Rectangular			Aluminium	Rotating	Visual Aesthetics	Multiple Number within Full-Storey High
Secchi et al. (2022)	Virtual Space	Rectangular			Sound-absorbing material / Wood	Rotating	Acoustic Performance	Multiple Number within Full-Storey High

The evaluation parameters become different and more complicated as the design parameters of the façades change and diversify. Many more parameters such as the type of actuators, response time, reacting factor, position, mechanical requirements can be added to these evaluations. Apart from the mentioned parameters, different digital tools and programs should be used to model and evaluate such façades. The evaluation of the results of these façades, which are algorithmic designs, is also tested as a result of simulations.

2.3. Tools Integrated into Adaptive Façade Design

Contemporary problems of the world such as climate change and population growth require sustainable and innovative approaches to energy efficiency and used resource reduction as well as greenhouse gas emissions. One promising solution to this problem is the application of adaptive façades to the buildings. Due to their high adaptability regarding changes in environmental conditions and user needs, adaptive façades can be the solution to the problems mentioned earlier. However, the performance of a dynamic system is influenced immensely by parameters like control strategy, location, and the goal of the façade. Thus, a proper adaptive façade design process becomes complex and highly interdisciplinary. This also means that to achieve an optimized design, many digital and non-digital tools need to be integrated into the AF design.

However, when correctly designed, an optimized adaptive façade can improve metrics such as daylight performance, the building's thermal environment, view, and efficiency in terms of solar energy utilization as well as the building's overall energy consumption (Chen and Tang, 2024; Voigt et al., 2023).

2.3.1. Integration of design, simulation, and optimization tools into AF design

The design of modern buildings and their elements, including adaptive façade systems, simulation programs, and modeling tools, can be thought of as inseparable elements from the design process. These tools help designers to evaluate various performance aspects of façades, such as thermal performance, daylight performance, efficiency and synergy with the building's structural system, and their responsiveness to environmental conditions around the building.

In the scope of adaptive façade design, digital tools such as Grasshopper, Honeybee, Ladybug, and EnergyPlus ease the parametric modeling phase and enhance performance-driven designs. With the integration of these tools into the design, designers can assess how their AF or their responsive elements interact with environmental and internal parameters like wind loads, user comfort, and solar radiation. For optimizing ventilation strategies inside the building, Computational Fluid Dynamics (CFD) software such as OpenFOAM or Autodesk CFD can also be integrated into the design process. This software allows designers

to assess and predict airflow patterns in and around the façade system, which is essential in terms of ventilation optimization.

For structural performance, Grasshopper plugins like Karamba3D, Alpaca4D, or software like SAP2000 can be used for evaluating the structural safety of AF's kinetic mechanism and frame structures.

In short, by combining several digital design tools, designers can make iterations and refinements in the design phase easier with a data-driven approach. This reduces the material used in design without sacrificing structural integrity while improving sustainability. This means that in a modern AF design process, integration of these tools should be a necessity rather than a convenience (Al-imam, 2024; Gediri Gökçen, 2023; Ulular, 2022).

Table 2.4 According to research the most used simulation programs are respectively:
Ecotect, eQuest, EnergyPlus, IES VE, Energy 10, DesignBuilder, DOE-2, HEED,
and Green Building Studio (Gediri Gökçen, 2023).

REVIT	RHINOCEROS 3D	ARCHICAD	SKETCHUP
Sefaira Insight 360 Dynamo Green Building Studio DesignBuilder	Grasshopper Ladybug Honeybee DIVA	EcoDesigner	Sefaria Greenspacelive

2.3.2. Integration of non-digital tools and technologies into AF design

Outer variable shading systems

Outer Variable Shading Systems (OVSS) are dynamic shading mechanisms that are integrated into AF design to increase daylight performance, energy efficiency, and regulation of solar radiation. Differing from the static shading elements, OVSS can change their position, angle, or their material properties to adapt to real-time changes in their environmental conditions, like the path of the sun, the speed of the wind, temperature, and user needs.

The main purposes of OVSS integration into AF design include:

- Controlling solar heat to improve cooling and reduce energy consumption.
- Preventing glare, thus increasing daylighting and visual comfort.
- Enabling the façade to dynamically respond to environmental stimuli for user comfort and performance.
- Achieving passive ventilation by enabling airflow through kinetic openings conceived by the façade's movement.

Inner variable louver systems

Inner Variable Louver Systems (IVLS) are dynamic interior shading mechanisms that can be adapted into designs of adaptive façades to help solar radiation regulation, glare, thermal comfort, and distribution of daylight inside the building. Unlike OVSS which was mentioned previously, IVLS primarily manages the internal environment by focusing heat control and internal light, which offers a more user-driven approach to the adaptability of the façade.

The main purposes of IVLS integration into AF design include:

- Adding adjustable louvers to prevent excessive brightness and maintain penetration of the natural light to indoor spaces that require precise visual comfort.
- IVLSs block or diffuse direct sunlight, thus preventing overheating and reducing reliance on other cooling systems.
- With the help of louvers, IVLS redirects sunlight deeper into the building. This enhances the autonomy of daylight thus reducing the need for artificial lighting.
- IVLS is often not fully automated and integrates manual or sensor-based controls for occupant usage, which enables customization.

Phase change materials

Phase Change Materials (PCMs) are materials that can store thermal energy they absorb, which they can release for thermal regulation. PCMs used in adaptive façade design to regulate temperature by passively maintaining heat indoors, thus decreasing energy consumption and increasing user comfort.

When considering the use of PCMs in adaptive façades, PCMs stabilize indoor conditions by storing heat during peak solar hours to release it when temperatures drop. This reduces the reliance on mechanical cooling and heating, lowering the overall energy consumption of the building.

Smart materials

Smart materials are synthetic materials that possess one or more properties that can respond to changes in the external environment without the need for a control mechanism or electronic component. These environmental factors can be stress, temperature, humidity, pH, magnetic field, light, or CO₂ concentration. In today's designs, many forms of smart materials are researched on implemented in architectural designs. Applied materials include shape-memory alloys, shape-memory polymers, thermos-bimetals, composite bilayers, electroactive polymers, wood, and hydrogels.

Based on their responsiveness these materials can be divided into three categories. These are photosensitive, humidity-sensitive, and thermal materials. They can also be distinguished by their production principles, such as anisotropy (programming material in the processing to achieve characteristic responses in different directions), hierarchy, and scale. They can also be categorized as programming and non-programming materials from a manufacturing perspective.

Integration of smart materials into adaptive façades enables façades to adapt to changes with minimal energy input and reduces façade's dependency on mechanical systems while improving occupant well-being.

Photovoltaic systems

Photovoltaic systems are one of the integrated systems into adaptive façades to enable solar energy harvesting from the building envelope, adding multifunctionality and aesthetic adaptability. Unlike the ones placed on rooftops, Building-Integrated Photovoltaics “and semi-transparent photovoltaic glazing can blend with the building's façade and its elements seamlessly.

Integration of PVs into façades can be done in many ways. They can be attached or applied to façade components such as walls, glasses, or blinds or replace them and act like a façade component. They can also be added to double curtain wall systems, which can provide electricity and heat simultaneously.

In short, integration of PVs into AFs can contribute to sustainability and self-sufficiency for high-performance buildings with a combination of energy production and environmental adaptability.

Agricultural integration:

Integration of agriculture into AF enhances the building's sustainability and efficiency by incorporating vegetating, vertical farming, and usage of bio-reactive systems. This integration transforms the building's façade into an active and living system that can produce food, purify the air, regulate temperature, and contribute to the biodiversity of the urban environment.

Integrating a vertical farming system into the AF grants the benefits of vertical greening and food production. However, it requires targeted design optimization for planting and picking. Façade planting systems also have high acceptability rates from residents, which can be seen as an additional pro.

2.4. Design Parameters of AF Design

Due to their multidisciplinary and complex nature, the performance and functionality of adaptive façades are influenced by a set of interrelated parameters that affect their response to the environment and user-driven changes. Factors like the façade's interactions with its external environment's conditions, its adaptation to properties, effectiveness on energy contribution, occupant comfort, or overall performance of the building are all defined by the façade's design parameters.

Choices and configurations on these parameters can vary by design and often depend on project-specific requirements and technological capabilities. For example, in the case of an

air traffic control tower, factors like, visual clarity, glaring, and adaptation of the façade to the climate govern the design, thus become the most important parameters. This subsection of the thesis explores the most influential parameters of adaptive façade design and their effects on the façade (Favoino et al., 2017; Loonen et al., 2013).

2.4.1. Control systems

Control systems are responsible for determining responses of adaptive façade to environmental stimuli and inputs coming from users. The type of control system dictates whether the adaptation process occurs automatically with the help of algorithms or user intervention. Control systems can be roughly divided into two.

Extrinsic control systems

This type of control system uses external inputs, user commands, or sensors as triggers. They are typically connected through a network of sensors which monitor external and internal environment parameters and activate the actuators based on real-time data to trigger façade adaptation (Addington and Schodek, 2005). Examples include electrochromic glass that darkens in response to solar intensity, dynamic shading systems that adapt based on daylight levels and indoor temperature, and ventilation façades that activate according to indoor air quality and wind conditions.

Table 2.5. Advantages and challenges of the extrinsic control systems (source: Author).

ADVANTAGES	Precise adaptability.	High synergy with building management systems (BMS) for higher energy efficiency.	Capability to respond fluctuations in indoor and outdoor environment.
CHALLENGES	System depends on external energy sources for operating.	Above average initial costs due to the complexity of automation systems and infrastructure.	Requires regular maintenance.

Intrinsic control systems

This type of system provides control without external commands by utilizing adaptive materials that react to the changes in the environment they belong to by going under physical or chemical transformations (Addington and Schodek, 2005). Because of that intrinsic control systems do not require active control mechanisms. Examples include thermochromic materials that change color based on temperature and shape-memory alloys that transform in response to heat.

Table 2.6. Advantages and challenges of the intrinsic control systems (source: Author).

ADVANTAGES	Doesn't require additional sensors, energy sources, or actuators.	Reliable and durable in long-term.	Easy integration with the building envelope.
CHALLENGES	Adaptability is limited by the material's capabilities.	Slower response time to changes and fluctuations in environment.	Limited control over performance optimization.

2.4.2. Actuators

Actuators are devices that convert electrical, thermal, hydraulic, mechanical, or pneumatic energy into movement to enable adaptation of AF elements (Loonen et al., 2013). In an adaptive façade, actuators often control shading, ventilation, or kinetic structure elements to optimize daylight, temperature, air, and energy. They work in response to data coming from sensors and occupant inputs.

Electrical actuators

Use electromagnetic energy as a source to conceive mechanical movements in adaptive façade elements. Due to their high sensitivity, they are ideal for façade elements where precise inputs are needed such as shading devices and glazing systems. However, their energy consumption can create another parameter for optimization and their mechanical wear over time can require regular maintenance.

Pneumatic actuators

Use compressed air and gas to conceive mechanical motion, usually by expansion or contraction of a diaphragm, bellows, or piston system (Addington and Schodek, 2005). They are often used in kinetic façade parts where energy efficiency is needed due to their lightweight and air-powered low energy consumption. They are also able to create soft and smooth movements. However, they have lower precision compared to electrical actuators.

Hydraulic actuators

Use fluid pressure (often oil or water) to move façade elements. They have high force output and thus are often used for the movement of large-scale façade elements where high forces are needed. They possess high load-bearing capacity, however, demand robust fluid management systems, maintenance, and high energy (Loonen et al., 2013).

Magnetic actuators

Use electromagnetic forces to conceive mechanical motion without physical contact. Magnetic actuators are suitable for providing small adjustments to the adaptive façade elements with smooth and silent motions. They also wear out very slowly due to the absence of friction and provide high precision. However, they require high energy and have limited load-bearing capacity.

Chemical actuators

Use chemical reactions to conceive movement. Chemical actuators are mostly used in adaptive façades that utilize material expansion, color change, or contraction in response to external conditions. They require no power to function along with minimal maintenance which makes them suitable for passive systems. However, they provide limited control and adaptability capabilities.

Natural/biological actuators

Use living organisms and organic growth for the adaptation process. Natural and biological actuators function mostly by growth, moisture absorption, or bacterial activity, which creates a response to environmental conditions for façades organically. They are self-sustaining, thus there is minimal need for mechanical intervention. However, their responses are very small, and they do not perform very well when there are fluctuations in the environment.

Thermal actuators

Utilizes temperature-sensitive materials to alter their shape, contract, and expand when there is a change in temperature. Thermal actuators are mostly used in façades with ventilation and glaze functions. Like natural actuators, they require no external energy sources and don't need complex control systems to operate. However, they can not control fully once their movement is triggered and they adapt to conditions slower than electronic-based systems.

2.4.3. Trigger events in adaptive façades

Trigger events in adaptive façade can be defined as conditions in environment, user action/behavior, or façade algorithm that triggers a response in façade. Adjustments a façade makes to its body and properties (ventilation, shading, transparency, insulation, etc.) are dictated by these events and are often aimed at optimizing efficiency, comfort, sustainability, or aesthetics.

Temperature

Temperature as a trigger event is linked to thermal comfort, energy efficiency, and behavior of the materials. Adaptive façades that use temperature as a trigger event can adapt passively through material properties or actively through mechanical and automated changes (Loonen et al., 2013).

Table 2.7. Adaptive responses linked to temperature as a trigger event (source: Author).

Strategy	Description	Application Example
Thermochromic material usage	Can change its color or transparency using temperature as a trigger	Reduced solar gain with the glazing coming from thermochromic material's darkening
Phase change materials (PCMs)	Can store thermal energy and release it when needed to maintain indoor temperature	Passive cooling and heating via PCM- infused panels in glazing or curtain walls
Smart ventilation systems	Automation of openings in the building for cooling and temperature maintenance	Smart louvers that can open at night to disperse heat and close during daytime to retain heat
Kinetic Shading Systems	Mobile external shades that can regulate exposure to sun	Cavities that allow pre-conditioned air intake, which reduces load on HVAC systems
Double Skin Façades (DSF)	A cavity between two skins of the façade that buffers temperature changes	Cavity enables pre-conditioned air intake, which also reduces load on HVAC systems

Precipitation

Precipitation as a trigger event is linked to rain, snow, and hail, which affect façade materials' durability, water management, and thermal insulation in adaptive façades. Adaptive façades that use precipitation as a trigger often aim for water resistance, water harvesting, and controlled drainage of water from the building (Loonen et al., 2013).

Table 2.8. Adaptive responses linked to precipitation as a trigger event (source: Author).

Strategy	Description	Application Example
Hydrophobic coated self-cleaning façades	Material that repels water and dirt, thus keeps façade clean	Adaptive façades with hydrophilic and photocatalytic glasses
Water-harvesting through façades	Collects water for reuse in watering and cooling	Perforated façade panels that can redirect rainwater into underground reservoirs
Kinetic waterproof panels	Panels that can deploy automatically during precipitation	Automatic rain shields on the exposed glass façades
Breathable Membrane Façades	Controlled vaporization and blocking of water	Façades with water runoff channels

Humidity

High humidity is related to a building's indoor air quality, energy efficiency, and material degradation. Adaptive façades that use humidity as a trigger event often utilize passive ventilation, materials with drying abilities, and sensor-controlled openings (Loonen et al., 2013).

Table 2.9. Adaptive responses linked to humidity as a trigger event (source: Author).

Strategy	Description	Application Example
Hygroscopic materials	Material that absorbs or releases moisture for balancing humidity	Wooden adaptive façades with expansion/contraction abilities based on humidity
Desiccant (Drying)- Based Façade Panels	Includes moisture-absorber substances to control indoor humidity	Façade panels with silica gels that can store and release water vapor
Smart ventilation systems	Air vents with sensors automatically triggered by the humidity level	Automatic rain shields on the exposed glass façades

Wind speed and direction

Wind speed and direction as a trigger event is related to natural ventilation, aerodynamic loads conceived by wind, and structural stability for tall building cases. Adaptive façades respond dynamically to wind to maintain user comfort, building resilience, and indoor air quality (Loonen et al., 2013).

Table 2.10. Adaptive responses linked to the occupant/user as a trigger event (s: Author).

Strategy	Description	Application Example
Wind-driven ventilation systems	Ability to control indoor airflow with wind force	Stack ventilations with towers that can capture wind.
Aerodynamic shape optimization	Can reduce turbulences and pressure differentials around the building	Façades with optimized curves to regulate airflow efficiently
Kinetic wind buffers	Façade elements that can mechanically mitigate wind stress	Retractable panels on façade that is deployed during high winds
Wind-responsive louvers	Adjustable louvers that can optimize airflow and ventilation depending on wind pressure	Façades that have panels with pivoting capabilities to intake fresh air.
Perforated or porous façades	Ability to reduce wind loads and control ventilation	Façades with perforated metals or meshes that can dissipate fierce winds

Light/solar radiation

Solar radiation can influence indoor temperature, lighting, and energy consumption (due to cooling need) heavily. Façades that control solar gain utilize passive cooling strategies in summer while utilizing heat retention strategies in winter (Loonen et al., 2013).

Table 2.11. Adaptive responses linked to light/solar radiation as a trigger event (s: Author).

Strategy	Description	Application Example
Solar-responsive louvers	Can adjust themselves automatically to control solar penetration	Façades with louvers that can change their position vertically and horizontally based on the intensity of the sun.
Photovoltaic-integrated façades (BIPV)	Façades that can convert sunlight into energy while also providing shading	Façades with solar glass panels that reduce heat gain and generate power.
Light-redirecting façades	Increases daylight by redirecting light and reduces artificial lighting need	Façades with prismatic or reflective panels that can redirect light into deeper interior spaces

Glare/sun location

Adaptive façades that use glare and sun location as triggers aims to optimize daylighting without harsh contrasts to avoid vision impairment, reduced creativity, and discomfort (Loonen et al., 2013).

Table 2.12. Adaptive responses linked to glare/sun radiation as a trigger event (s: Author).

Strategy	Description	Application Example
Automated electrochromic glazing	Can change façade's opacity based on glare intensity	Façades with smart glasses that can dim when glare is increased
Responsive solar shading systems	Kinetic shading elements that can adapt according to the sun's position	Façades with dynamic shadings that move throughout the day
Parametric sun-tracker façades	Uses real-time data to adapt façade positioning	Façades with algorithm-controlled panels that rotate to minimize glare

3. KINETIC RECIPROCAL FRAME (KRF) STRUCTURES

To understand KRF structures, it is first necessary to understand reciprocal frame (RF) structures. RF structures are self-supporting frameworks that consist of interdependent linear elements, each of which is supported by another within a closed structural loop. These structures can stand stably with or without the use of any connection, and they also allow small parts to come together and span large openings. KRF structures are reciprocal frame elements connected to each other with connections that will allow movement on each other instead of fixed connections. With this connection design, the position of the elements is not fixed but varies on each other. This position difference changes the geometry of the system in both plan and section planes (see Figure 3.1).

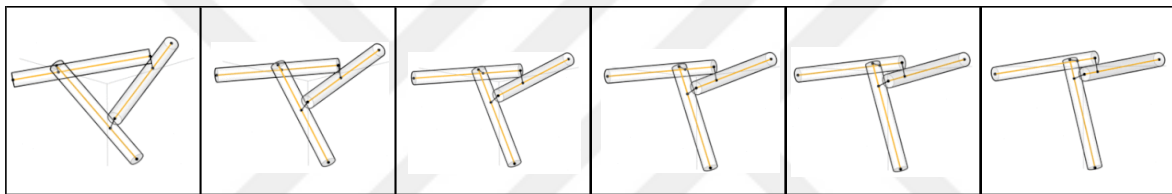


Figure 3.1. Geometric and elevation change of KRF structures (source: Author).

This movement arising from the displacement of the elements on each other is adaptive. The factors that make up these frames, such as the number, form, and length of the members, come together to create different designs. For this relationship between the members, Asefi and Bahremandi-Tolou (2019) state that no matter what the composition is, the geometry should always have two connected members at a time. Members come together to form a frame. For this frame, the minimum number of members required is three while there is no limit for the maximum number (Baverel and Saidani, 1999). If we consider the application of KRF structures, when the number of bars increases, the diameter of the frame should increase and the length of the members should shorten.

The installed frames can come together to form a more complex RF system. In the same way, this modular replicability feature in RF systems can also be said for KRF systems. The kinematic analysis of these systems is more complex and the mobility of the system can be limited by the relationship between the elements. In the design of KRF structures consisting of multiple frames, the length, shape and number of members affect the mobility of the system.

3.1. Reciprocal Frame Structures

Although RF structures have been used by many civilizations and designers throughout history, this design has not been given any name. The name Reciprocal Frame was first used by Graham Brown in 1987 for a roof structure he wanted to build for his own home and commercial structures (Chilton, 2009). This name is due to the originality of the way in which the elements of the roof support each other. So, RF structures are not the name of a geometric form or a model, but the name of a method of constructing a system.

This system is formed by the combination of frames and this system is called nexorade (see Figure 3.2). The member that makes up Nexorade is called a nexor. This word is of Latin origin and means 'link' (Baverel, 2000).

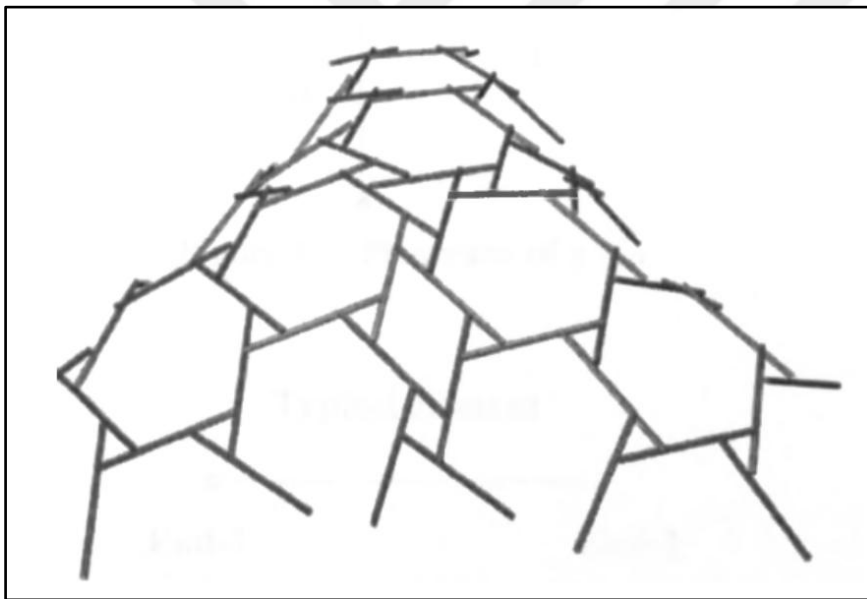


Figure 3.2. Nexorade (Baverel, 2000).

Members called nexors come together to form a 'fan'. The fan is characterized as the most basic element that constitutes these systems (Özen, 2022). At least 3 nexors are required to form a fan and there is no limit to the maximum number. As can be seen in Figure 3.3, as the number of nexors increases, the geometry in which the fans are formed also changes. As mentioned in KRF structures, in these systems, one nexor is connected to two different nexors regardless of the geometry.

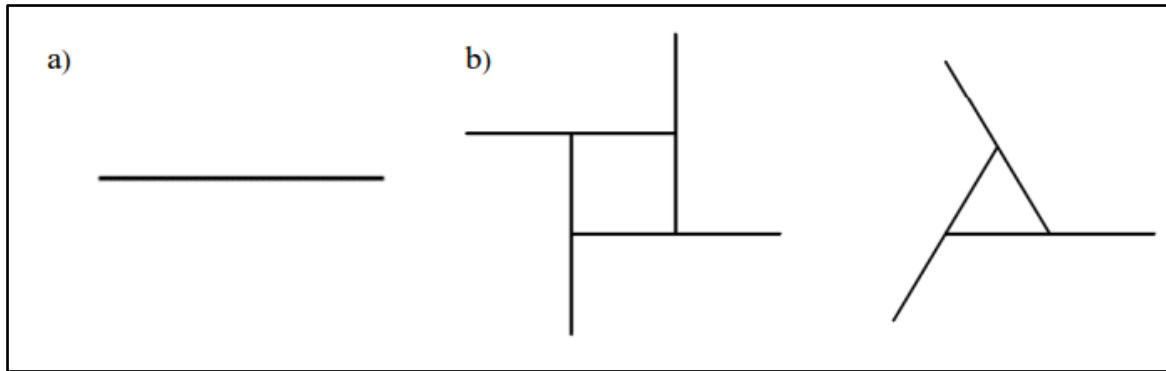


Figure 3.3. a) Nexor, b) Triangular and rectangular fans created by nexors (Özen, 2022).

When the fan formation parameters and methodology are examined, Chilton and Choo (1992) first put forward the geometric parameters of this formation. They created equations using simple trigonometry and made explanations (see Figure 3.4). Popovic Larsen (1996) explained and visualized these parameters in detail. Parameters introduced by Chilton and Choo (1992):

n - the number of nexus

r_0 - outer radius

r_i - inner radius

H - vertical rise between the outer supports and nexor intersection points

h_2 - vertical spacing between nexor centerlines

L_n - nexor length

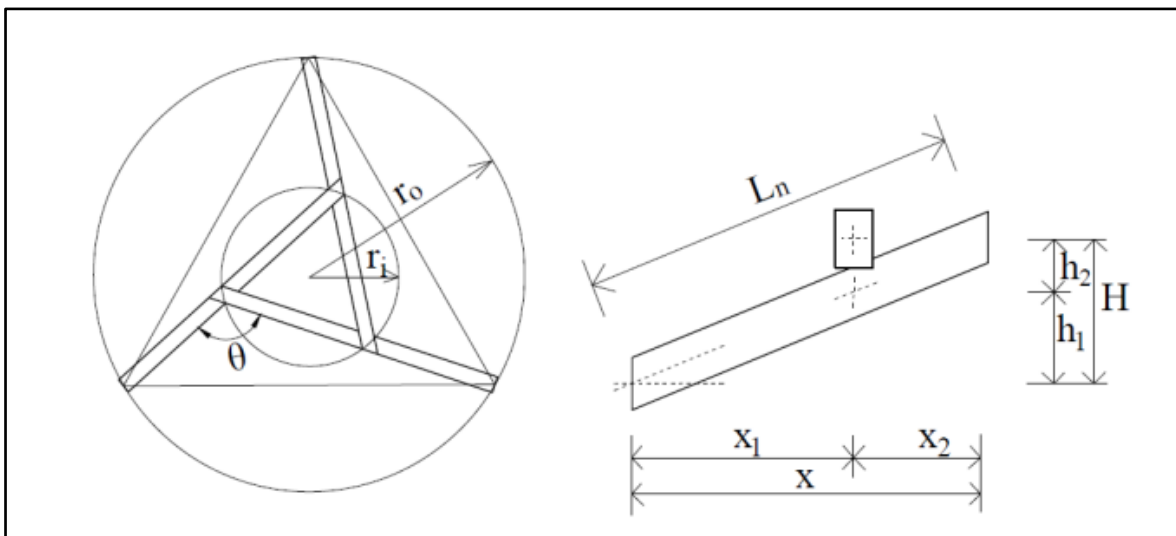


Figure 3.4. Geometric parameters of a fan (Reillustrated by (Özen, 2022) and source: (Popovic Larsen, 1996).

A fan is basically formed concerning two circles. One of these circles is the inner circle, and the other is the outer circle. The inner circle refers to the position where the inner junction points of the nexors will meet, while the outer circle determines the position of the outermost points of the nexors. L_n refers to the length of the nexors. In other words, this length is also the distance between the positions of the nexor on the inner circle and the outer circle.

As seen in Figure 3.4, the angle shown as ' θ ' represents the angle of the junction between two nexors. This angle can change independently of the geometry. This angle is called 'side angle' (Baverel, 2000). When a rectangular fan is formed, $\theta = 90^\circ$, but it is possible to change this angle by decreasing or increasing the radius of the inner circle. This means that instead of an orthogonal fan, a fan is formed with more oblique angles.

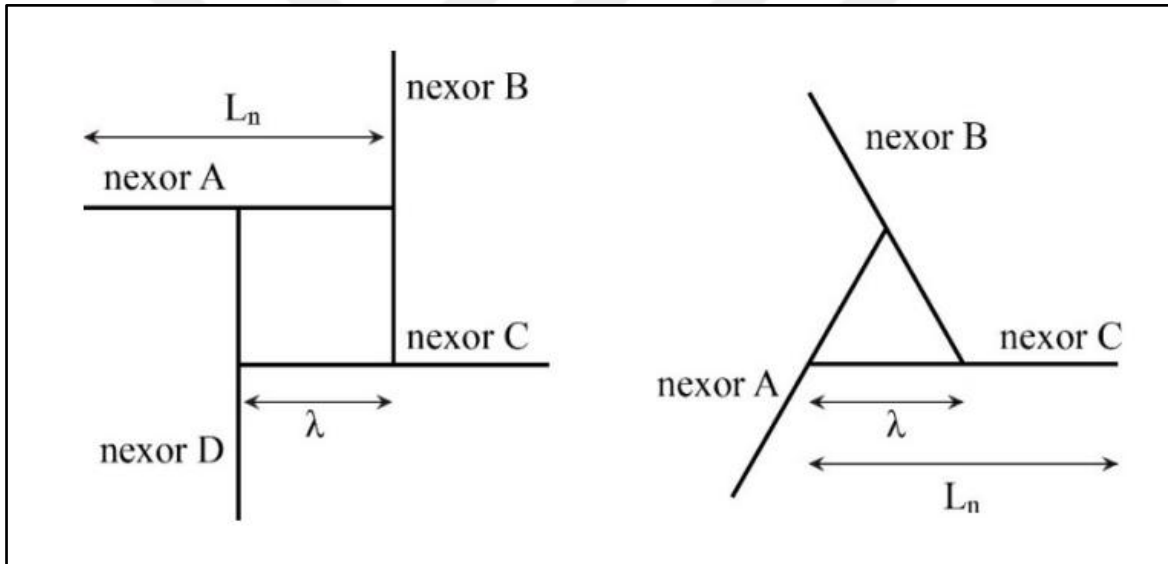


Figure 3.5. Member and details of fan (Reillustrated by (Özen, 2022) and s: (Baverel, 2000).

As can be seen in Figure 3.5, the formation system of RF structures results in two points arising from the intersection of one nexor with two other nexors. The distance between these two points is denoted by ' λ '. This distance is also called 'engagement length' (Baverel, 2000). The intersection points of the Nexors on the inner circle create a geometry. This geometry also defines the type of fan. Baverel (2000) calls the geometry formed by the intersection of nexors around the inner circle 'engagement window'.

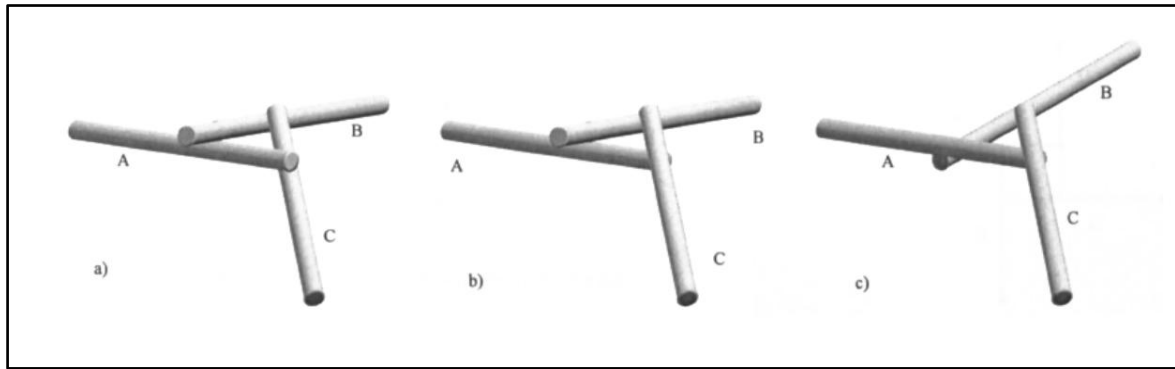


Figure 3.6. End dispositions variety of a triangular fan (Baverel, 2000).

A fan can be formed in more than one way. This is related to the above-below relationship of the nexors with each other. A nexor can be below one of the other two nexors it intersects and above, completely below, or above the other (see Figure 3.6). In the case where it is completely above or below, inter-nexor connectivity is required for the stability of the system, whereas in the case shown in Figure 3.6a, the system can be stable on its own.

Baverel (2000) also mentions a different classification of fans. This classification is related to the direction of nexors coming together. The clockwise fan is defined as a rightward fan and the counterclockwise fan is defined as a leftward fan (see Figure 3.7). This difference in fan direction can completely change the formation of nexorade. This change is related to the perspective from which the nexorade is viewed. Someone looking from the bottom of the system can see a rightward fan, and someone looking from the top of the system can see a leftward fan.

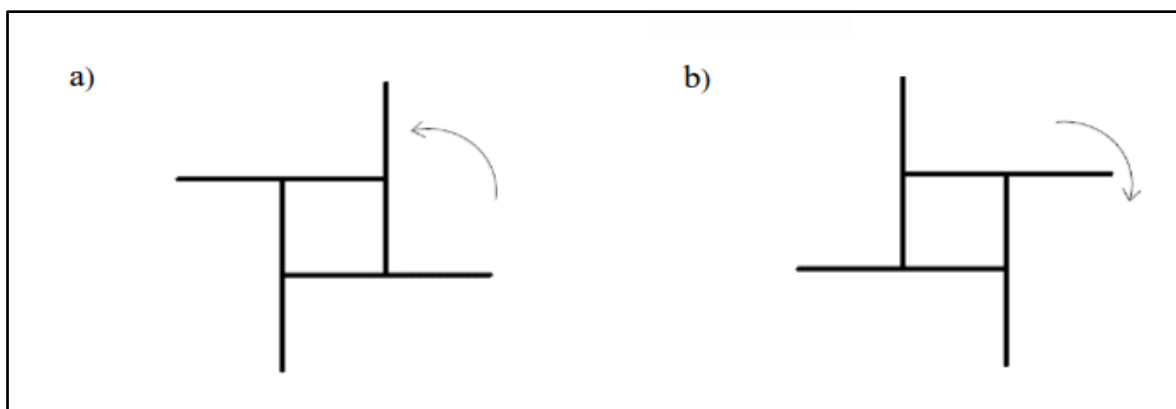


Figure 3.7. a) Leftward fan plan view, b) Rightward fan plan view (Özen, 2022).

Özen (2022) defines eccentricity as the minimum perpendicular distance between the centroids of these cross-sections at the connection of two nexors (see Figure 3.8). It is indicated by 'e'. This parameter is related to the thickness and cross-section of the nexor. The side angle change between nexors does not change this value (Baverel, 2000). However, the base angle, the angle between the nexor and the ground, will affect this value. As the base angle increases, the nexors will meet each other more obliquely and the 'e' value will increase. When the base angle decreases, this value will decrease and when the nexors are at the same level, $e = 0$.

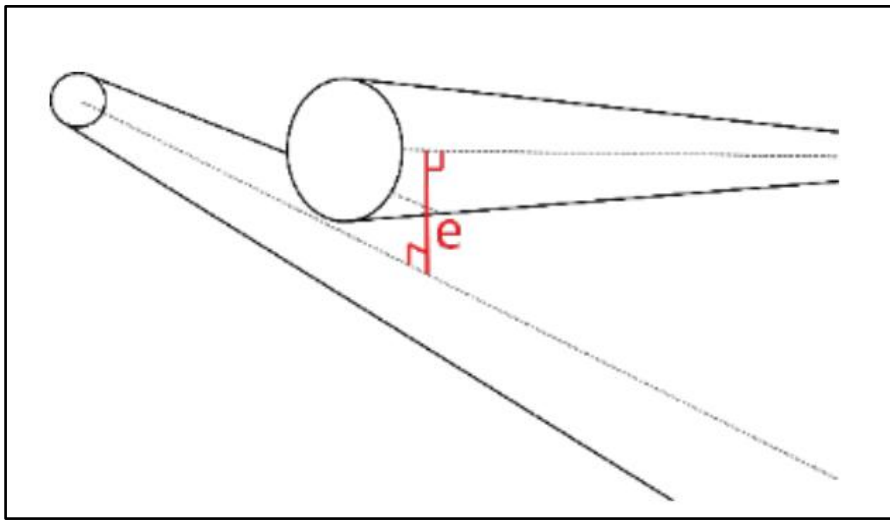


Figure 3.8. Eccentricity (Özen, 2022).

Although all these parameters are mentioned separately, together they form a system and are interdependent. If we want to change any parameter in the system, either the design changes or other parameters need to change to balance it. This equation of parameters allows the system to be easily implemented in different ways in real life. For example, you can increase the nexor length and base angle to increase the height you need. To get a large space, you can increase the number of nexors to get geometries close to a circle and avoid corner problems. To give an example of parameter changes that do not change the design, you can statically balance this by reducing the number of elements and increasing the thickness of the cross-section. Increasing nexor lengths can be balanced by decreasing the radius of the inner circle, or by increasing the base angle. Different practitioners and civilizations discovered these parameters centuries ago and applied them in their cultures.

3.1.1. Background of reciprocity

Although the potential of RF structures to allow rods supporting each other to pass through openings has been used by many civilizations, the origin of this system is unknown. The principle of reciprocity in structural design has been known for several thousand years in many cultures. One of the first known uses of reciprocal frames occurred in prehistoric shelters, with primitive woven branches and wooden elements set up to create self-supporting structures.

The Indian tepee is one example of early reciprocal structures. The construction used long wood poles leaned against each other in a circular manner (see Figure 3.9). The wooden bars form a space by supporting each other, and there is no need for any column in the center. These were covered with animal hides or fabric. Using a reciprocal method meant it was easy to assemble and disassemble, which suited nomadic use. (Popovic Larsen, 2007).

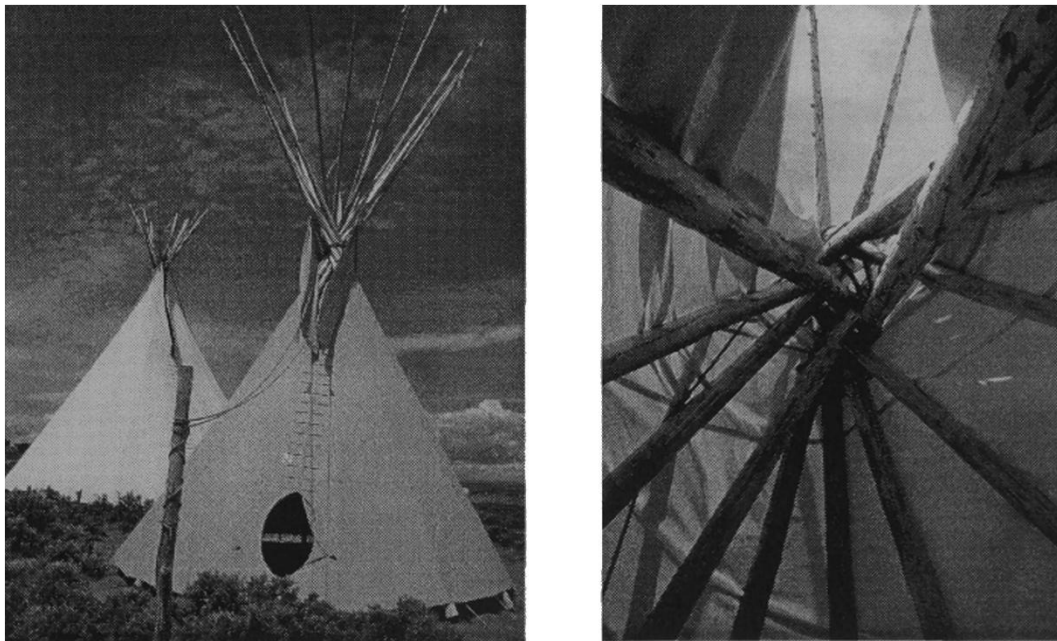


Figure 3.9. Indian Tepee (Popovic Larsen, 1996).

Such non-permanent tent typologies are similar and evolving due to their fast and low-cost erection principles. Columns built on each other have become one of the most basic construction techniques as they do not need to span large distance.

The use of reciprocal systems to form the roof in stable and small pieces is one of the most important discoveries in architecture. As seen in Figure 3.10, the stacking of beams on top of each other to form a roof can be observed both in the old Turkish lantern roof and in the Hogan dwellings. Stacked on top of each other, these beams can span wide openings by locking each other and provide a rigid structure. In order to close the gaps between the wooden beams and to make the structure more resistant to harsh climatic conditions, this structure is covered with materials such as mud or adobe. (Popovic Larsen, 2007).

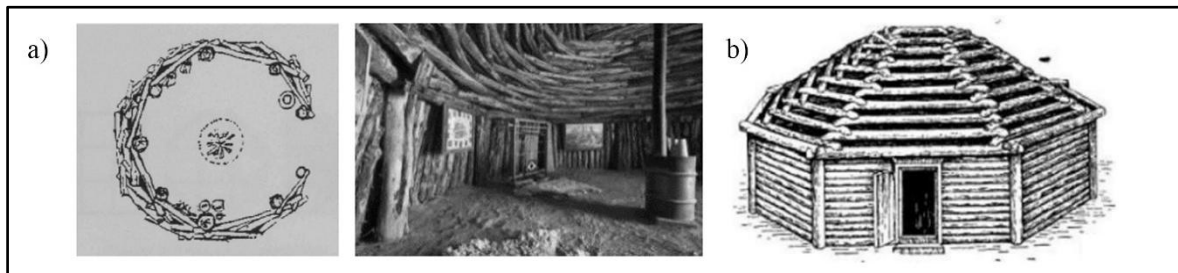


Figure 3.10. a) Hogan dwellings (Popovic Larsen, 1996), b) Old Turkish lantern roof (Kutlu, 2020).

Traditional timber pagodas and bridges in ancient China were constructed using reciprocal principles. One of the most incredible is the Rainbow Bridge in Shandong, where the interlocking of wooden members improves load distribution while reducing the use of external supports (see Figure 3.11). This construction method built stronger defenses against natural disasters like earthquakes and floods showing an advanced understanding of reciprocal systems (Karakoç, 2017).

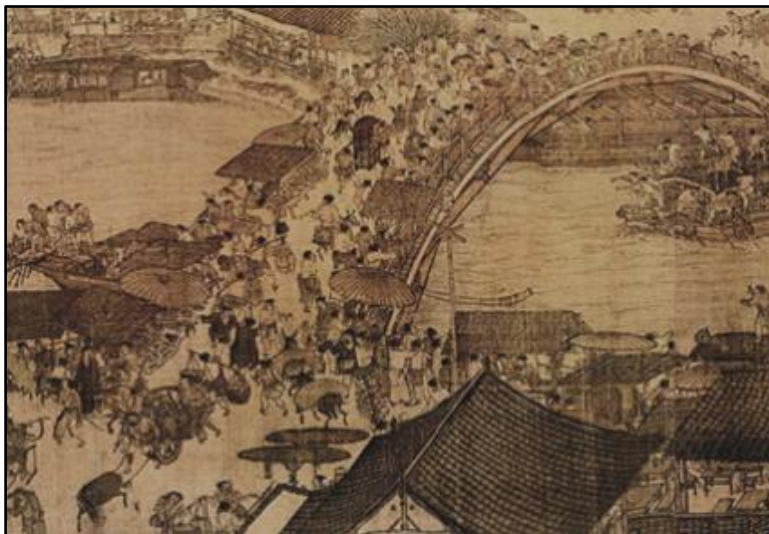


Figure 3.11. Rainbow Bridge (Karakoç, 2017).

Reciprocal frames were also used in medieval Japanese architecture, especially for temples and shrines. In 12th-century Japan, the monk Chogen invented methods for spiraling layers of timber beams. The measures taken not only helped reinforce the building but also helped it cope with environmental loads like typhoons and quakes (Popovic Larsen, 1996). This technique, understood early on, was the concept of dynamic load distributions, a basic feature of reciprocating frames.

The use of this technique, which has the same system as RF structures, is seen to be used in the concept of Mandala, a Buddhist symbol. Mandala is a Sanskrit word and means 'magic circle' (Gombrich, 1979). The geometries that Chogen used for temples with this system were directly referenced from Mandala geometries and used in the development of systems that can be described as 'fan' for the roof design of these temples. (Pugnale and Sassone, 2014, p. 14).

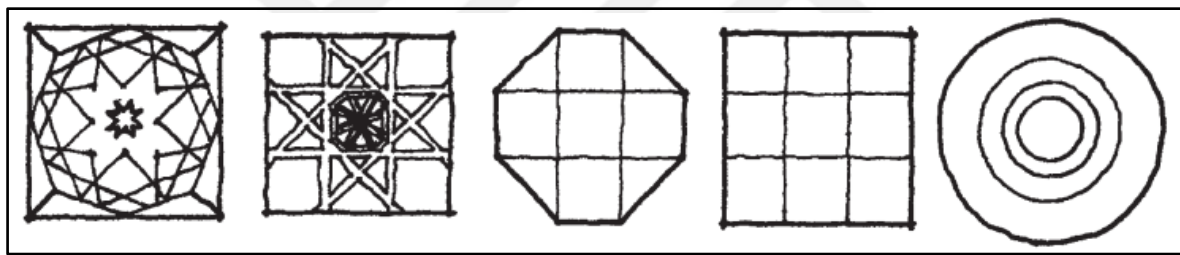


Figure 3.12. Sketches of Mandala geometry (Popovic Larsen, 2007, p. 8).

In the medieval times of Europe, flooring and roofing systems were often composed of reciprocal frames. Architectural drawings by Villard de Honnecourt (13th century) contain one of the first technical illustrations of reciprocal floor and roof beams that depend upon and support each other for material economy and load-bearing (Pugnale and Sassone, 2014). As seen in Figure 3.13, these girder systems consist of an RF structure with 4 main beams, and intermediate beams are connected to these main beams with the same system. Popovic Larsen (1996) states that this four-beam girder system is generally planar, but 3-dimensional Rf structures can also be seen. These examples, similar to KRF Structures, are a testament to the potential of such systems, similar to KRF Structures, to gain height in the third dimension.

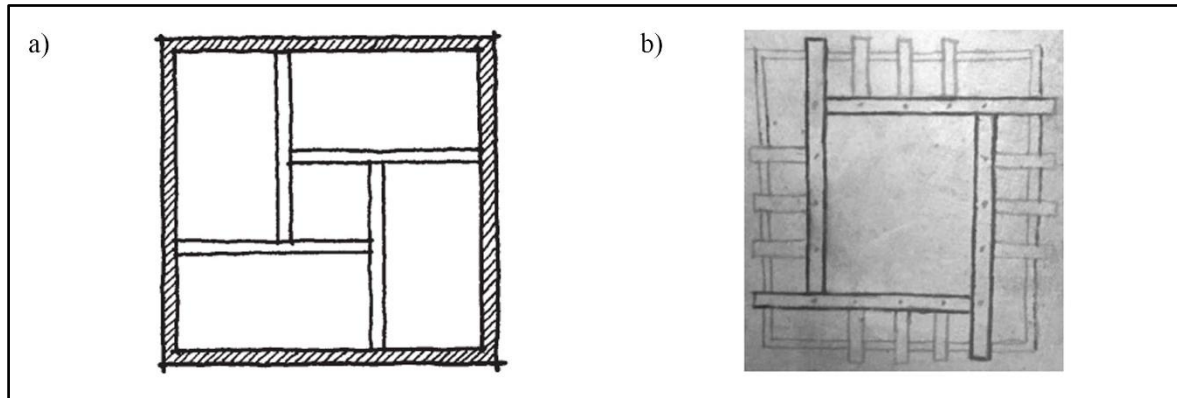


Figure 3.13. a) Medieval floor grillage (Popovic Larsen, 2007), b) Sketch of Villard Honnecourt planar grillage (Barnes, 2009).

The concept of reciprocity was further explored in Renaissance architecture, with Leonardo da Vinci being one of the first to systematically analyze the geometric and structural potential of reciprocal arrangements. Leonardo da Vinci also clarified the application of RF structures by studying the spatial, nexorade-like arrangements, as in the bridge sketch (Douthe and Baverel, 2009).

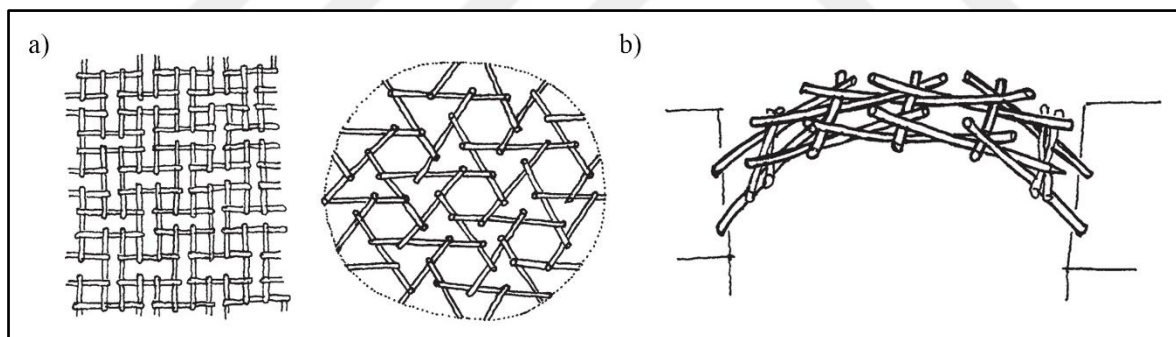


Figure 3.14. a) Sketches of gridding assemblies by Leonardo da Vinci (Popovic Larsen, 2007, p. 10) b) Sketch of Leonardo da Vinci Bridge (Popovic Larsen, 2007, p. 11).

Davinci further developed the 4-beam planar RF structures system and designed beams in complex geometries in the RF structures system (see Figure 3.14a). Again, by utilizing the potential of these systems to gain height in the third dimension, he designed a bridge that does not require any connection and uses only reciprocity principles (see Figure 3.14b). His bridge drawings show how beams that are short and interdependent could be laid out in a reciprocal manner to build lightweight but stable structures that can span over rivers without intermediate supports (Douthe and Baverel, 2009). The idea was first proposed using short, dependent beams arranged in a reciprocal network.

The problem of spanning large distances through short beams was similarly analyzed by the Italian architect Sebastiano Serlio in the case of roofs. Popovic Larsen (1996) states that Serlio solved the problem that arises when the span is 4.57 meters wide and the available beams are 4.26 meters long with planar grillages, as shown in Figure 3.15a. In addition, this solution is similar to Honnecourt's flooring solution. This again demonstrates the potential of these systems in architecture for openness and durability.

Wallis (1972) is the first known study investigating the load transfer principles of RF structures. He did not do these studies on real buildings but on small-scale models and analyzed them in detail (Popovic Larsen, 2007). As can be seen in Figure 3.15b, a complex system similar to Davinci's designs was established, and the joints were named. He then performed moment and load transfer analyses and obtained important data on the applicability of these systems.

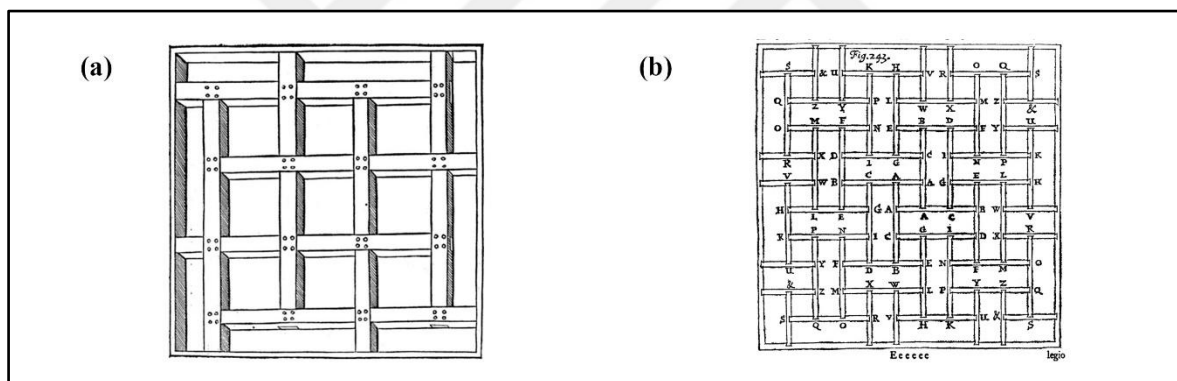


Figure 3.15. a) Sebastiano Serlio RF gridding (Houlsby, 2014, p. 209) b) John Wallis's planar RF gridding (Alizade, 2019; Houlsby, 2014, p. 210).

In the 1800s, engineers codified reciprocating structures for large developments. Friedrich Zollinger invented the Lamella Roof System, which used a pattern of interlocking wooden beams repeating geometrically as an alternative to wooden trusses to respond to the need for rapid housing (Karakoç, 2017). This meant designers could turn to reciprocal frameworks for large structures in industrial and military buildings, as the Orvieto Hangar by Pier Luigi Nervi witnessed scenario (Baverel, 2000). This roof system is used even in residential buildings. Figure 3.16 shows a model of this roof system by Pier Luigi Nervi. Very large spans are made possible by short beams and can be built quickly.



Figure 3.16. Physical model of the Orvieto hangar by Pier Luigi Nervi (Popovic Larsen, 2014).

The design of reciprocal frame structures has changed a lot in modern architecture and engineering, largely due to advances in digital fabrication, computational modeling, and materials science. The move from normal wood reciprocal frames to CNC routers and robot accurate assembly and 3D printing has allowed new levels of precision and efficiency. Modern architects and engineers get access to parametric design software like Grasshopper, Rhinoceros, and Karamba to realize structurally optimized RF configurations for any given environment and functional design.

One of the biggest advantages of modern reciprocal frames is that they can effectively distribute loads which will strengthen their structure and reduce the amount of material they use. They make low-weight yet highly stable modular constructions due to the efficient usage of loads. The modular nature of RF systems allows them to be used in temporary, deployable, and kinetic structures where flexibility and reconfigurability are important. Due to these benefits, RF structures are suitable for emergency sheltering, adaptable building façades, and sustainable pavilion designs.

In addition to that, current research is investigating multi-material reciprocal frames incorporating composites, carbon fiber, and bio-based materials to improve performance properties. To guarantee that reciprocal frames not only fulfill current architectural standards but also proactively optimize for impending structural necessities, real-time structural monitoring and AI-enabled load adjustment are in the works.

Today's reciprocal frames can distribute loads and dynamic forces evenly, or in other words, they reduce material consumption. Also, the modular nature of RF systems makes them suitable for a variety of temporary, deployable, and kinetic structures that can be moved and reassembled. It renders them especially relevant for disaster relief shelters, green pavilions, or changing building façades.

The Bibracte Archaeological Shelter in France is an example of how reciprocal frame structures are used in contemporary conservation architecture. This shelter is designed to protect excavation sites temporarily and features lightweight and prefabricated reciprocal sheltering. It can be easily dismantled and reassembled as needed. These systems, which allow the produced aluminum modules to be quickly connected and produced with pin connection, show the role of RF structures in the use of architecture (see Figure 3.17). The computational optimization of the structure would guarantee stability and flexibility for archaeologists working inside. There is also a case that involves RF structures that could be adapted to protect archaeological sites, which have a lesser environmental footprint (Gelez et al., 2011).

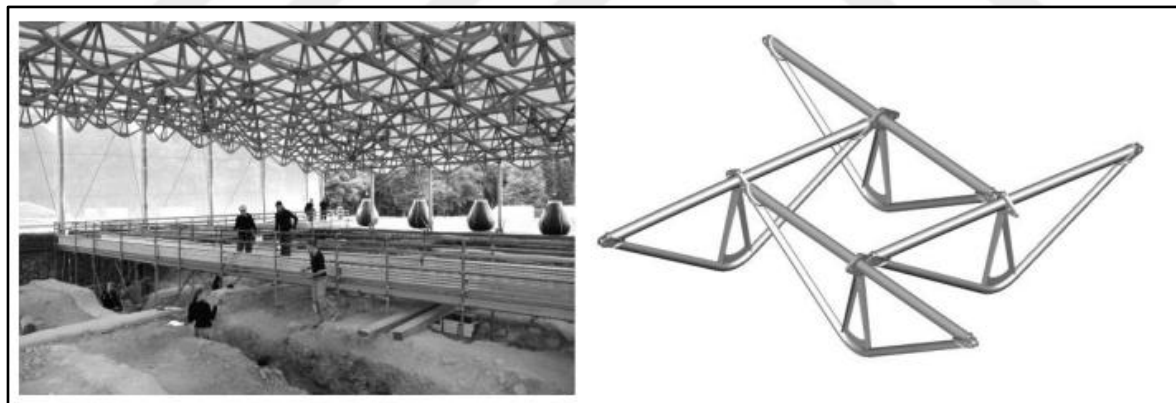


Figure 3.17. RF roof structures of the archaeological excavation site in Bibracte, France (Gustafsson, 2016).

The Mount Rokko Observatory, designed by Hiroshi Sambuichi and executed by Ove Arup and Partners, is a reciprocal frame structure applied to a building. Seated 900 meters above Kobe Bay, the observatory's fixed, welded reciprocal frame shell employs natural ventilation and shading principles. The structural framework, comprising steel and Japanese cypress wood, consists of an irregular mesh lattice designed to allow controlled airflow through passive cooling, without mechanical intervention (see Figure 3.17). Drawing

inspiration from the natural formation of trees, the observatory features a lightweight, porous form that engages with the wind, temperature, and sunlight, a sustainable approach to form and environmental integration (Popovic Larsen, 2014).

The Mount Rokko Observatory's architectural innovation lies in the reciprocally framed structures as a façade system, which is not in its commonly drawn application in the roofing system but rather less so. The reciprocal frame shell's complex geometry results in an envelope that is visually striking and functionally effective, providing structural stability and environmental performance. The observatory provides solar shading at the same time as natural ventilation by achieving a balance between openness and enclosure, showing that RF structures could replace solid façades with lightweight three-dimensional alternatives. This method improves not only the energy effectiveness of the building but also its aesthetics and experience, making it a great example of innovative sustainable design.

The observatory was modeled digitally using advanced computational analysis to optimize the configuration of its materials and achieve its complex geometry. The reciprocal design was adjusted to be constant in the building so as not to cause instability in the rest of the structure. The geodesic dome structure is designed to allow wind to flow through the dome. Bamboo wind tubes were created within the frame to provide natural sensory experiences by making sound and heat. The Mount Rokko Observatory is an excellent example of the modern use of reciprocal frames in façade construction and the lightweight expressive architecture that can be achieved using reciprocal frames (Popovic Larsen, 2014).



Figure 3.18. Mount Rokko-Shidare Observatory RF structure façade (Popovic Larsen, 2014).

The Palestine Ceriko Pavilion constructed by AAU Anastas, marks the first time reciprocal frame structures have been employed on double-curved surfaces. The pavilion illustrates that RF frameworks may be adapted to complex shape geometries not usually conceived as achievable in architectural surfaces, with their use in conventional RF applications limited to planar or shallow curved forms. Utilizing stone as a key structural element, the design illustrates the potential of reciprocal techniques to maintain a balance between elegance and performance, allowing for the creation of self-supporting enclosures without the need for additional structural reinforcement.

One of the major innovations of this pavilion is the combination of computations with optimized design and materialization, allowing for the precise interlocking of stones (see Figure 3.19). By streamlining the construction process and minimizing material waste, this approach exemplifies a sustainable and low-carbon solution for contemporary architectural design. RF structures challenge the conventional thinking of hard, rigid, and repetitive structures. Instead, they can showcase fluid, organic forms. The pavilion showcases how RF structures can effectively marry traditional craft and modern digital fabrication capabilities.

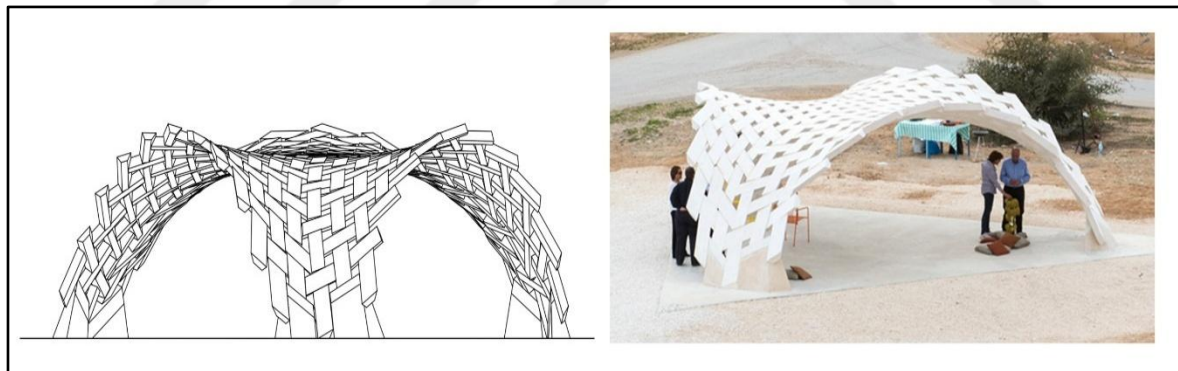


Figure 3.19. Double-curved RF structures pavilion in Ceriko, Palestine (Alyn, 2017).

The architectural community is increasingly exploring kinetic and adaptive reciprocal systems as research in RF structures develops. Although projects such as Palestine Ceriko Pavilion have taken RF structures into new geometric territories, the next frontier and challenge is to incorporate movement and transformation. Kinetic RF structures seek responsive architectural solutions to adapt to environmental effects that further push the limits of reciprocal structures. In other words, the move towards dynamic, form-finding structures indicates how much architects are designing architecture that is efficient and expressive, but also adaptable and intelligent.

3.2. KRF Structures in Architecture

Kinetic reciprocal frame (KRF) structures, also known as Kinetic Reciprocal Systems (KRS) in the literature, are situations where the motion potential of RF structures is unlocked so that nexors can stay together in different positions instead of locking on each other without disturbing the frame. It is possible to move the system in many ways without disturbing the frame. This differentiation is based on essentially the same principles but is defined differently by the diversity of the system design and the design of the connection of the nexors. These differences in designs change the degree of freedom (DoF) of the system, thus the mobility and method of the system also change. In this context, although many studies have been carried out on RF structures such as detailed geometric, static, and mathematical analyses, the studies on KRF structures are very limited and there is a lack of studies on the applicability of KRF structures in architecture.

Pellegrino and Calladine (1986) analyzed the static and kinematic indeterminacy of a pin-joint RF structure by creating a matrix and presented clear results on these behaviors. Such an analysis of RF structures provides a basis for further studies on its applicability as a KRF. Chilton et al. (1994) first mentioned the movement potential of RF structures as retractable roofs. This study also mentions that this movement creates a potential for longer spans in roofs. Popovic Larsen (1996), referring to the retractable roof study, mentions that the application of such studies is quite difficult and that new research is needed for kinematic design. Popovic Larsen and Lee (2013) take this work further and propose quick-built deployable emergency shelters using RF structures. These shelters are designed by rotating the cages prepared using RF structures around a pivot connection to gain a position and to form a structure with membrane coverings on top of them (see Figure 3.20).

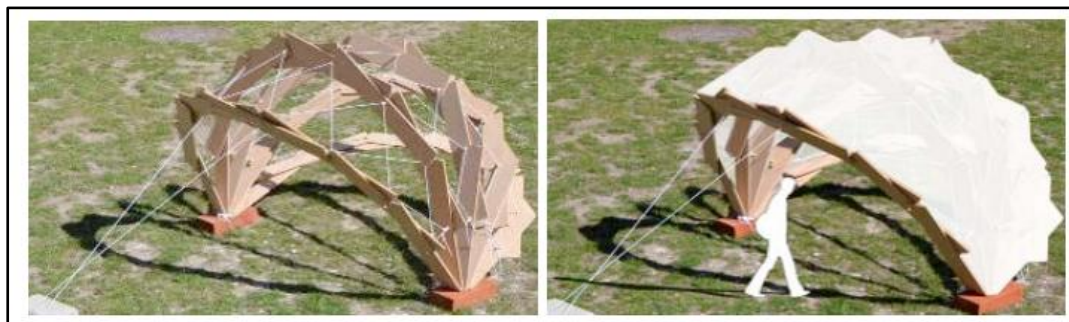


Figure 3.20. Model of quick-built deployable emergency shelter source: (Popovic Larsen and Lee, 2013).

Pérez-Valcárcel et al. (2021) carried this research further and developed the movement mechanism of the system through reciprocity. He designed and patented a ‘reciprocal linkage’ for RF structures. With this connection, the system has gained the ability to move, and these systems have been proposed as emergency buildings as ‘deployable structures’ (see Figure 3.21). Such designs work on the principle of load SLE, and when they are loaded, deformations, displacements, or collapses may occur. Such problems are caused by parameters such as connections or structural elements in cross-sectional areas.

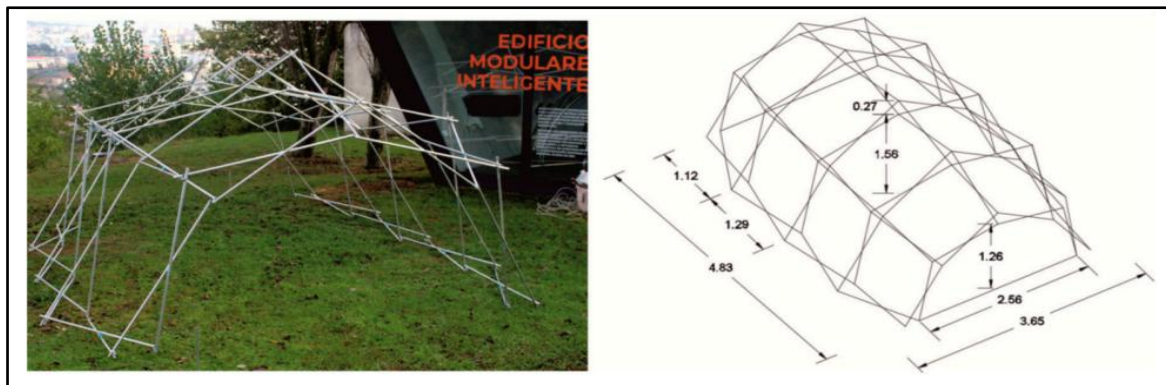


Figure 3.21. Model of the structure (Pérez-Valcárcel et al., 2024).

The application of reciprocity principles in this connection has solved many problems and provided new advantages. As seen in Figure 3.22a, with this reciprocal linkage folding of the system at these points has been prevented, stiffness has been increased, and displacement and bending stress have been reduced (Pérez-Valcárcel et al., 2021). Thus, it is seen that innovative designs are possible by using reciprocity-based connections in systems that change form with expand and contract movements such as SLE.

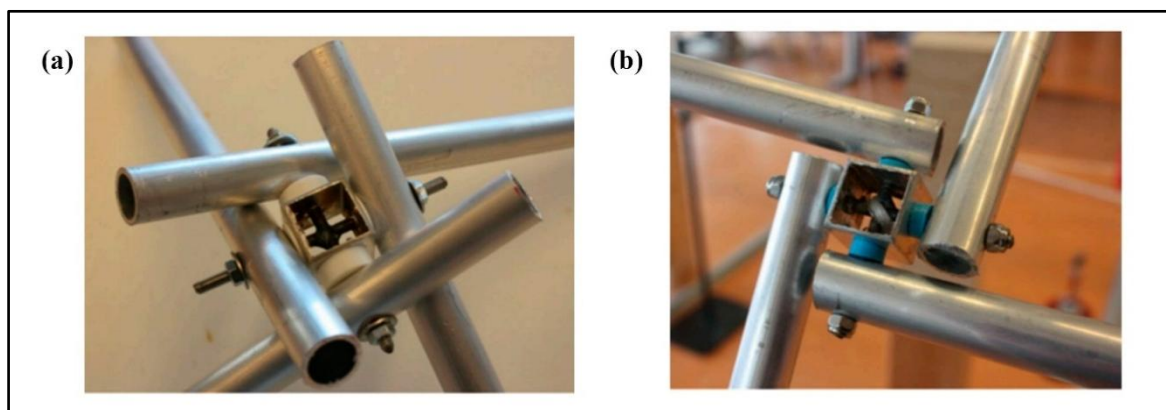


Figure 3.22. a) Reciprocal linkage, b) Articulated linkages (Pérez-Valcárcel et al., 2024).

Parigi and Sassone (2010, 2011) developed and formulated a system called ‘Parigi Mechanism’ for RF structures. With this mechanism, the ability of nexors to move on each other as a new type of movement for KRF structures has been systematized. Parigi (2021) describes this system as the endpoint of one nexor always connecting to one of the intermediate points on the nexor instead of connecting to the endpoint of another nexor. The mechanism being studied is one with a single degree of freedom (1-DoF) and whose elements are connected through pin-slot joints. A defining quality of this mechanism is that its 1-DOF is preserved when elements are added and the mechanism becomes indeterminate.

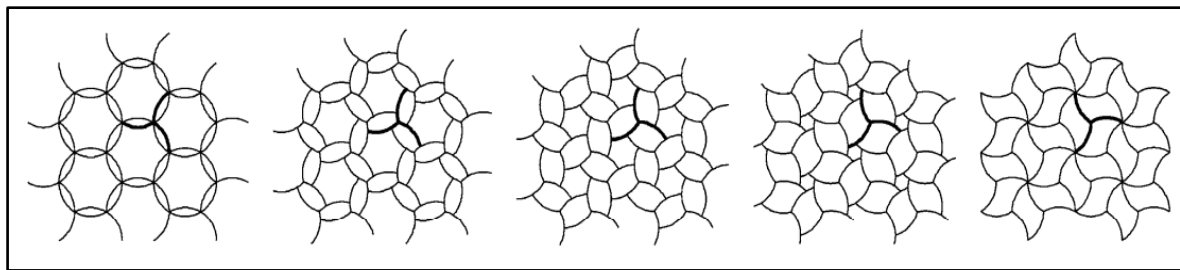


Figure 3.23. Movement stages of the mechanism from left to right with 0°, 15°, 30°, 45°, and 60° rotation angle (Parigi, 2021).

Parigi (2021) designed an adaptive façade using KRF structures. This is another example of the potential of using KRF structures in architecture. The façade consists of 2-layer panels, and a mechanism stands behind the panel in the lower layer, and the panels in the upper layer are connected to this mechanism. The elements rotate and change position while moving on this mechanism (see Figure 3.24). Thus, daylight control, natural ventilation, privacy, and sound insulation are provided by changing the aperture size on the façade.

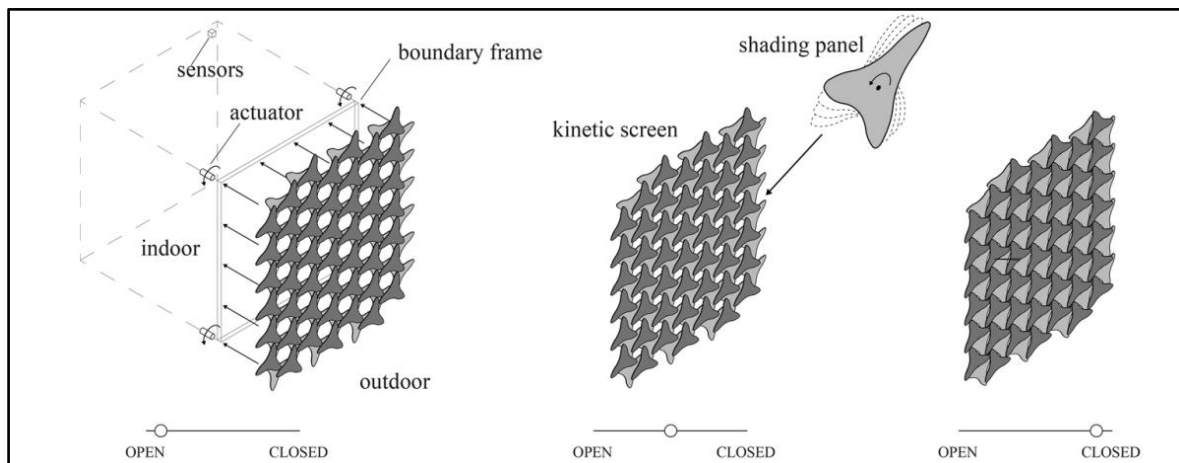


Figure 3.24. Adaptive façade design with KRF structures (Parigi, 2021).

Similarly, Şenel et al. (2024) used KRF structures as an adaptive façade and evaluated the geomorphology of the design in terms of cost, daylight control, and applicability. For this study, a high-rise office building was selected as the study area, and a steel construction was installed on the south façade of this building. In front of the steel construction, 1-DoF KRF modules consisting of different geometries were installed with parametric design tools (see Figure 3.25). These modules consist of nexors in curvilinear form, and an elastic membrane is placed between them, and this membrane is stretched and relaxed by the movement of the nexors. This change in aperture size provides daylight control, and hexagonal geometries were found to be more successful than other geometries.

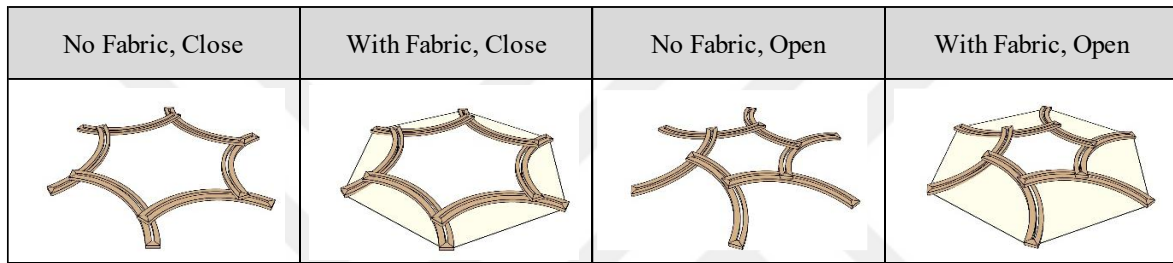


Figure 3.25. KRF façade module (Şenel et al., 2024).

Özen et al. (2024) expand the existing literature on kinetic reciprocal frame (KRF) structures with a new rollable and deployable RF network whose motion mechanism is different from that of KRF structures. Earlier research on KRFs has focused on the retractable configuration using revolute joints. In contrast, this articulation incorporates C and P joints to achieve a multi-DoF motion system. The paper proposes a 2-DoF quadrilateral RF fan-based network, whose mobility is analyzed using Freudenstein and Alizade's mobility formula. By setting up the nexors in a systematic yet adaptive way, a rollable mechanism is obtained, which transits from a compact, transportable state to a vault-deployed state (see Figure 3.26).



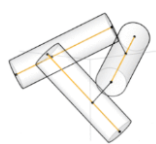
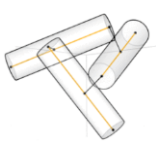
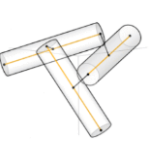
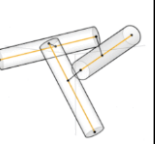
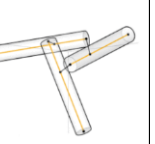
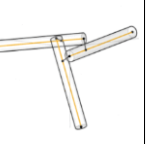
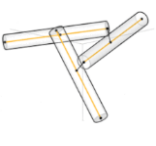
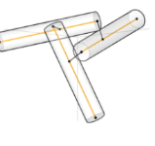
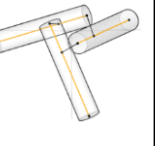
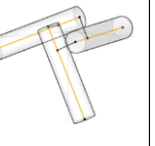
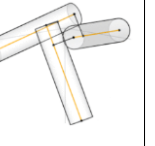
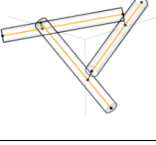
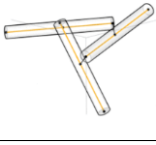
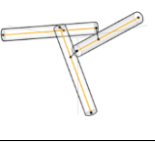
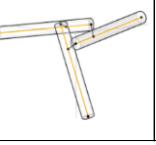
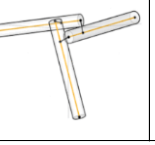
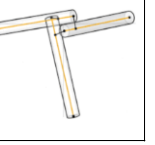
Figure 3.26. Motion stages of network (Özen et al., 2024).

Recent new possibilities for KRF structures and systems beyond traditional use for static and limited kinetic applications have been extended due to recent developments. The use of computational modeling and parametric design tools has further aided the trajectory of evolving optimized configurations for structural efficiency and adaptability. The KRF systems can adjust according to the needs of the environment and function in real time due to the development. As we seek to comprehend the kinematics of these structures, understanding their motion behaviors, joint actions, and transformation capacities will facilitate their refinement for many more architectural applications.

3.2.1. Mobility analysis

KRF structures are differentiated from other kinetic façade systems with their unique mobility capabilities. This mobility contains multiple parameters within itself, and changing any of the parameters enables a different movement to occur. The number of nexors, length, geometry, type of connection, and where they are located are the parameters that determine the movement of a fan. As seen in Table 3.1, as the nexor thickness increases, the mobility is restricted, the engagement window widens, and the system cannot be opened and closed completely. If the engagement window width should not change, the starting points of the nexors have to move, and in this case, the system cannot gain height. When the nexor starting points are fixed to the ground, the nexor thickness and nexor length determine the maximum height that the fan can rise as a result of movement.

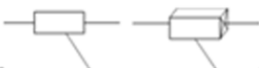
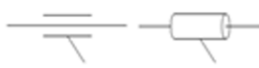
Table 3.1. Variation of movement according to parameters (Şenel et al., 2024).

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

KRF systems are modular and consist of a combination of fans. The way the fans come together also affects the movement and depends on the geometry of the fans. One of the advantages of this modular structure is the use of actuators. Looking at the movements of kinetic façades today, it is seen that one or more actuators are used for each façade module. In KRF system designs, since the nexors are connected to each other, a single actuator is sufficient to move the whole system.

The movement to be triggered by the actuator is related to the design of the bearings and the system. Alizade (2019) study on the structural synthesis of robot manipulators using screws with variable pitch provides a systematic approach to analyzing mobility in robotic systems, particularly in parallel manipulators. His studies on bearing properties and joint designs were used for mobility analysis of KRF structures. Table 3.2 shows the properties of revolute, prismatic, and cylindrical bearings. The system may consist of these single types of joints or it may have a mixed mechanism by using more than one type of joint.

Table 3.2. Joint types and parameters (Reillustrated by (Özen and Korkmaz, 2022), and source: (Alizade, 2019).

Name	Symbol	DoF	Rotational	Translational	Diagram
Revolute	R	1	1	0	
Prismatic	P	1	0	1	
Cylindrical	C	2	1	1	

R and P joints are 1-DoF (one-degree-of-freedom) joints, where the R joint allows for rotational motion, while the P joint enables translational motion. C joint is a two-degree-of-freedom (2-DoF) joint, allowing for rotation and translation. After the systems are designed, the parameter that determines whether the system can move or not, and how it will move, is called degrees of freedom (DoF). This is also the mobility (M) parameter of the system. The value of M is calculated by a formula (Eq. 3.1) found by Freudenstein and Alizade (1975). $M = 0$ or $M < 0$ means that the system cannot move, and it is a structure. When $M > 0$, the system can move and the result describes the freedom of movement of the system.

$$M = \sum_{i=1}^j f_i - \sum_{k=1}^L \lambda_k \quad (3.1)$$

M = mobility

j = number of joints

f_i = DoF of joint i

Σf_i = connectivity sum

L = number of independent loops

λ_k = DoF of space in which the loop k of the mechanism operates ($\lambda_k = 2, 3, 4, 5, 6$)

The value of λ_k is accepted as 3 for planar mechanisms and 6 for spatial mechanisms. When this formula is evaluated on KRF structures, $\lambda_k = 6$ will be calculated. A new formula is developed by Alizade (2019) to obtain more accurate results in KRF kinematic analysis (Eq. 3.2). In this formula, the variable ‘ E = Excessive Mobility’ is added.

$$M = \sum_{i=1}^j f_i - \sum_{k=1}^N \lambda_k - E \quad (3.2)$$

As seen in Figure 3.27, two different triangular fans are designed but neither of them has mobility. Although the number of Joints increases, the ‘ M ’ value does not change. The reason is that a single nexor is equipped with two R|| joints which allows the nexor to rotate about itself. However, this rotation does not change or affect the shape of the fan. For that reason, one rotational movement per nexor can be ignored for mobility (Özen, 2022).

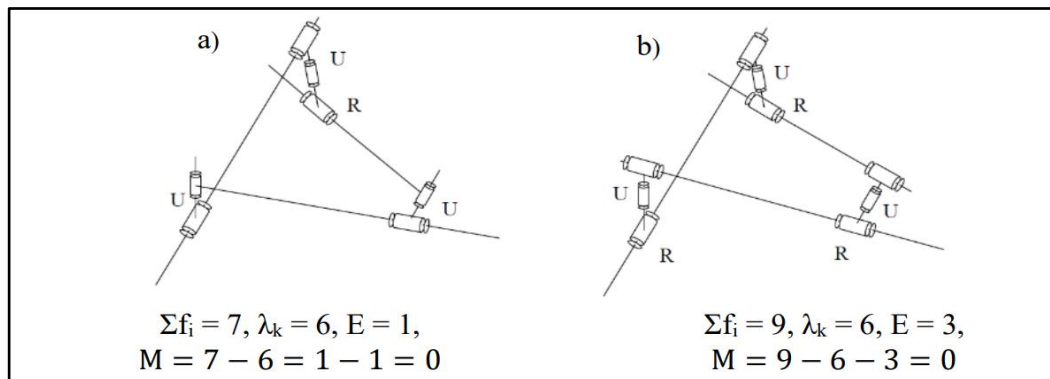


Figure 3.27. Triangular fans a) UR||-U-U fan, b) UR||-UR||-UR|| fan (Özen, 2022).

The quadrilateral fans in Figure 3.28 consist of 4 C type joints. The system is in contact with the ground and will be in contact with the ground throughout the movement. The ‘M’ value of these KRF structures is 2 and the system can move in more than one axis. As the slide angle decreases, the system height rises, the engagement window gets wider and the position of the nexors on the ground must change in order to move more. This is due to the fan and nexor geometry.

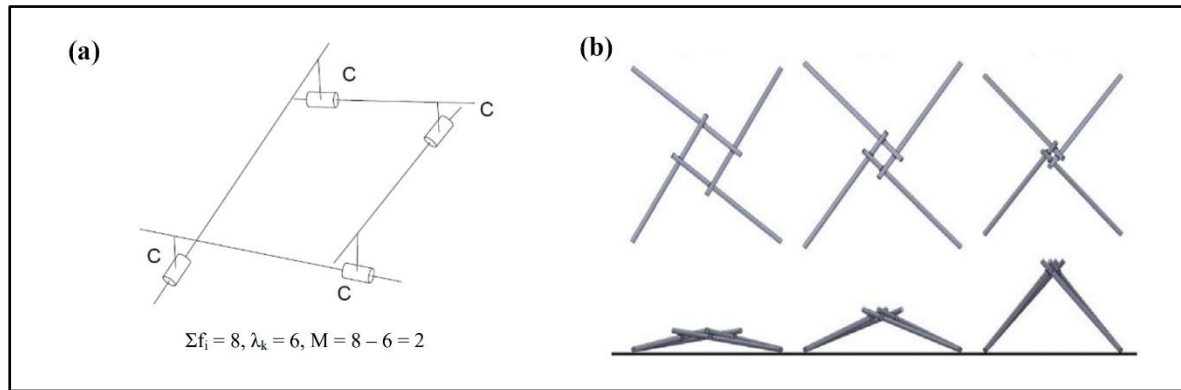


Figure 3.28. a) Quadrilateral fans with four C joints, b) Motion stages of fan source: (Özen et al., 2024).

This system has a second motion potential (see Figure 3.29b). Instead of 4 C-type joints, the motion consists of 2 C-type joints and 2 P-type joints. In this motion, it can be seen that the two nexors are out of contact with the ground. Considering the DoF values of the joints, the value of ‘ Σf_i ’ is 6. According to Eq. 3.2, the value of ‘M’ should be $6 - 6 = 0$, and the system should not be able to move. However, the value of ‘ λ_k ’ decreases to 4 in this particular motion. Özen et al. (2024) show that this decrease occurs since only rotations around axes along the parallel nexors are possible, while rotations around axes perpendicular to them are not included in the motion space.

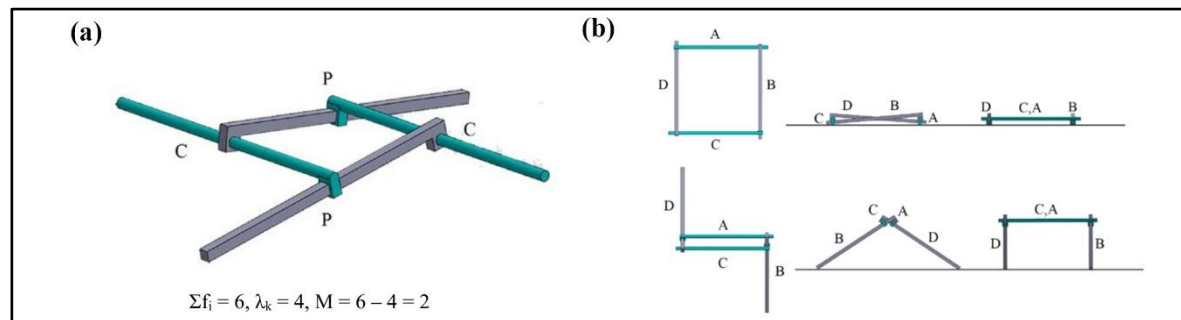


Figure 3.29. a) Alternative motion of the Quadrilateral fan, b) Motion stages of fan source: (Özen et al., 2024).

3.2.2. Geometric analysis

Literature researches show that there is a limitation in façade designs and new geometric searches are made. These systems consisting of many parameters can turn into a completely different design with the change of one of the parameters. In addition, the most important factor affecting the function, type of movement, mobility, and design of KRF structures is its geometry. Again, the geometry of KRF structures affects how and for what purpose it will be applied. As the motion takes place, the geometry changes, the aperture size increases and decreases, the aperture geometry varies, the system height decreases and increases, and the angles and geometries between the nexors change.

In Figure 3.30, a triangular fan is designed, and the change of aperture size and aperture geometry with the movement of nexors is shown. The 'A' value describes the engagement window size and aperture size value, and the 'B' value describes the area value of the polygon. When $A = 0$, the system is closed, and when $A = B$, the system is fully open. It can be said that as movement occurs in an architectural application, the system becomes more permeable, and many factors such as natural light, natural ventilation, or sound affect the building more.

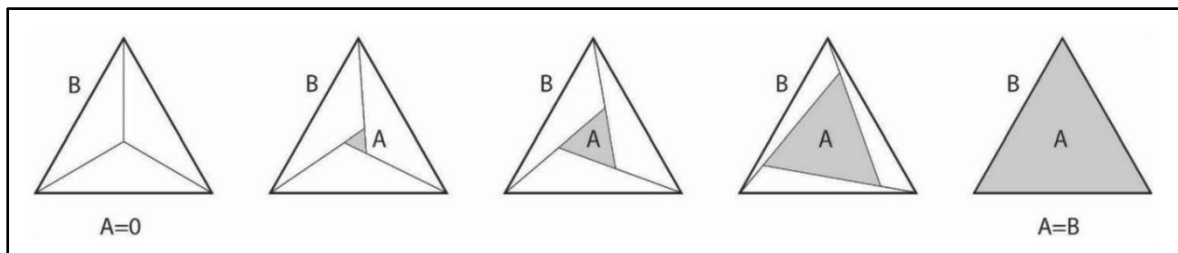


Figure 3.30. Variation of aperture size and aperture geometry according to the state of motion (Nazarzadeh and Asefi, 2022).

When this motion is analyzed, it is seen that the nexor starting points remain constant, there is no nexor thickness and the nexor lengths lengthen and shorten along this motion. These parameters also limit the applicability of this system. The nexor lengths should remain constant, and a variable design can also be made, but this makes the applicability difficult, the nexor thickness should not be ignored and the connection between the nexors should be designed, and 'Mobility' calculation should be made.

In the case where the nexor lengths remain the same, the starting points of the nexors change as the movement is realized. In Figure 3.31, point B is the starting position of the fan while point A shows the position of the fan when the motion is completed. The axis formed between point A and point B is called the movement path. This freedom in the starting positions of the nexors allows the motion to be fully switched on and off without any restrictions.

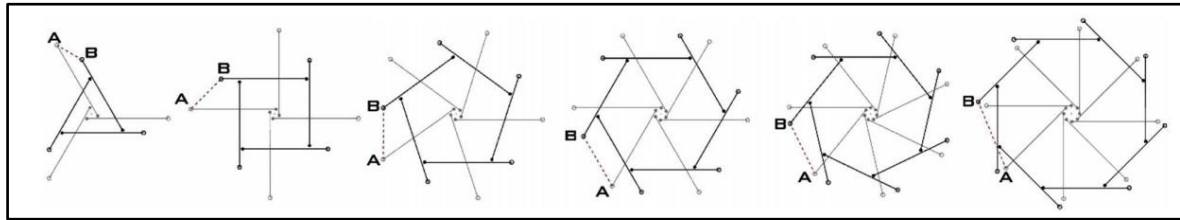


Figure 3.31. Motion paths of fans (Nazarzadeh and Asefi, 2022).

By combining multiple KRF structures, it is possible to build a complex multiple KRF system that can act holistically. Nazarzadeh and Asefi (2022) state that this system can only be constructed from hexagonal polygons. The mobility of multiple KRF systems depends on the form and length of the nexors. In these systems consisting of linear nexors, the motion of the system is limited by the length of the nexors, and the system can move as much as the length of the nexors is sufficient. Figure 3.32 shows a multiple KRF system consisting of hexagonal modules, where 'n' is the number of sides of the polygon. This system cannot be switched on and off completely.

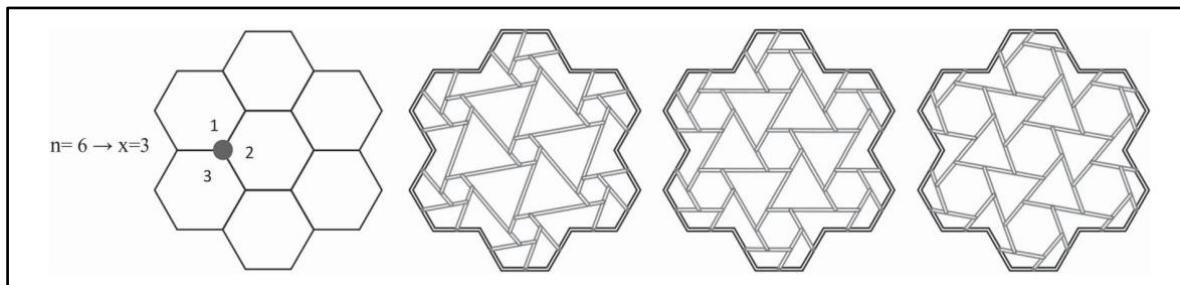


Figure 3.32. Motion of multiple KRF system (Nazarzadeh and Asefi, 2022).

Kitajima and Suehiro (2023) took the research to an advanced stage with multi-KRF systems and put it into practice. They designed a rectangular multi-KRF system from geodetic grids and analyzed the deformations of this system after motion. When this system consisting of linear nexors moves, the system gains height while the corner points move and the system

is displaced. While the system has a rectangular form when it is open, it has a parallel edge geometry with an angle of 37.8° when it is closed (see Figure 3.33). These deformations were calculated using digital simulation and calculation tools Kangaroo2 and K2 Engineering, and then the system was manufactured.

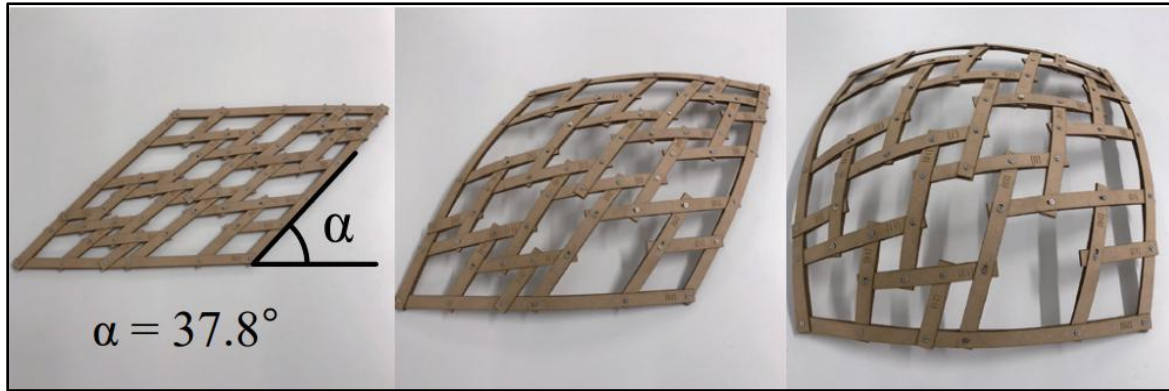


Figure 3.33. Motion stages of rectangular multi-KRF system (Kitajima and Suehiro, 2023).

There is another method to increase the movement potential of KRF structures and to build more homogeneous and smoothly working multi-KRF systems. This method uses a curved nexor instead of a linear nexor. Table 3.3 shows the hexagonal fans reconstructed with this method. In Model 1, the 60° rotated nexors are completely closed and it can be seen that the linear nexor lengths are insufficient to ensure the continuity of the motion while performing the opening movement. In Model 2, the same fan is created with a curved nexor, and the movement is completed without interruption. In Model 3, the case where the motion is completed without interruption with a linear nexor is examined. In order to do this, the nexor length needs to be extended from 2.1 meters to 2.3 meters. Also, in this case, it is observed that the nexors protrude out of the system when the KRF structure is fully open (0° rotation).

Table 3.3. KRF fans created with linear and curved nexors (Şenel et al., 2024).

	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

In Table 3.4, the geometric analysis of the curved nexor is analyzed by examining the opening and closing motion in 6 stages. It is observed that as the number of polygon edges increases, the nexor curvilinearity increases, the nexor length shortens, and the system's height increases. When the relationship between fan geometry and nexor geometry is analyzed, it is seen that the most compatible fan is the hexagonal KRF structure. In other fans, nexor lengths extend beyond the nexor joints. When multi-KRF systems are designed, these overflows may cause problems for system movement.

Table 3.4. Geometric analysis of the curved nexor utilization method (Şenel et al., 2024).

		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

When the use of curvilinear nexors is applied in multi-KRF systems, it is seen that the mobility of the systems increases (see Figure 3.34). This improvement in mobility increases the maximum height of the system and increases the control over the aperture size parameter. In this sense, the system is more applicable. It means that the permeability of external factors such as light, air, and sound can be completely cut and completely provided.

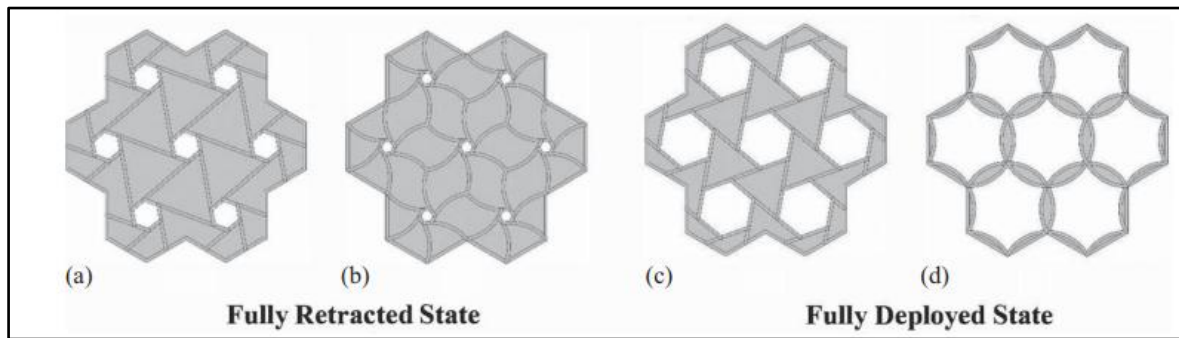


Figure 3.34. Comparison of the use of linear nexor (a and c) and curvilinear nexor (b and d) on system movement capacity (Nazarzadeh and Asefi, 2022).

It is also possible to create multi-KRF systems from different geometries. Fan geometries are multiplied according to tessellation principles to form a plane. In the center of these geometries, a hexagonal KRF structure is placed. The fixed joints of the adjacent hexagonal KRF structures in contact with each other are removed, and movable bearings are placed. In this way, it is possible to produce different types of multi-KRF systems.

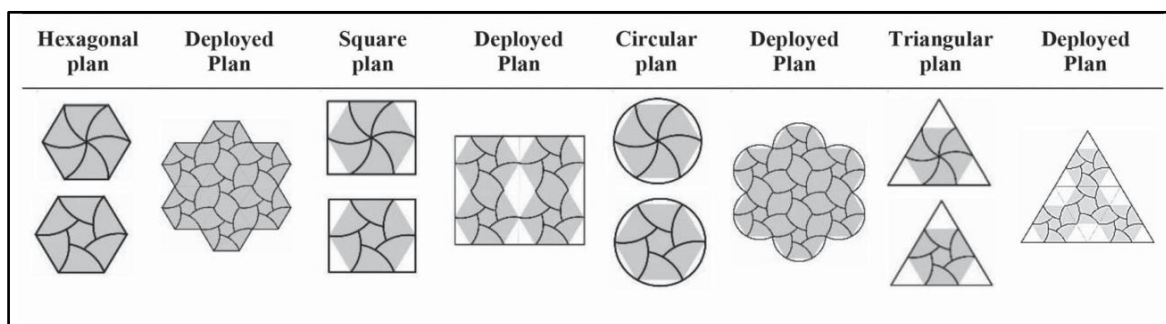


Figure 3.35. Design of a multi-KRF system with fans of different geometries (Nazarzadeh and Asefi, 2022).

This richness in the design and mobility of KRF structures creates great potential in architectural applications. Especially in aviation infrastructures, the application of such systems can help structures adapt to environmental factors and meet operational requirements, as an innovative solution to the needs of the modern aviation industry.

4. AIR TRAFFIC CONTROL TOWERS

Air Traffic Control (ATC) towers are crucial for the safety and operational efficiency of contemporary aviation systems. They serve as the nerve center for managing the movement of the aircraft in the air and on the ground within the aerodrome. Air traffic controllers (ATCOs) are responsible for the process from the engine start of the aircraft to the parking lot at the destination airport, such as ensuring separation between aircraft, ensuring efficient, fast, orderly, and safe air navigation, preventing collisions between aircraft and obstacles, providing information to assist aircraft in their flights, assisting aircraft in search and rescue operations in case of a possible incident. Due to growing air traffic over time, ATC Towers' functions have increased gradually; therefore, it is necessary to have ATC towers more advanced and responsive.

Air traffic worldwide is managed by three units, namely Area Control Centre (ACC), Approach Control Unit (APP), and Aerodrome Control Tower (TWR). These three units are constantly coordinating with each other to ensure the flow, order, and safety of traffic between airspaces of different heights and widths. Both terms, "air traffic control tower" and "aerodrome control tower," are commonly used and refer to the same building. The choice of terminology can depend on regional or national preferences. In the United States, for example, the term "air traffic control tower" is commonly used. In many other countries, especially those following ICAO terminology, it is used as 'Aerodrome Control Towers', meaning a unit established to provide air traffic control service to aerodrome traffic. In ATC towers, TWR, APP, or TWR and APP can be found together as a combined unit among air traffic control units.

ATC towers are not merely just functional structures. They have become architectural icons that signify the sophistication and technological prowess of modern aerodromes. ATC towers are essential instruments aiding with traffic management in the aviation sector today. They help coordinate the safe movement of thousands of flights every day. Apart from doing their job, such towers have become very important pieces of national and regional pride as they show a country's commitment to a world-class aerodrome. With growing demand globally, ATC towers serve a dual purpose today. They not only facilitate operations but also serve as architectural landmarks. The ATC towers showcase excellent design,

engineering, and technology and signify advanced accomplishments of the country's aviation sector. In this sense, if ATC towers are not designed according to certain standards, the form may override function in this process and air navigation operations may suffer.

ATC tower designs have gone through remarkable changes in recent times. This development represents the growth of the aviation sector. Also, a rise in the need for sustainability in airports and more. Today's ATC towers need to be designed green that is low carbon, energy-efficient, and includes renewable energy systems. Today's architecture encompasses sustainable design that uses energy-friendly materials, flexible façades, and resilient technologies to reduce their environmental impact. The aviation sector should incorporate these developments to ensure that ATC towers fulfill operational requirements while making an impact against global climate change efforts.

4.1. Brief History of ATC Tower

The history of ATC towers began in the early 1900s. This was when flying changed from a fun, spectacular episode to a controlled activity. Aircraft in the early days of aviation operated without the control of any central authority. The pilots organized their separation themselves. Also, no restrictions regarding the type of flight were imposed. As aerodromes became more complicated and traffic levels grew, it became clear that more structure was needed to manage aircraft movements efficiently. The world's first airport air traffic control tower was set up at London's Croydon Airport. The aerodrome control tower was a wooden hut measuring 4.6 meters in height with four windows. On February 25, 1920, employment was commissioned, which offered basic traffic, weather, and location information to pilots (Transportheritage, 2018).

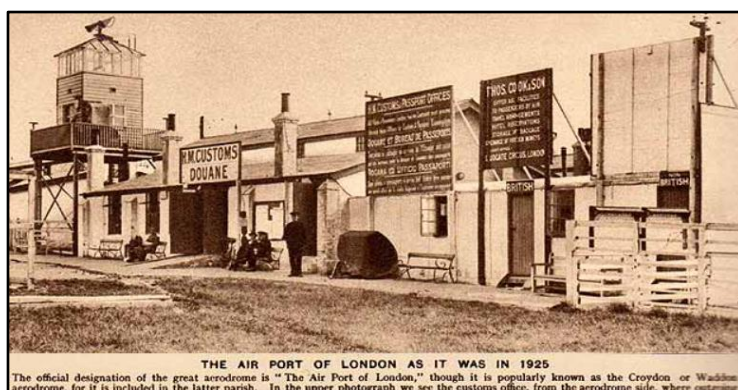


Figure 4.1. Croydon ATC tower (Controltowers, 2018).

Although the first ATC tower was announced in 1920, the first known air traffic controller was Archie W. League. He began his work in 1929 at St. Louis Lambert International Airport. Using simple tools such as a checkered flag to signal pilots, League played a fundamental role in shaping modern air traffic control practices (see Figure 4.2a). Manages aerodrome traffic by simply saying 'hold' and 'go' to aircraft and ensures separations between aircraft (FAA, 2021). In addition to this task, for League the ATC tower is a simple umbrella and table that protects him from the sun and allows him to rest and plan (see Figure 4.2b).

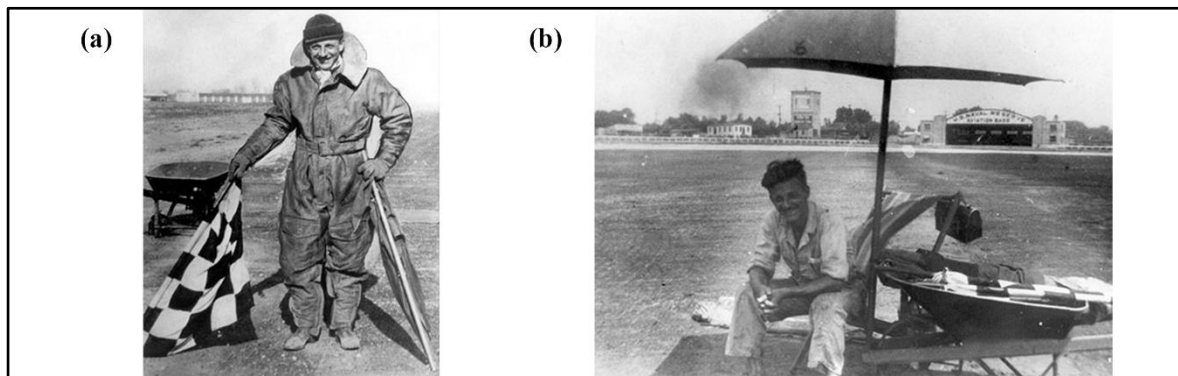


Figure 4.2. a) Photograph of Archie League during the operation, b) League's office source: (FAA, 2021).

The first control tower in the USA began operation in 1930 at Cleveland Municipal Airport, manned by air traffic controllers who directed aircraft using two-way radio, greatly improving operational safety. This single-story, octagonal tower is a simple office where the devices are located and can be seen around. The tower only regulated surface movements of departing and arriving traffic. Moreover, some flight-related information services were made available to the pilots in addition to the control instructions by the tower (Memon, 2023).

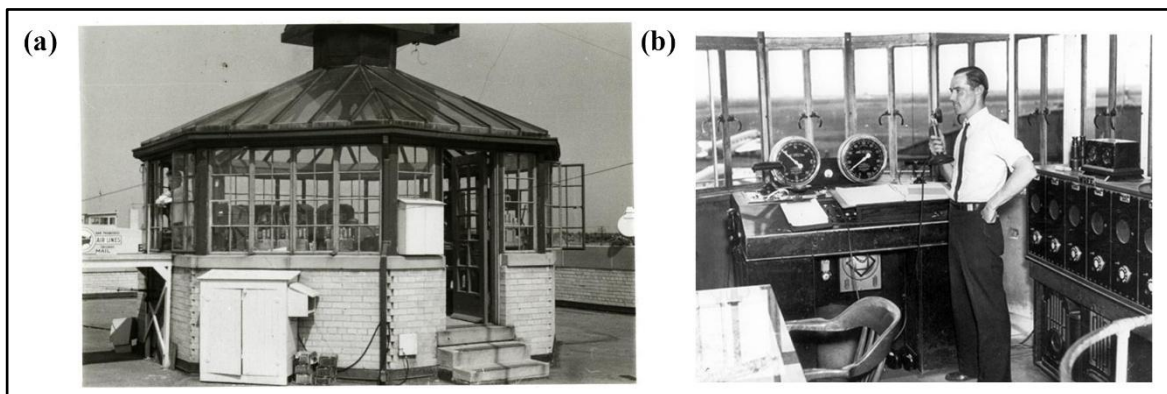


Figure 4.3. a) Cleveland Municipal ATC tower (Museum, 2022), b) Two-way radio communication (FAA, 2021).

In the 1930s and 1940s, technological improvements in aviation such as the development of the radio and radar made air traffic control much more efficient. In the United States, the formation of the Civil Aeronautics Administration (CAA) in 1938 laid the groundwork for organized air traffic control activities, instituting uniform techniques for aircraft separation, and communication (Bilstein, 2001). Radar technology was fine-tuned during World War II for military purposes, allowing controllers to monitor planes beyond what could be seen. After the war, this tech was made use of in civil ATC, and radars were fitted in ATC towers at major aerodromes. By the 1940s and early 1950s, ATC towers had developed into not just observation posts, but rather operational centers able to control traffic within an airspace. This enabled controllers to spot the aircraft at any time, due to the reduction of visual spotting (Petrescu et al., 2017).

The ATC tower designs and their functions went through a major change during the aviation boom after the war in the 1960s and 1970s. The expansion of commercial jet travel and the rising number of passengers created a demand for larger aerodromes with more sophisticated air traffic management systems. To improve accuracy in tracking aircraft and landing, automated radar systems, instrument landing systems (ILS), and secondary surveillance radar (SSR) were introduced (Kazda and Caves, 2010). During this time, controllers were aided in managing the resulting complicated traffic by new ATC towers which were being designed for computerized air traffic control systems. In the 1980s and 1990s, advances in digital communications and satellite navigation saw further modernization of ATC operations, enabling controllers to more accurately and efficiently manage multiple layers of airspace (Kahne and Frolow, 1996).

In the last few decades, the ATC towers have continued to evolve with automation, sustainability, and ergonomics in focus. The remote and digital tower technology, exemplified by Remote ATC towers, allows controllers to control traffic from centralized locations without being physically present at the aerodromes (Eurocontrol, 2024b). These developments have made ATC operations more flexible and applicable in aerodromes that are remote or have a low level of traffic. Moreover, today's ATC towers are being developed intelligently with energy-efficient systems, responsive façades, and ongoing environmental monitoring (FAA, 2023b). The evolution of ATC towers has been a gradual development due to the air traffic management system's need to adapt to that ever-increasing demand of civil aviation and alter accordingly to serve civil aviation.

4.2. ATC Towers Nowadays

In a period when today's aviation technology is developing rapidly, air traffic control towers are faced with the difficulties of not being able to adapt to technological innovations in their architectural designs. This situation brings along the problem of not being able to progress in parallel with the general development of the aviation sector. In particular, the architectural infrastructures of these towers are generally based on old and complex systems. This situation makes it difficult to adapt to the innovations offered by aviation technology, such as new-generation aircraft, autopilot systems, and aircraft communication systems.

From an architectural point of view, the current design of control towers is generally based on functional considerations before aesthetics (see Figure 4.4a). In some buildings, there is no relationship between aesthetics and functionality (see Figure 4.4b). However, today, the increase in air traffic density and the diversification of technological requirements require these structures to be not only functional but also aesthetically attractive. In this context, the use of adaptive façades has the potential to not only increase energy efficiency but also provide architectural flexibility, giving control towers a modern and contemporary appearance. This architectural feature can contribute to achieving a balance in both functional and aesthetic aspects by enhancing their ability to integrate control towers into their surroundings and adapt to various environmental conditions.

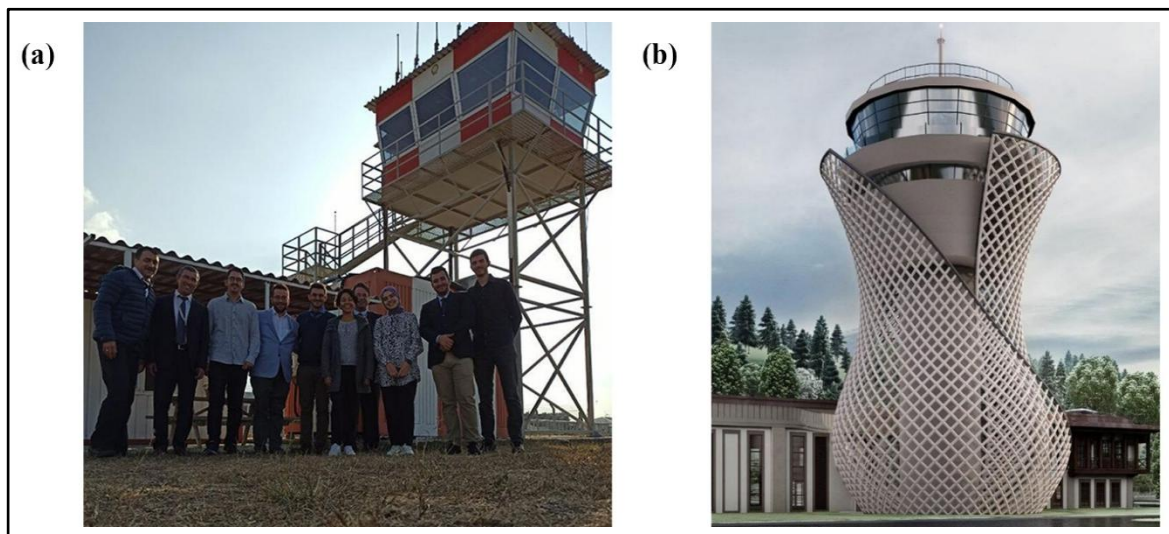


Figure 4.4. a) ATC Tower in Uşak Airport, Türkiye photographed by ATCO Efecan Güleş, b) ATC tower in Rize-Artvin Airport, Türkiye (Santiye, 2021).

Table 4.1 analyzes 26 ATC towers between 1974 and 2023. Control room geometries are analyzed as hexagonal, octagonal, and circular. Since it is quite costly to produce curved glass, control rooms are designed close to a circle by increasing the number of edges. In this sense, control rooms with more than eight sides are classified as circular.

Table 4.1. Analysis of ATC towers (source: Author).

ATC Tower	Location	Year Built	Height (m)	Control Room Geometry	Features
Sabiha Gökçen ATC Tower	Türkiye	2023	91	Circular	One of the tallest towers in Europe
Beijing Daxing ATC Tower	China	2019	90	Circular	One of the largest airport towers in the world
Istanbul Airport ATC Tower	Türkiye	2018	90	Elliptical	Tulip-inspired iconic sustainable tower
King Abdul Aziz ATC Tower	Saudi Arabia	2017	136	Circular	World's tallest ATC tower
San Francisco International ATC Tower	The USA	2016	67	Circular	Wind-resistant, modernized navigation systems
O'Hare International South ATC Tower	The USA	2015	63	Octagonal	LEED Gold certified, green roof, geothermal heating system
Hamad International ATC Tower	Qatar	2014	85	Circular	Smart glass, wind-resistant modern structure
Kuala Lumpur International ATC Tower	Malaysia	2013	133.8	Octagonal	One of the tallest ATC towers in the world
Dubai International ATC Tower	United Arab Emirates	2012	87	Circular	One of the busiest airport control towers in the world
London Heathrow ATC Tower	United Kingdom	2007	87	Circular	360-degree glass panel control room
Vienna International ATC Tower	Austria	2006	109	Rectangular	Energy-efficient design, optimized for air traffic management
Barcelona El Prat ATC Tower	Spain	2004	62	Octagonal	Modernized navigation and communication systems
Toronto Pearson International ATC Tower	Canada	2002	92	Circular	Canada's busiest airport control tower
Stockholm Arlanda ATC Tower	Sweden	2001	83	Circular	Award-winning innovative concrete design
Hong Kong International ATC Tower	China	1998	86	Circular	Modernized for high traffic management
Houston George Bush International ATC Tower	USA	1997	102.4	Octagonal	Handles a major part of US air traffic
Los Angeles International ATC Tower	The USA	1996	77	Octagonal	One of the most technologically advanced ATC towers
Kingsford Smith ATC Tower	Australia	1995	42.85	Hexagonal	Spiral staircase, sea-resilient structure
Frankfurt International ATC Tower	Germany	1994	70	Circular	Advanced panoramic visibility for air traffic control
Kansai International ATC Tower	Japan	1994	80	Octagonal	Earthquake-resistant, built on an artificial island
Tokyo Narita International ATC Ramp Tower	Japan	1993	64	Rectangular	Earthquake-resistant tower, critical for Japan's aviation
John F. Kennedy International ATC Tower	The USA	1992	98	Hexagonal	One of the busiest airport control centers in the world
Amsterdam Schiphol ATC Tower	Netherlands	1991	101	Octagonal	Historical yet modernized for European air traffic
Izmir Adnan Menderes ATC Tower	Türkiye	1987	45	Hexagonal	Award-winning steel structure and LEED certified
Riyadh King Khalid ATC Tower	Saudi Arabia	1983	81	Hexagonal	Equipped with state-of-the-art security systems
Paris Charles de Gaulle ATC Tower	France	1974	80	Circular	Serving one of the busiest airports in Europe

4.2.1. İstanbul Airport ATC tower

Built in 2018, the 90-meter-high Pininfarina-designed building in Istanbul, Türkiye, is seen as a contemporary architectural work that merges technology, art, and function effortlessly. The arrangement of the interiors is worked through a deep spatial analysis focused on maximizing efficiency while maintaining a balance between work and leisure. In large airports, the aerodrome control units are split into many sections, which makes it difficult to monitor all of the entire airport from a single point. To respond to this condition, these units are located at the top of the tower. The vista is completely redecorated so that the air traffic controllers get a 360-degree view. There are two control rooms at different levels.



Figure 4.5. İstanbul ATC Tower views (Metalyapı, 2013).

The design of the glazing system of the iconic Istanbul Airport ATC tower is optimized for irradiation and acoustic comfort. The tower is the leading element of the building, inspired by the iconic tulip, which has a historical culture in Türkiye. The elliptical shape, as if shaped by the wind, has a significant impact on the contours and overall layout of the technical building below. To ensure sustainability, solar analysis will maximize energy efficiency in the design of the building. The high-performance glass provides natural light while achieving a high degree of insulation for energy savings. To further reduce the water consumption footprint of the building, a rainwater harvesting system is done. This project aims to comply with the ASHRAE 90.1-2010 Standard with the implementation of energy-efficient mechanical systems and electrical installations, efficient façade design, and selected glass (Altensis, 2023). Low-flow water fixtures will be installed to ensure water efficiency. In addition, the angle of the glass façade design limits the sunlight which in turn helps reduce reflections and overheating inside the building.

4.2.2. Incheon International Airport ATC tower

Built-in 2001 in Incheon, South Korea, Incheon International Airport (IIA) tower is 100.4 meters high, and the control room stands 83.8 meters high (see Figure 4.6). This height is designed to give the tower a clear view of the terminal building and its surroundings with the naked eye. Rising on an octagonal reinforced concrete structure, this tower maintains its octagonal form when it reaches the control room, and the structural system continues with steel construction after this height. This change in the system prevents the columns of the structural system from obstructing the view and provides ATCO with an uninterrupted 360-degree view.

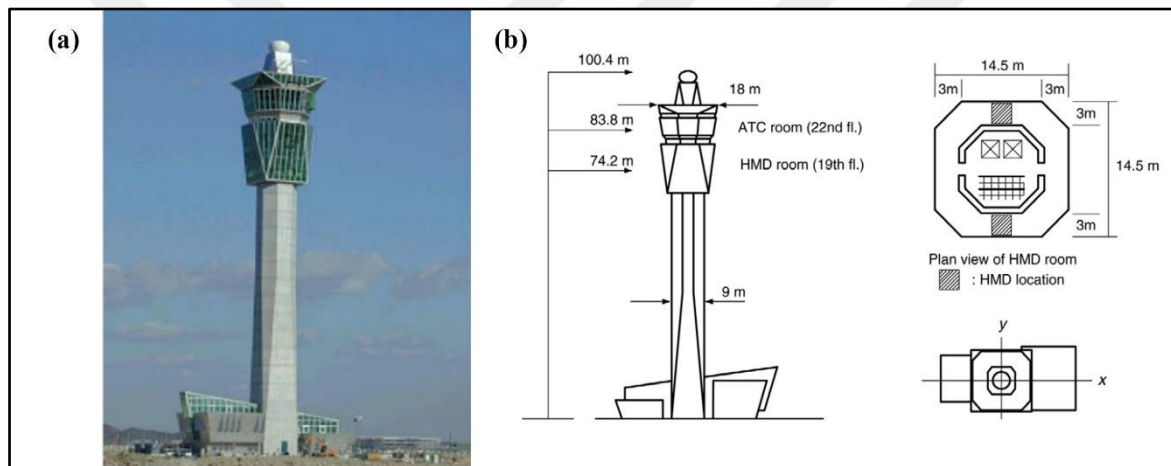


Figure 4.6. a) Incheon Airport ATC tower view, b) Drawings of the ATC tower source: (Park et al., 2006).

Park et al. (2006) show that the IIA tower and similarly designed tall towers with slender sections are vulnerable to wind. Additional systems are required to make tall towers of this slenderness more resistant to wind load. In addition, the fact that such towers are designed high so that they can see everywhere actually restricts visibility. Exposure to many meteorological phenomena such as cloudiness, haze, and precipitation is higher and more frequent in high towers and the operation is carried out with cameras and radars. Also, the placement and angle of the glass panels reduce glare and reflections which helps the controllers not strain their eyes. They can see the entire moving aircraft in all lights. Also, the angled glass panels minimize solar heat gain, further enhancing visibility and comfort.

4.2.3. Heathrow Airport ATC tower

Built in 2007 in London, United Kingdom, the 87-meter Heathrow Airport ATC tower is another example of a tall, slender tower. The main feature of this tower is that it was built quickly thanks to its modular frame. The control room was assembled in place by sliding upwards over the triangular section structural system (Archello, 2010). In order for a tower of this slenderness to withstand wind loads like the IIC tower, the structure is supported by steel cables (see Figure 4.7a). A technical block is located below the tower and serves the tower.

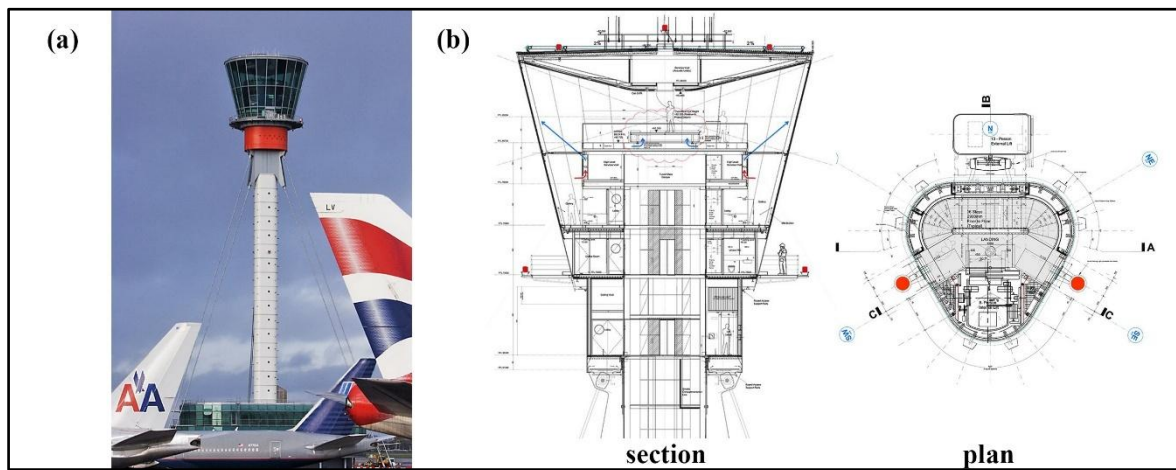


Figure 4.7. a) Heathrow ATC tower view, b) Drawings of the ATC tower source: (Archello, 2010).

As can be seen in Figure 4.7b, the control room and many units are located within the same glass mass. In this way, it was aimed to maximize the visibility of all units, and it was also thought that this design would speed up the construction process. However, this design approach will expose all units to the sun and increase reflections, heating, and cooling loads. The interiors will heat up considerably due to the greenhouse effect. The design of the control room is a triangular form with curved corners, which is not seen in other towers. The absence of corners makes this tower more resistant to wind. Although the use of curvilinear glass is also seen in this tower, it is seen that there are no eaves designed to protect this glass from precipitation.

4.2.5. O'Hare International Airport south ATC tower

Built in 2015 in Chicago, USA, the 66.5-meter-high O'Hare International Airport's south ATC tower has an octagonal shape with a 42 square meter wide cabin (Walshgroup, 2017). The tower was sited to minimize working blind spots and enhance connectivity between the ATC tower and the ground control teams on the main line (see Figure 4.9b). The tower has a unique façade of vertical fins that serve a dual purpose as solar shading devices to help keep the building cool and as aesthetic elements for the structure. One of the most important features that distinguishes this tower from other ATC towers is that while other towers rise with a circulation module, this tower has many spaces underneath. Each floor of the tower is actively used.

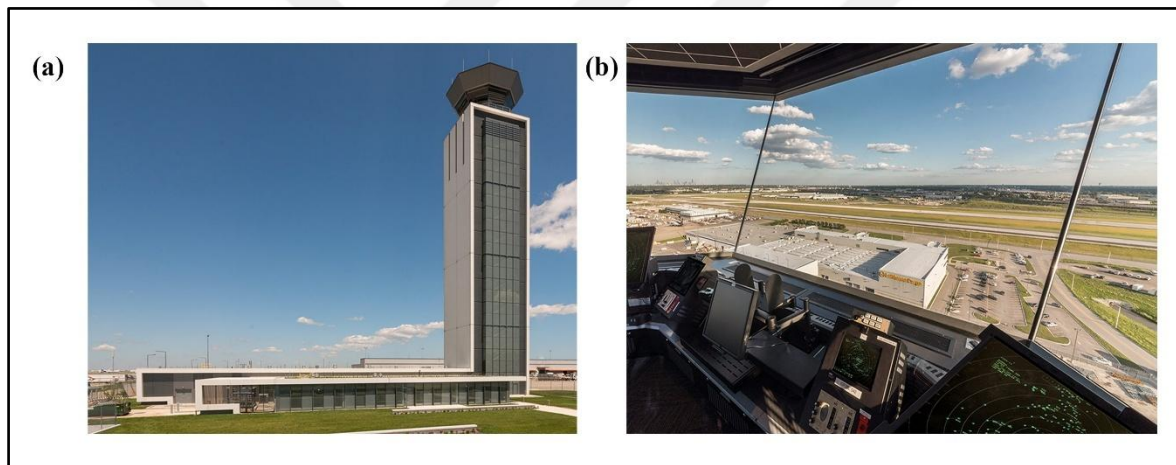


Figure 4.9. a) ATC tower and technical block view, b) a view from inside the tower source: (Walshgroup, 2017).

In accordance with sustainability goals, the South ATC Tower has received LEED Gold Certification as an energy-efficient structure built through sustainable construction. The control room is equipped with low-emissivity (Low-E) glass that allows sunlight into the area while retaining cooler air inside. Moreover, the building has a rainwater collection system and low-flow plumbing fittings to minimize its overall environmental footprint. The energy-efficient LED lighting system with smart occupancy sensors prevents the wastage of electricity, in the tower's approach to sustainable aviation infrastructure. Besides its technical and ecological developments, the tower is a symbol of modernity, blending high technology with its structures and environment. It sets a trend for air traffic control towers worldwide.

4.2.6. Federal Aviation Administration Sustainable Tower Design Initiative

The FAA wanted a design consisting of standardized parts to ensure construction and operating costs were low, while also being capable of working in a wide range of conditions, including hot and cold temperatures, humidity, and strong wind (see Figure 4.10). According to Practice for Architecture and Urbanism (PAU), the design allows for uniformity and flexibility so that the tower heights can be modified as per airport traffic requirements and optimum sightlines. Also, the design supports colors and materials that the local context uses, adding to its architectural identity. The design of the building's interior systems integrates the health and well-being of the air traffic controllers.

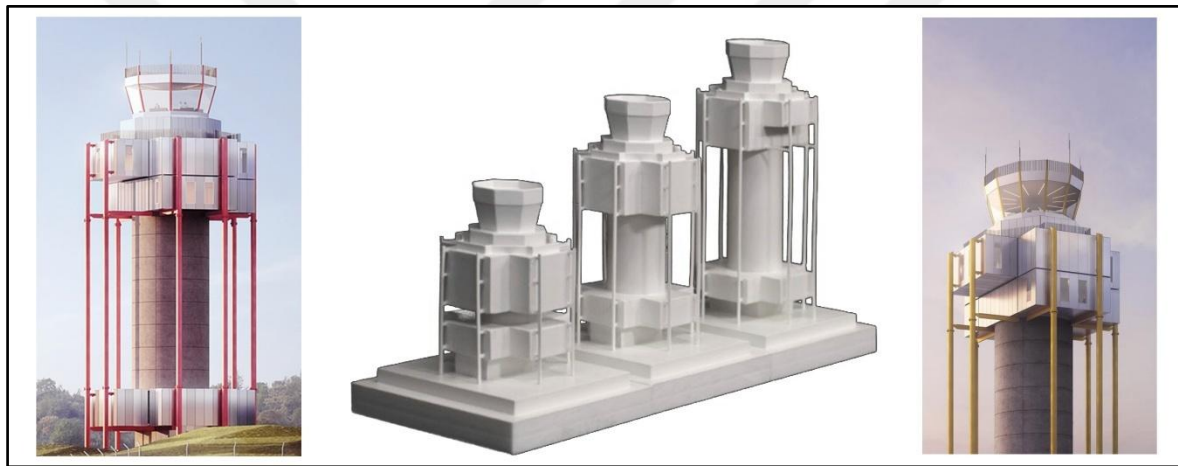


Figure 4.10. The FAA sustainable tower project views (FAA, 2023b).

The replacement of decrepit air traffic control towers will see the construction of 31 new towers that are said to be efficiently operating. The new towers will have heights ranging from 18 to 36 meters. Incorporating all-electric building systems and chemical-free materials, these towers ensure a sustainable and well-planned lifecycle. Better walls that are thermally efficient will help save energy. The use of high-recycled steel, metal products, and renewable mass timber will ensure the negation of impact. In addition, ground-source heating and cooling systems are installed where appropriate, to improve energy performance, and reduce conventional heating and cooling. All these studies show that innovative and sustainable searches in aviation also show their effects on air traffic control towers. These studies are of great importance for air traffic control towers that work visually and all façades are covered with glass.

4.3. Architectural Standards and Limitations

The design of ATC towers globally or regionally is driven by the struggle of aviation rules that help in the stable structure, working, as well as safety. Nonetheless, varying designs, heights, and sustainability approaches arise from a lack of a universally agreed framework. The International Civil Aviation Organization (ICAO) sets general international guidelines for 193 member states particularly Europe, Asia, and Latin America while in the United States, there are approved design specifications that are enforced through the Federal Aviation Administration (FAA). In a similar manner, Eurocontrol issues technical recommendations for air traffic management in Europe. Further, China, Australia, and the UK use their own civil aviation authorities for national regulation. These differences will lead to different restrictions on the heights of ATC towers, seismic safety, and energy efficiency.

AFTIL (Airport Facilities Terminal Integration Laboratory) 's primary mission is to provide a modeling and simulation platform to support proof-of-concept evaluations; control tower siting and evaluation with interior design, tower layout, site selection, orientation, and height determination; as well as supporting human-in-the-loop simulations, operational and procedural concepts, and line-of-sight studies in the terminal environment. The standards shared by the FAA are also derived from these laboratories and include the entire United States, the Atlantic and Pacific Oceans, and most of the Gulf of Mexico, all of which are FAA members.

As a member of EUROCONTROL and ICAO (International Civil Aviation Organization), Türkiye is not obliged to comply with these FAA standards. Türkiye accepts and applies ICAO and EUROCONTROL standards, which are accepted and shared by its civil aviation authority, the Directorate General of Civil Aviation (DGCA). Although the air traffic control buildings constructed throughout Europe are similar to each other, they are built according to the local regulations of the countries and differ from each other. For example, the type of glass used, the angles, the color of the coatings, the height of the towers, and the fire resistance vary. Although all this freedom offers aesthetic value in terms of architecture and is an architectural richness, the fact that a number of critical points are not determined by standards constitutes a weakness for the towers.

Table 4.2 analyzes the regulations on ATC towers in the world. In general, although ATC Tower design is addressed as a sub-heading in airport design regulations, the number of regulations containing such information is quite small. In this sense, ICAO Annex 14-Volume 1 (Aerodrome), ICAO Doc. 9184, FAA 6480.7, FAA 6480.4, Earthquake Regulations for Airfield Structures in Türkiye (Republic of Türkiye, 2018), and EASA CS-ADR-DSN regulations are examined. The review shows that while ICAO regulations leave the design much freer except for general statements on tower designs, the FAA has broader and more detailed standards on these issues and controls the design of towers.

Table 4.2. Analysis of standards on ATC tower (source: Author).

Standart/Regulation	Applicable Region	Content	Architectural Design Deficiencies
ICAO Annex 14 – Volume I (Aerodromes)	United Nations Members	Provides general guidelines on aerodrome design, siting, obstacle clearance, and lighting.	No specific provisions on ATC tower architectural design, spatial planning, or human factors.
ICAO Doc 9184 (Airport Planning Manual - Part 1 Master Planning)	United Nations Members	It makes recommendations on the height and position of the tower and control room ergonomics.	Such recommendations are general provisions and not detailed. There are also no recommendations on the architectural structure of the tower.
ICAO Circulation 451 (Human Factors in Air Traffic Control)	United Nations Members	It gives partial visualizations of control room design and talks about general principles.	Clearer standards should be set for the tower's architecture and material details. General statements made for the Control room are not enough.
ICAO Doc 9426 (Air Traffic Services Planning Manual)	United Nations Members	Detailed information and visuals about the equipment, general layout and requirements for control rooms are presented.	Sustainable approaches to climate change should be included in this regulation. In addition, a guide with more detailed and mathematical data on tower architecture should be presented.
FAA 6480.7 – Airport Traffic Control Tower And Terminal Radar Approach Control Facility Design Guidelines	The USA	An appropriate guide to the architectural details of the towers has been created with architectural drawings and material recommendations.	The recommendations are more detailed than other standards and adequately express the requirements for architectural design. However, clearer data on visibility, reflections and tower height should be used.
FAA 6480.4 – Airport Traffic Control Tower Siting Process	The USA	General recommendations on the view inside the towers gave more detailed recommendations on the height, lighting, ventilation and materials for the ergonomic design of the tower.	The information overlaps with FAA 6480.7, but more mathematical data and visual expressions of the standards should be included.
Earthquake Regulations for Airfield Structures in Türkiye (THMYDY)	Türkiye	Although it has its own earthquake code, it would be valuable to develop a specific code for airport structures, including ATC towers.	ICAO provisions also apply here and a local regulation on ATC tower design could be developed.
EASA CS-ADR-DSN (Certification Specifications and Guidance Material for Aerodrome Design)	European Union (EU)	While it provides information on the equipment and systems required for square design, information on towers is weak.	The architectural design of the ATC tower and the design of the electrical systems must be integrated. Tower architecture should also be included in this certification process.

4.3.1. Design regulations

In the design of control towers, aesthetic as well as functional considerations should be taken into account. There are some basic rules for the construction of control towers. For example, towers built with concrete or masonry load-bearing walls should not exceed 48.7 meters in height, but almost every tower built today is taller than this. The choice of color should be homogeneous, with a preference for medium-light tones, and surfaces should not be reflective or eye-catching (FAA, 2004, p. 5-15).

In addition, the exterior façades of the towers should be designed to maintain the indoor temperature, and each façade should be customized to take into account environmental factors such as solar radiation and wind direction. Passive air conditioning solutions such as eaves, louvers, reflective films, or tinted glass should be used to minimize solar gain. However, it is also important to ensure that all windows at ground level are made of tempered glass for safety reasons (FAA, 2004, p. 15).

Control room design

In Figure 4.11, sample control room designs are proposed according to airport densities. Small cabins are preferred for small activities and one person's access to many places in the same place is taken into consideration, while for large cabins, a design suitable for task distribution is made. Looking at today's towers, it is seen that the control room area increases as the number of personnel required increases as the density increases, but no geometric coherence is observed.

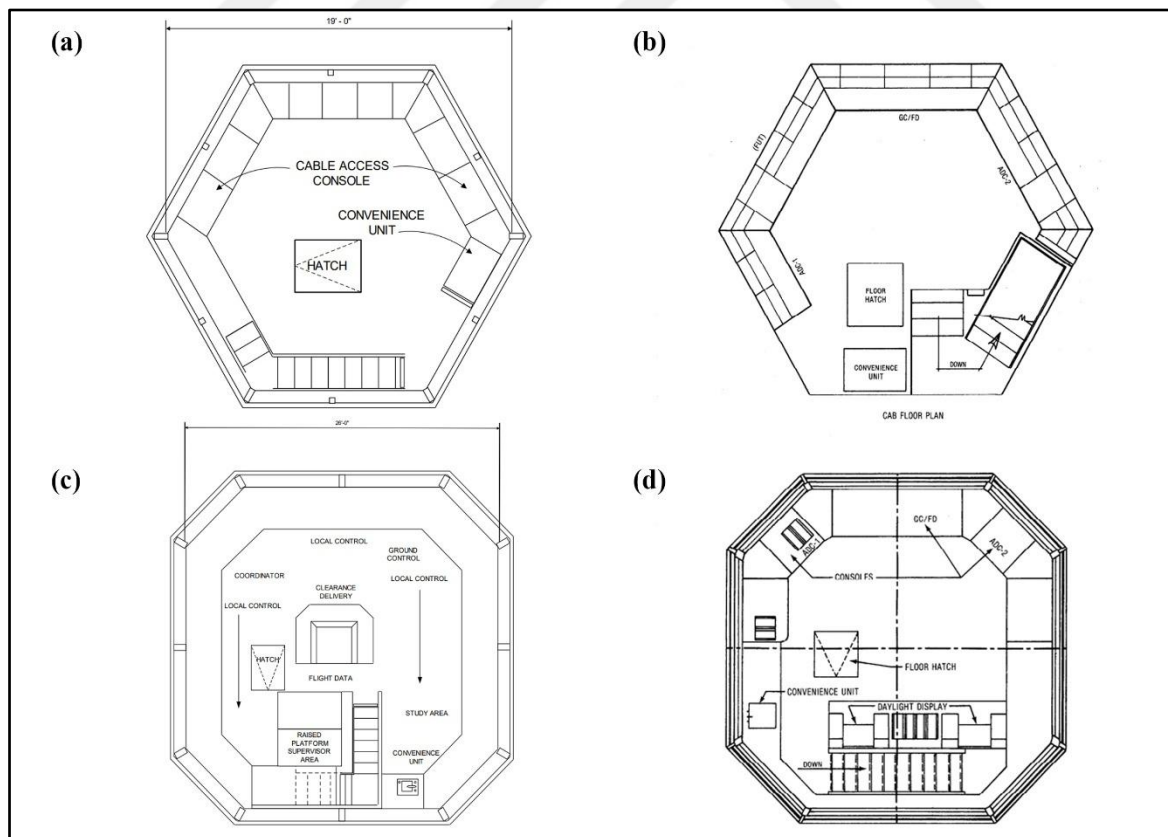


Figure 4.11. FAA control room layout a) low activity, b) major activity (FAA, 2004, 1-7 appendix 3), ICAO control room layout, c) low activity, d) major activity (ICAO, 1984).

For flooring, these regulations recommend the use of common noise-blocking materials. A low electrostatic, non-reflective rubber mat is seen as a suitable material (FAA, 2004, p. 47 chapter 5). ICAO recommends carpeted floors (ICAO, 1993, p. 8). Today, due to the large number of electrical and mechanical installations passing under the floors, raised floors are preferred because they can be easily dismantled and maintained (see Figure 4.12). Suspended ceilings are also a frequently preferred design for control rooms. It provides convenience for regular maintenance of mechanical and electrical installations inside. It would be advantageous to prefer materials to prevent noise and reflections. However, many towers today do not pay attention to these standards.

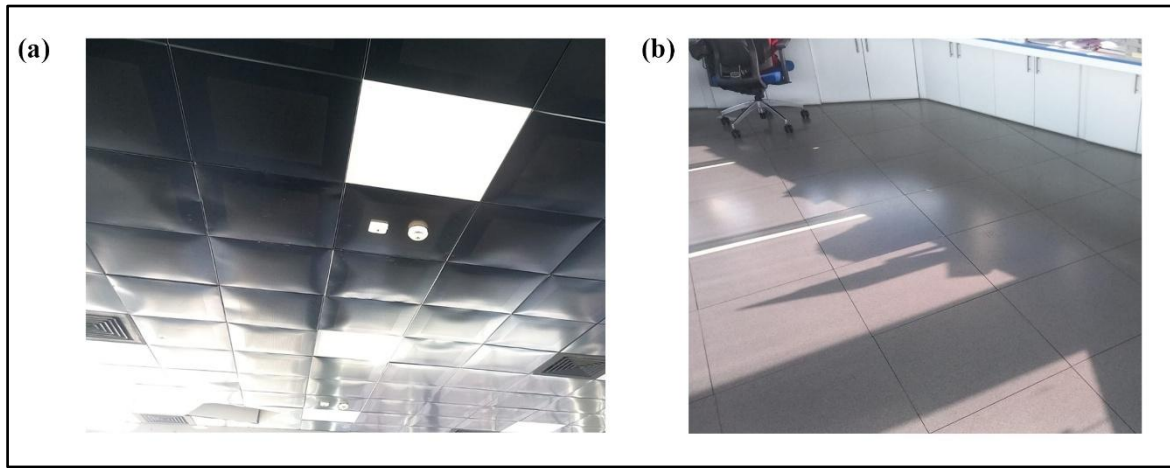


Figure 4.12. a) Ceiling material, b) Flooring material (photographed by ATCO Evren Cayir at Canakkale Airport, Türkiye).

Façade design is one of the most important issues for control rooms. All regulations mention that the ATCO must have a clear view of the airport and its surroundings. Façade visibility should be as high as possible, but internal reflections should be unobtrusive. This situation creates a contradiction in itself. In order to maximize visibility, attention should be paid to the design of the structural system, and systems that will not obstruct the view should be designed. In addition, glass joinery should be thin-sectioned and few in number. This requires the choice of glass and joinery with high strength. It is also stated that colored glass should not be preferred, and Low-E glass should be preferred if possible in order not to prevent the communication between the aircraft and the tower with the lights (FAA, 2004, 47-48 chapter 5). In applications, heat-glass types with laminated inner glass and tempered outer glass are preferred.

One of the most important decisions about the façade is the sloping design of the façade. The sloping design of the façades reduces the retention of precipitation on the façade and provides an advantage for visibility by reducing reflections. This slope is recommended to be 15° (see Figure 4.13). ICAO does not give any angle value for this. In today's towers, it is seen that this slope is applied differently due to both application errors and local requirements. Each tower has specific parameters such as wind loads, latitude, height, and width of the tower, and the design should be developed around these parameters. Outside the control room, there should be a balcony for the controllers to observe and get fresh air. Again, by designing a console on the roof of the rooms, the effect of reflections and external factors on the façade can be reduced.

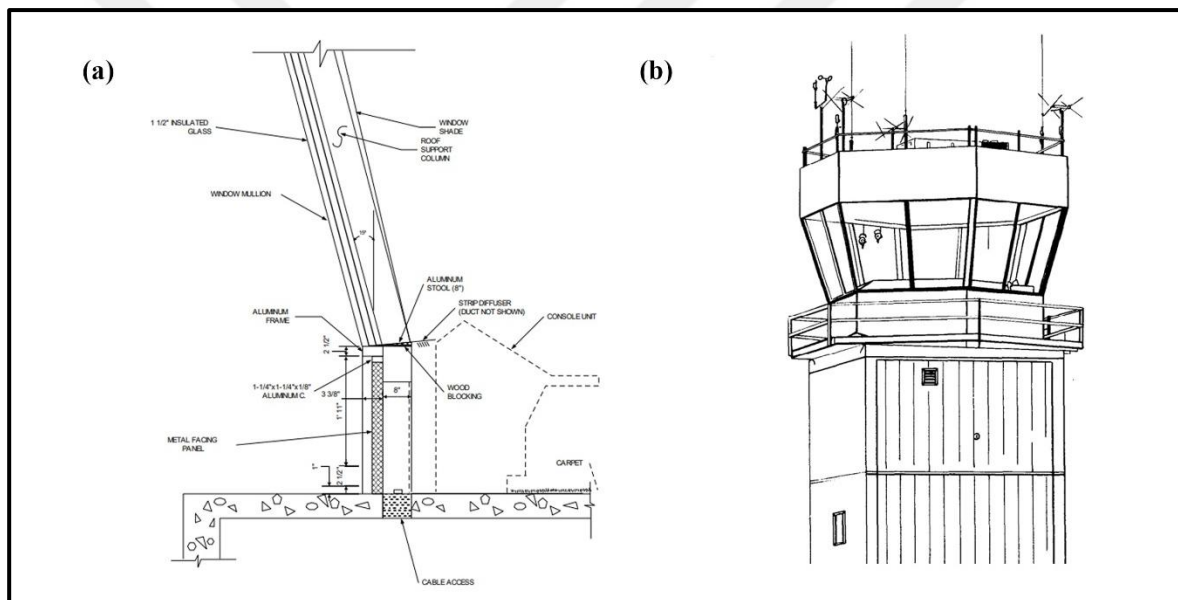


Figure 4.13. a) Angular façade design (FAA, 2004, p. 17 appendix 3), b) Sample tower design (ICAO, 1984).

Finally, circulation is very important in architectural layouts. ATCOs should not block each other's view during movement, and placement and capacity should be considered, such as the number of personnel that will increase in case of guests or emergencies (ICAO, 1993, p. 9). This area is approximately 21 square meters for low-activity control rooms, 32 square meters for medium activity, and 50 square meters for large activity, and the height from floor to ceiling for the control room should be 3 meters (ICAO, 1984). This height is important for controllers to see the maneuvering area more easily, to work comfortably, and for the placement of equipment. Today, with the use of suspended ceilings, the clear height limit can be violated.

4.4. Problems of ATC Towers

ATC towers are critical infrastructures of the aviation sector allowing the safe and efficient management of airspace. Nonetheless, ATC towers are considered to be significant facilities in the operational context but face a lot of challenges due to regulatory, design, environmental, and occupational health issues. The issues affect how air traffic control operates and are hindering efficiency at the operational end.

Each tower has a different traffic density, number of personnel, service (TWR or TWR + APP), location, meteorological conditions, height, geometry, and design. In this sense, although a universally optimal tower design is not possible, it is possible to make arrangements to improve the design. For this purpose, ATC towers built with existing standards should be analyzed, problematic and missing parts should be identified, and improvement suggestions should be developed.

4.4.1. Visibility limitation

One of the most critical issues affecting ATC towers is visibility limitations. The design and positioning of these towers should provide an unobstructed view of the entire airport. For this purpose, regulations recommend angling the façades of the control room and using dark-colored materials. In addition, the location and orientation of the tower should be such that it is less affected by such external factors, but currently, the interaction with such natural factors is seen in all architectural structures. The location and orientation of ATC towers should be within the boundaries of the existing terrain, away from the terminal, and in a location that can control air traffic and have a view of the airport, so the number of locations is not very flexible.

Visibility in towers can be restricted for many reasons. The most important of these is the sun factor because control rooms are built with all glass around for maximum visibility. The angle of the sun's rays and their strong reflections can cause glare, limiting ATCO visibility. The sun comes at different angles in winter, summer, sunrise, or sunset. Existing regulations are inadequate to protect against these rays. ATCO may experience discomfort with these situations and has developed its own sun protection methods.

Towers are 360-degree service buildings. Therefore, it is necessary to examine the control room layout to discuss any orientation. The working layout and equipment in the tower should be in the direction of the runway. This means that people will generally concentrate on a certain side and will be more exposed to the sun coming from that side during the day. Visibility is most critically affected at sunrise due to direct sun exposure. At sunrise, the angle of the sunlight directly enters the control room, making it difficult for the controller to visually monitor the air traffic outside. This effect is seen all day long in towers in hot climate zones where the solar effect is high. As can be seen in Figure 4.14, although dark-colored materials reduce reflections, the ATCO's view of the external environment is still limited.



Figure 4.14. Sunrise glare and reflections at ATC Tower (photographed by ATCO Evren Cayir at Canakkale Airport, Türkiye).

Sunset rays are one of the most precautionary lights in architecture. This is also the case for the ATC tower. The sunset rays penetrate the inside of the tower because they are more oblique. ATCOs cannot follow the airplane traffic outside and have difficulty seeing the monitors inside (see Figure 4.15a). This is one of the lights that also makes approaching difficult for airplanes. Since ATCOs cannot cope with this situation, they try to manage the air traffic at the points they can see and may even use the opposite runway. Although this is an appropriate solution in calm or non-severe winds, when the winds are strong or meteorological events such as cloud cover occur, traffic is tried to be managed with reflections and glare. Such operations become difficult to conduct and increase the workload of ATCOs.

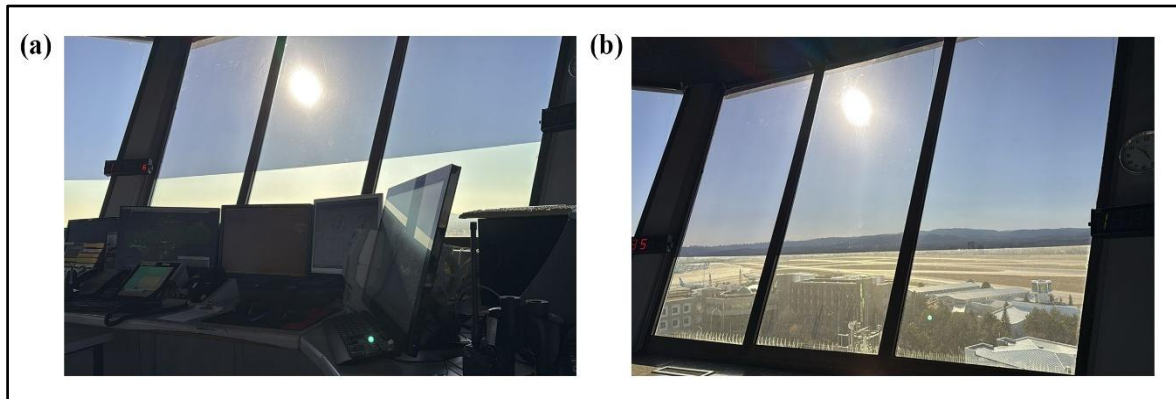


Figure 4.15. Restriction of visibility by sunset lights and inadequate film coating measures on glass (photographed by ATCO Gurcan Sinar at Esenboga Airport, Türkiye).

While the sloping façade design and special glazing designed to prevent reflections and glare are effective against reflections and glare during the day, they cause another problem at night by causing internal reflections. Turning on the interior lights during night operations causes reflections and restricts ATCOs' visibility. As seen in Figure 4.16, when the interior lights are switched on during a night operation, the glass acts as a mirror and reflects the interior. In order for operations to be carried out properly, the lights must be kept off or turned on to a limited extent. The light is switched on when operations are light or absent and necessary work is taken care of. Solving the reflection problems with special layers on the inner glass layer causes these problems, and the solution to this problem is that the solar control elements to be used inside and outside should be in a structure that can be turned on and off when needed.

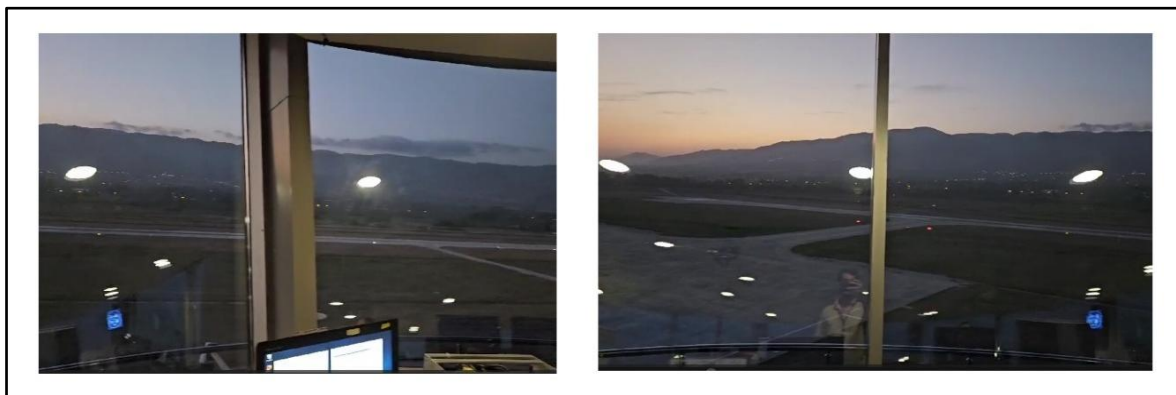


Figure 4.16. Light reflections inside the ATC tower during night operations (photographed by the author at Tokat Airport, Türkiye).

Existing daylight control methods

After the construction of ATC towers is completed, some sun control elements are used to prevent this loss of visibility and to increase user comfort. These measures include the use of sun-blocking elements such as portable semi-transparent coatings or panels on the side where the sun is coming from when the sun is uncomfortable, the use of manually controlled curtain elements, or motorized curtains. These elements can be used on every façade of the tower or only in one part of the tower. Since the installation of curtain elements is costly, time-consuming, and inconvenient to use due to the electrical installation and construction processes required, solar control is done with portable elements in the first place. These elements, which are placed in the direction of the sun when it restricts visibility during the day, provide partial solar control and provide a temporary solution (see Figure 4.17).

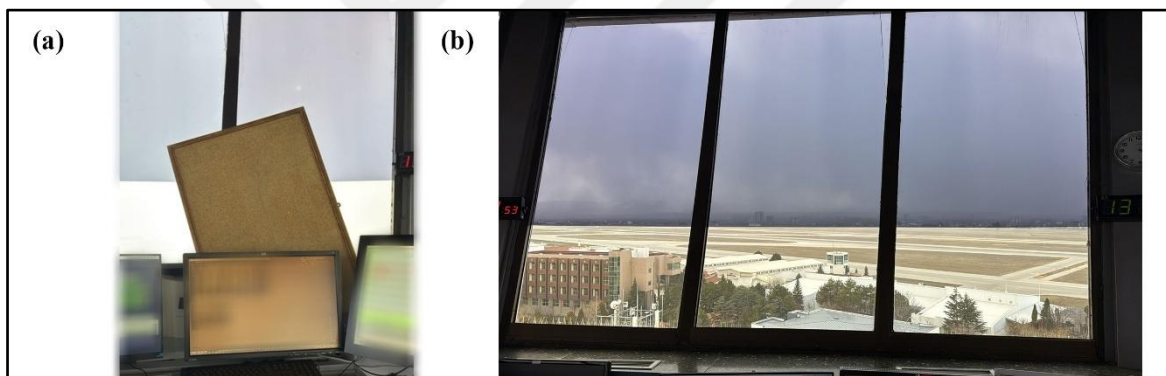


Figure 4.17. a) Use of cork board to block the sun, b) Semi-transparent coatings placed manually on glass (photographed by ATCO Gurcan Sinar at Esenboga Airport, Türkiye).

In cases where solar control with portable elements is insufficient, curtains are used for daylight control. The material of these curtains varies and curtain types such as fabric curtains, roller blinds, or blinds are used. However, except for the black semi-transparent curtains used for ships, the other curtains used are very poor in performance. These curtains can be opened manually by ATCOs when necessary to provide daylight control. Fabric curtains are successful in daylight control but they block visibility to a great extent (see Figure 4.18). Venetian blinds and roller blinds are unsuccessful in situations where the sun's rays come from oblique angles such as sunset, but are effective in other situations. Black semi-transparent film curtains provide a more balanced result in terms of visibility and daylight control.

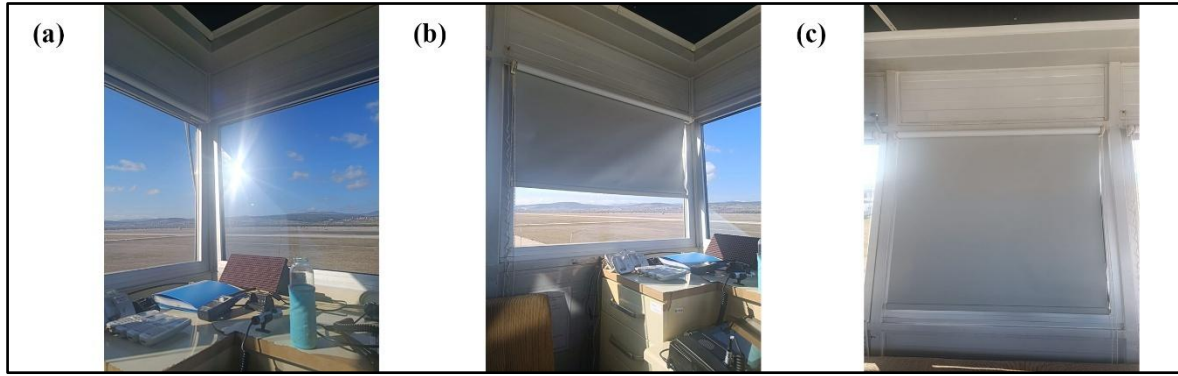


Figure 4.18. Daylight control stages of manual fabric curtain a) closed, b) half open, c) open (photographed by ATCO Efecan Gulec at Usak Airport, Türkiye).

Motorized curtains are the closest control method that comes close to meeting the need for adaptive daylight control façades in ATC towers. The roll-shaped semi-transparent materials are connected to a motor and can be opened and closed by remote control. Each motor can be controlled independently of each other via the remote control. Since these systems are expensive, they are usually installed on the façades where the sun comes the most, but if that is not enough, they can also be installed on all façades. Since a motor is placed between each mullion on the façade, the degree of adaptability of the façade depends on the mullion frequency. As the number of mullions increases, visibility is restricted (see Figure 4.19).

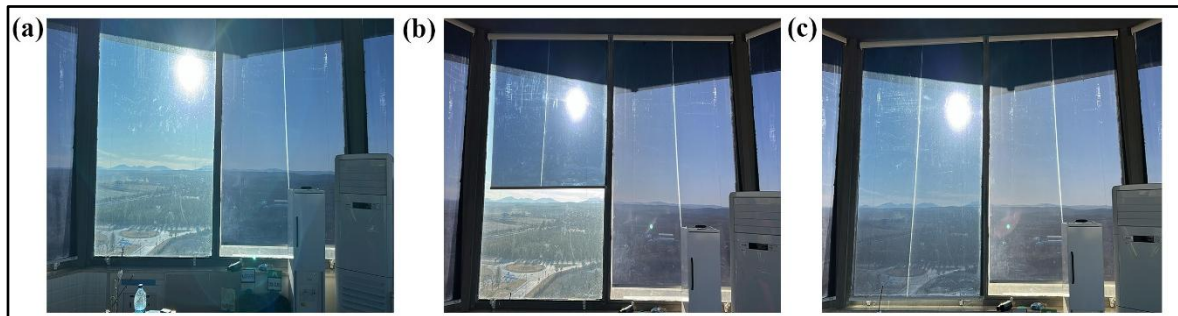


Figure 4.19. Daylight control with motorized blinds a) closed, b) half open, c) open (photographed by ATCO Gokhan Mutlu at Nevsehir Cappadocia Airport, Türkiye).

Motorized curtains, on the other hand, require regular maintenance, add an extra workload for the ATCO, and make operations difficult by constantly restricting visibility when they break down. The quality of the motors and the practice of the manufacturer are very important here. In the future, with the development of materials that are better at daylight control, these curtains may be a solution, but with current materials, even with the curtain fully open, the sun continues to restrict visibility (see Figure 4.19c).

In addition, the use of solar control elements in the interior causes the curtains to come into contact with the glass due to the oblique design of the façades. Special low-e and low-reflective glasses in the towers are damaged due to these contacts (see Figure 4.20b). Considering that a curtain element is opened and closed many times a day, scratches, stains, and even cracks are inevitable.

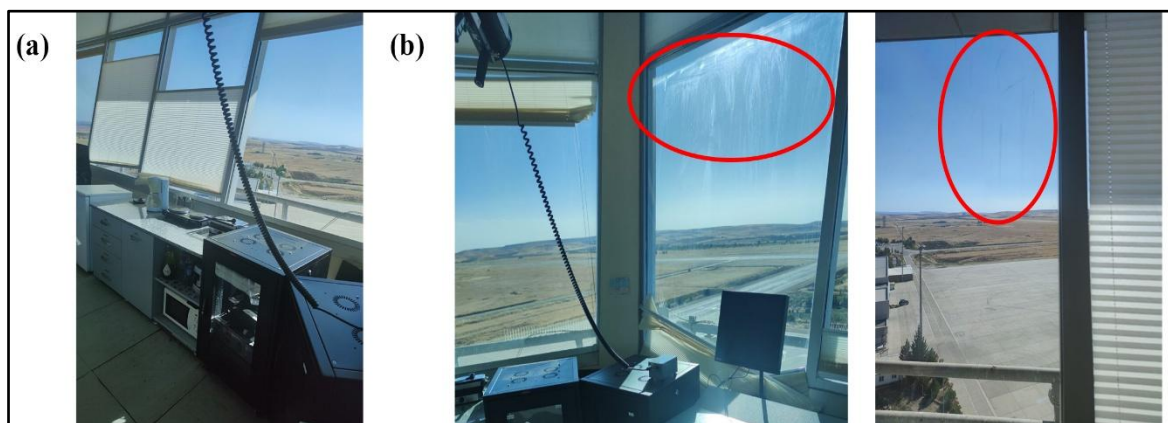


Figure 4.20. a) Attempts to prevent daylight control by placing the curtains at different points
b) Scratches, stains and damages on sensitive glasses during the movement
(photographed by ATCO Munir Atabey at Sanliurfa GAP Airport, Türkiye).

4.4.2. Air conditioning problem

Air traffic control towers that have all-glass façades face big air conditioning trouble. A lot of glass causes a lot of cold or heat to pass in or out: sunlight comes in and heats the cab quickly. But, as soon as night falls or when the weather is cold, the tower also loses heat quickly. Simply put, glass walls offer little insulation so there are large temperature variations. Controllers frequently state that direct sunlight can convert the tower cab into a greenhouse, which can result in subsequent cold drafts causing the sun to be lost, further complicating their efforts to maintain a comfort zone.

These highly glazed environments put pressure on HVAC systems. The HVAC system must work harder because it gets hot in the summer and loses heat in the winter through the glass. In any case, the temperature is difficult to keep constant, with it being hot on one side of the cab and cool on the other. Recognizing this, design rules recommend that control rooms have temperature sensors on them at several locations to average their readings (FAA, 2004). When the HVAC doesn't work properly (frequent cycling or uneven airflow), it wastes

energy and also leaves some spots too warm while others are too cold, which doesn't help the comfort of the controller.

Thermal instability affects ATCO performance and well-being. Research conducted in tower environments has shown that temperatures outside of the acceptable range are the principal cause of discomfort experienced by controllers (Helmis et al., 2009). When the cab is too hot or too cold, controllers can become tired, lose focus, and get physical symptoms (like headaches or sweating) that distract them. In addition, since the work requires continuous conversation, the relative humidity of the environment should be above 50% (Aydın, 2009). In a line of work where attention is key, even mild heat stress can affect the brain power or slow response times.

4.4.3. Noise problems

ATCOs are affected by both external and internal noise. Outside sounds coming from the environment (especially the weather) can enter the control tower and impact the controllers. The strong winds cause fluctuations and resonance in pressure around the cab leading to a howling sound. Furthermore, heavy rainfall or hail hitting the glass roof and windows creates loud drumming noises. During stormy weather, wind gusts can cause heavy interference and the rain can create distracting noise just before critical tasks. Despite the insulation and thick glass used in tower designs, the sudden loud rumbles (thunder and storm gusts) still come as a shock to controllers, distracting them and impairing focus on aircraft calls.

Internal noise generated within the tower is a constant concern as well. The ambient noise floor in a busy control cab is filled with hums and sounds from equipment and conversations. Radar displays, computer servers, ventilation fans, and other electronics emit continuous background noise. On top of that, controllers wear headsets and speak to pilots and each other, adding to the auditory load in the room. Studies have measured typical noise levels of about 66–68 dB inside an active tower cab, which exceeds the 55 dB limit recommended by ICAO for controller work environments (Krisman et al., 2024). This means controllers are often working in noise conditions louder than ideal, forcing them to speak loudly and listen closely to discern important audio (like radio calls or alarms) from the background. Over time, equipment noise or a loud HVAC system can blend into a constant din that mentally tires staff.

Excessive noise pollution affects the performance and health of controllers. Research focused on control room ergonomics found that high levels of background noise can interfere with communication between operators, disrupting workflow. In the tower, important verbal messages may require repeating if they are drowned out, and misunderstanding a transmission can have dire consequences. Being in a place that is noisy for long periods raises the level of stress hormones and mental fatigue. Krisman et al. (2024) indicate that high noise levels cause the release of cortisol, which leads to tiredness and reduces concentration. According to studies done in workplaces, constant chatter and noise in the background lead to huge drops in task productivity (50-60% in extreme cases) due to people's failure to focus.

4.4.4. ATCO health problems

Air traffic controllers experience a range of occupational health issues stemming from stress, workload, and the nature of their work environment. Major health risk factors and their impacts include:

Chronic stress and mental health: The ATC profession is inherently stressful – controllers must maintain intense focus and make high-stakes decisions with no room for error (Aydin, 2009). Prolonged exposure to such stress, especially without sufficient rest, can lead to burnout, anxiety, depression, and other mental health disorders (Rutledge et al., 2024). Surveys of ATCO populations show that while many cope within normal ranges, a significant subset (roughly 10–15% in one study) exhibit elevated stress symptoms at levels indicating serious trouble coping (Zeier, 1994). This chronic stress can manifest in physical ways too (sleep disturbances, headaches, irritability) and is even linked to higher rates of stress-related illnesses like peptic ulcers among controllers at high-pressure facilities (Salleh, 2008). Mental health support and stress management programs are therefore critical to maintaining ATCO well-being.

Sleep-related and cardiovascular issues: ATCOs usually do shift work including nights which can disrupt their normal sleep pattern with consequent heart issues and sleep-related illnesses. Your job stress and lack of adequate restorative sleep can increase your risk of heart disease. Research confirms that shift work and sleep deprivation in ATC are associated with increased incidence of hypertension, heart disease, metabolic syndrome, and obesity

(Sonati et al., 2015). For example, one study of controllers on different schedules found elevated body fat percentages (around 28–31% on average) and poorer self-reported health among those working longer, rotating shifts (Sonati et al., 2015). The results point out that ATC work (out-of-schedule meals, adrenaline spike, etc.) and a sedentary lifestyle together can cause health hazards like hypertension and cardiac strain in the long run. Interventions to reduce such risks include managing workload, limiting working hours, and encouraging good sleeping habits.

Since air traffic control is mainly a desk-bound job with work at the computer console, there can be musculoskeletal and ergonomic issues. Numerous controllers claim to suffer from chronic musculoskeletal disorders due to their prolonged sitting, constant repetition of movement (e.g. regular scanning of the radar), and awkward postural (e.g. looking up at planes or down at screens). Research shows that the ATCOs tend to have a high prevalence of neck shoulder and upper back problems even under modern computerized systems (Arvidsson et al., 2006). Sitting for prolonged periods without much movement can lead to stiffness, and lower-back pain, and cause circulatory problems (like varicose veins or leg cramps). To address these issues, ergonomic interventions can help. It would be good to use adjustable sit/stand workstations, anti-fatigue mats, adequate seating support, and regular break schedules to stretch. Evaluating the ergonomics of ATC workstations can reveal risk factors (eg not at eye level, glare, etc.) and inform improvements to reduce physical strain. Agencies can help improve controller health by redesigning the workstation and promoting physical activities (e.g. short exercise during shift).

The overall health problems of ATCO are interconnected, with high levels of stress aggravating physical problems and poor physical health affecting fatigue and stress. Preventive measures such as stress management training, regular medical assessments, optimized scheduling, workstation ergonomics and more can greatly enhance controller health and longevity on the job. Keeping controllers healthy benefits them personally, but it also ensures they will be at a high level of alertness so they can work at the high precision that air safety requires (Rutledge et al., 2024). Thus, maintaining healthy controllers is both a human and an operational issue in the aviation system.

5. METHODOLOGY

The methodology of this research is based on a performance-based strategy in architectural design, combining qualitative problem analysis with quantitative simulation and parametric optimization processes. The aim of the study is to identify the architectural aspects of the environmental and operational problems encountered in air traffic control (ATC) towers and to investigate the potential of using Kinetic Reciprocal Frame (KRF) structures as an adaptive façade to solve these problems. The methodology is divided into three interrelated phases: (1) problem and literature analysis, (2) modeling and simulation, and (3) multi-objective optimization and pareto-front analysis (see Figure 5.1).

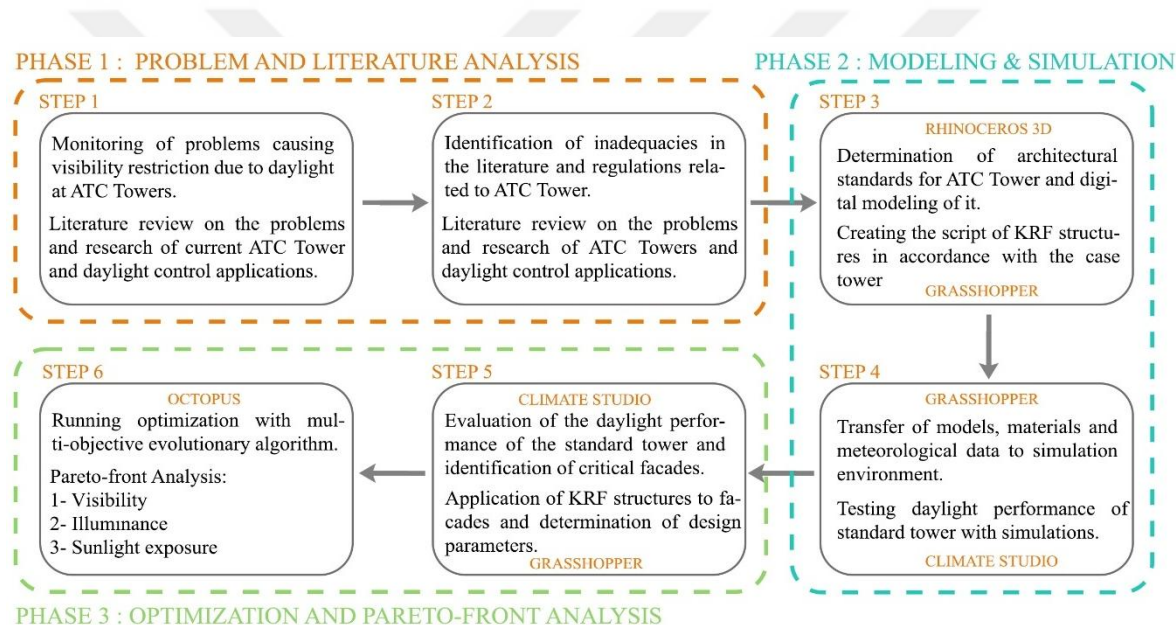


Figure 5.1. Workflow Diagram (source: Author).

5.1. Phase 1: Problem and Literature Analysis

The main objective of this phase is to identify the architectural and environmental problems observed in existing air traffic control (ATC) towers and to compile existing knowledge on these problems. In particular, visual discomforts associated with daylight control were identified based on field observations and user experiences. Glare, sunlight exposure, and field of view loss due to direct exposure of controllers to light sources are among the main problems addressed in this phase.

Following these observations, current architectural approaches, kinetic façade systems, and examples of adaptive design in the literature were reviewed in detail. At the same time, the regulations issued by the International Civil Aviation Organization (ICAO), the Federal Aviation Administration (FAA), and the European Union Aviation Safety Agency (EASA), the international regulatory bodies for airport infrastructure, were evaluated (see Section 4.2. Table 2). The requirements for ATC tower architectural design in the standards have been examined, and it has been determined that there are uncertainties and deficiencies regarding the items that address the problems identified. In the literature review, it was found that the studies on ATC tower architecture are quite limited.

In addition, air traffic control tower designs, geometries, heights, and most important features built between 1974-2023 were analyzed (see Section 4.2. Table 1). When the examples are examined, it is seen that the air traffic control towers around the world are quite different from each other, and the design of the towers is shaped as prestige structures rather than operational requirements. When the ATC towers constructed within the framework of these standards in Türkiye are observed, it is determined that the problems mentioned in Section 4.4. are observed and experienced, and that the existing standards are insufficient to solve these problems. In this context, new architectural solutions and geometric searches are required for the façades that cause problems.

During the literature analysis process, it was observed that especially static shading systems cannot adapt to environmental variations sufficiently, and architectural design is based on passive elements. In this context, Kinetic Reciprocal Frame (KRF) systems, which offer an adaptive and dynamic approach, have emerged as an alternative solution with both structural and aesthetic potential. At the end of this phase, the research question of the study was clarified, and the effectiveness of KRF systems in solving daylight-based problems in ATC towers was identified as a hypothesis worth testing.

5.2. Phase 2: Modeling and Simulation

Simulations in a digital environment will be used to test the findings from the literature analysis and provide solutions to the existing problems. A sample tower design to be simulated is required to demonstrate the existence of the identified problems and metric data. The data required for the design will be obtained from existing regulations, and for the data

that cannot be obtained, current tower designs will be examined and analyzed, and average data will be taken as a basis.

Rhinoceros 3D, a NURBS model-based three-dimensional modeling program, will be used to model the sample tower. It is also CAD software and is widely used in architecture, engineering, and industrial design (McNeel, 2010). To apply the KRF structures to the created sample ATC tower, parametric design tools are needed. For this, the Grasshopper plugin, which is used as a plugin of the Rhinoceros 3D program, will be used. Grasshopper allows users to algorithmically generate geometry and manage variables in a controlled manner through visual programming (Rutten, 2013).

Environmental performance simulations will be performed through ClimateStudio software. ClimateStudio is an advanced simulation platform that can perform physically based daylight analysis using the Radiance engine (Solemma LLC, 2021). The fact that it can work integrated with both Rhinoceros 3D and Grasshopper is very positive for the study, as it provides fast and accurate results. If there are materials recommended for tower control cabins in EASA, ICAO, and FAA standards, they will be selected from the ClimateStudio material pool; if not, the material will be transferred to the simulation environment by contacting the current manufacturers of the material and following the material technical documents.

The tower formed with standard materials and geometries will be evaluated in terms of mean lux and annular sunlight exposure values. In line with the results obtained, the most sun-receiving façades will be determined, and optimization studies will be started for the design of KRF structures' façades suitable for these façades.

5.3. Phase 3: Optimization and Pareto-Front Analysis

Each tower has different design criteria due to its environmental conditions and air traffic capacity. KRF structures, on the other hand, have the potential to create very different façade designs for these façades for different purposes with variable design parameters. This reveals the aim of finding the most suitable design for each tower for each different façade. For this, the third phase aims to find and evaluate the optimum façade for the case ATC tower.

After determining the parameters of the KRF structures' adaptive façade design, 3 objectives were set to evaluate and analyze the resulting design. This objective is to optimize the useful daylight illuminance (UDI) and annual sunlight exposure (ASE) while keeping the view-out value as high as possible. This optimization requires a multi-objective optimization since 2 target values are tried to be reduced and 1 target value is tried to be increased. For the multi-objective optimization of the developed parametric model, the Octopus plugin running on the Grasshopper platform will be used. Octopus is an NSGA-II-based genetic algorithm engine that allows users to simultaneously optimize design variations based on multiple performance criteria (Vierlinger, 2013).

Pareto-optimum is the situation where a solution cannot be made better without improving any performance criterion while worsening others. In this context, Pareto-Front represents the set of solutions that provide the most balanced performance across all criteria. If we look at the values in the cluster, UDI refers to the illuminance level that should be within the hours used in the control room for a year. Within the scope of this study, the range of 300-3000 lux was set as the target value for the UDI value. Many studies have evaluated Illuminance range less than 100 lux as inadequate and above 3000 lux as discomfort (Kızılörenli and Maden, 2023; Talaei et al., 2021; Felicia Wagiri et al., 2024).

The ASE metric refers to the amount of time an interior space is exposed to direct sunlight and measures the amount of time an illuminance level above 1000 lux is above 250 hours per year. In ATC towers, this increases reflection glare problems from glass surfaces in the control room, limiting air traffic controllers' visual access to the outdoors (USGBC, 2018). According to the IES LM-83-12 and LEED v4 standard, ASE must be below 10%.

Finally, there is no standard for the view value that can be evaluated for control towers. It is stated that the visibility at ATC towers should be as high as possible and sufficient to carry out the operation. (FAA, 2004; ICAO, 1984). However, these standards do not address a scientific metric for visibility. Considering today's tower designs, it is known that even columns and glazing frames obstruct the view (see section 4.4). In this sense, the view value is used as a meaningful field of view from which external objects can be identified (Konstantzos and Tzempelikos, 2017; Nadiri et al., 2019). This area changes according to the movement and design of the façade.

In this study, view-out values will be calculated by defining a 360° visual field in the horizontal plane and a 60° visual field in the vertical plane. Each view ray is oriented in the horizontal plane, centered on the horizon line, and the first opaque object encountered by this ray is considered as “obstructing the view” for that pixel. This will determine the field of view on the façade. In the sample tower design, which does not include any additional façade design, the visibility will be assumed to be 100%, and how much the adaptive façade designs obstruct the view will be found with this scanning method. This value means that there is no solar control element, such as column design or vision-blocking curtains in the space. The visibility restriction caused by the glass joinery is ignored in this study.

While the values obtained as a result of the optimization are expected to meet these standards or make a meaningful improvement in order to comply with these standards, the maximum visibility should be as high as possible. These façade designs that meet these conditions will be selected and analyzed as the Pareto-optimal result.

5.4. Limitations

Although this study is conducted within the framework of a structured and data-driven methodology, there are several limitations that may affect the scope and depth of the research. These limitations are mainly data availability and legal constraints, gaps and regulatory deficiencies in international regulations, and limited literature on KRF structures and ATC Tower architecture.

One of the main challenges encountered during the research process was the limited access to architectural and operational data on ATC towers. Data such as detailed plans, control room layouts, and façade systems are generally not publicly available due to national security reasons and institutional secrecy policies. This necessitated some design assumptions to be based solely on visual materials, estimated measurements and indirect sources. The data shared in the study was used with permission from the State Airports Authority of Türkiye (DHMI).

Another limitation is the lack of binding international standards to directly guide the architectural design of ATC towers. While organizations such as ICAO, FAA, and EASA provide technical guidelines for operational functioning, recommendations on the

architectural requirements of towers are lacking. Standardization of criteria such as height, amount of daylight, façade designs, and visibility is required for towers. The data not included in the standards on the model will be determined by the researcher by analyzing the existing towers.

As a result of the examinations, there are many improvements to be made on ATC towers, and daylight comfort is considered the main element within the scope of the study. Therefore, simulations are carried out on hot climate regions where this problem is most common. Factors such as different climate scenarios, energy efficiency, heating and cooling loads, noise, façade static strength, and wind loads were not addressed. These requirements can be examined and standardized in future studies.

Studies on KRF structures are mostly limited to structural and geometric analyses; increasing the architectural applications of these systems will help to reveal more optimal designs. Similarly, the architectural literature on ATC towers is generally focused on operational arrangements and limited in terms of environmental performance and design strategies. This makes this study's contribution to both the architectural potential of KRF systems and the environmental issues in ATC towers unique.

6. CASE STUDY

This section describes the application of the phases mentioned in the methodology section to work on the developed design scenario. This process includes an ATC Tower developed around the standards, an adaptive façade related to the existing problems, and a simulation and optimization process to test the solution potential. All materials used and design decisions are within the framework of regulations and performance, and it is aimed to evaluate the adaptive system through a realistic scenario.

6.1. Study Area and Weather Data

In this study, the case building is developed based on the climatic conditions of Antalya province, which is located in southern Türkiye and is exposed to high levels of solar radiation throughout the year (see Figure 6.1). Antalya is located at the coordinates 36.9° north latitude and 30.7° east longitude with an altitude of 54 meters (DHMI, 2019). It has a typical Mediterranean climate characterized by hot summers and bright sky conditions. As noted in the literature, in such hot and bright climate zones, sun-induced visual and thermal problems are more frequent and more intense in control rooms with a high proportion of glass surfaces than in temperate climate zones (Wienold and Christoffersen, 2006). For this reason, Antalya was deliberately chosen to test the performance of the adaptive system proposed in the study and to provide a realistic problem ground. In such geographies that require high solar control systems, the improvement rate is very important, even if the evaluation parameters in the simulation results are not within the expected standards.

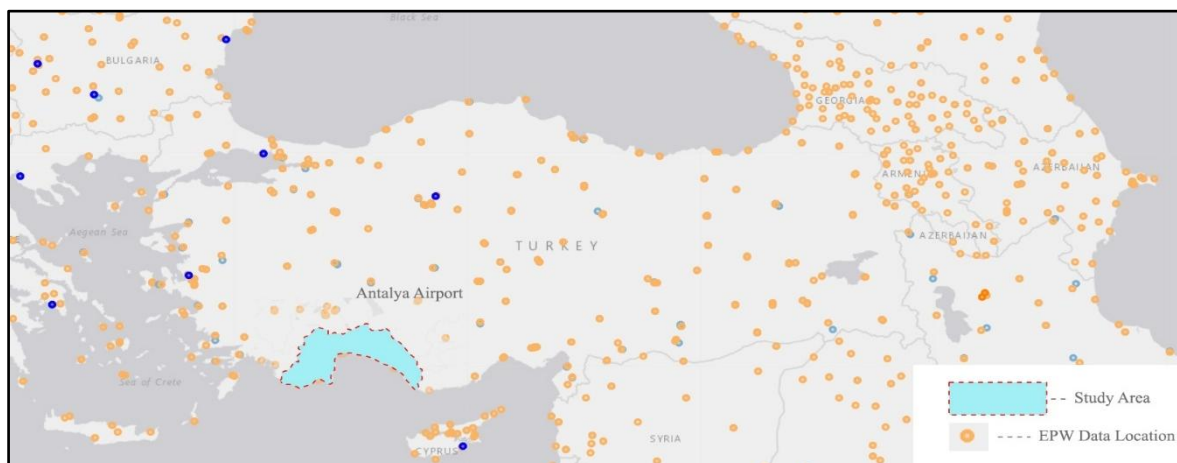


Figure 6.1. Location of Antalya Airport EPW data and other datas (LadybugTools, 2024).

The meteorological dataset used in the simulations is defined from the EnergyPlus Weather (EPW) file of Antalya Airport (see Figure 6.2). The average annual outdoor temperature is 19°C, and the total annual global horizontal solar radiation is approximately 1854 kWh/m². The location of the EPW file is classified as ASHRAE climate zone warm. The average annual wind speed is 3 m/s, and the hottest month is July. For cooling design conditions, the design temperature is 38°C. The coldest month is January, and for heating design conditions, the design temperature is 3.3°C. In line with these data, long-term direct solar radiation and high temperatures, especially in summer, cause problems such as intense glare, visual discomfort, and thermal instability in the control room. Especially for control rooms with 360° glass façades, solar control system designs are very important for hot climate zones.

Climate Zone	
Koppen climate zone:	Temperate, Dry Hot Summer (Csa)
ASHRAE climate zone:	Warm (3)
Average annual temperature:	19 °C
Annual total solar radiation:	1.854 kWh/m ²
Average annual wind speed:	3 m/s
Hottest month:	July
Hottest week:	7/20 - 7/26
Typical summer week:	6/29 - 7/ 5
Annual CDD for 18 °C is:	1.307
Design temperature 99.6 %:	38 °C
Coldest month:	January
Coldest week:	1/13 - 1/19
Typical winter week:	12/22 - 1/ 5
Annual HDD for 18 °C is:	962
Design temperature 0.04 %:	3,3 °C

Figure 6.2. Meteorological dataset of EPW file.

These data are then transferred to the SKY data for processing in Grasshopper environment. Antalya Airport EPW file is chosen as the EPW file (see Figure 6.3a) and Perez_FromWeatherData, a sky model used worldwide for daylighting calculations, was chosen for the sky type (see Figure 6.3b). This model type is used to create the sky between specified dates from the data in the file (ClimateStudio, 2024).

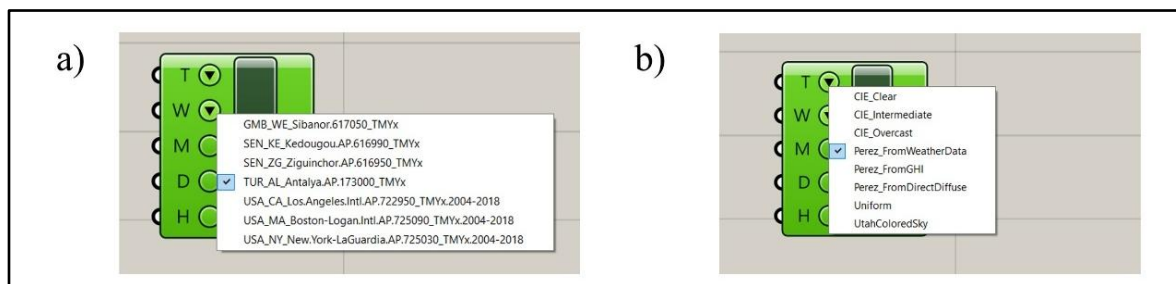


Figure 6.3. Creating SKY data on Grasshopper: a) Defining EPW file, b) Defining sky data (source: Author).

6.2. ATC Tower

After the selection of the terrain and the definition of the required data in digital environment, a standard ATC tower modeling is needed. Rhinoceros 3D computer program will be used for this model as mentioned in the methodology. In Section 4.3. Architectural Standards and Limitations, the regulations regarding towers are mentioned. The data required for the digital tower model will be obtained from these standards, and for the missing data, the researcher will examine the sample towers and make assumptions in line with the performance criteria.

The data required to make a digital model of a sample ATC tower are: The geometry of the tower, the height of the tower, the area of the control room, the geometry of the control room, the slope of the control room façade, the height of the control room façade, the width of the control room balcony and the location of any other support units. These support units may be the approach control unit, rest rooms, meteorological unit or any other relevant technical unit.

Among all these variables, the parameters that will affect the daylight control simulations are the geometry of the tower, the height of the tower, any parameter related to the control room, and the width of the balcony, as it may cause reflections. The choice of other parameters will not affect the simulation results, and area designed by the researcher based on the sample towers and the FAA-ICAO sample tower (see Figure 6.4a).

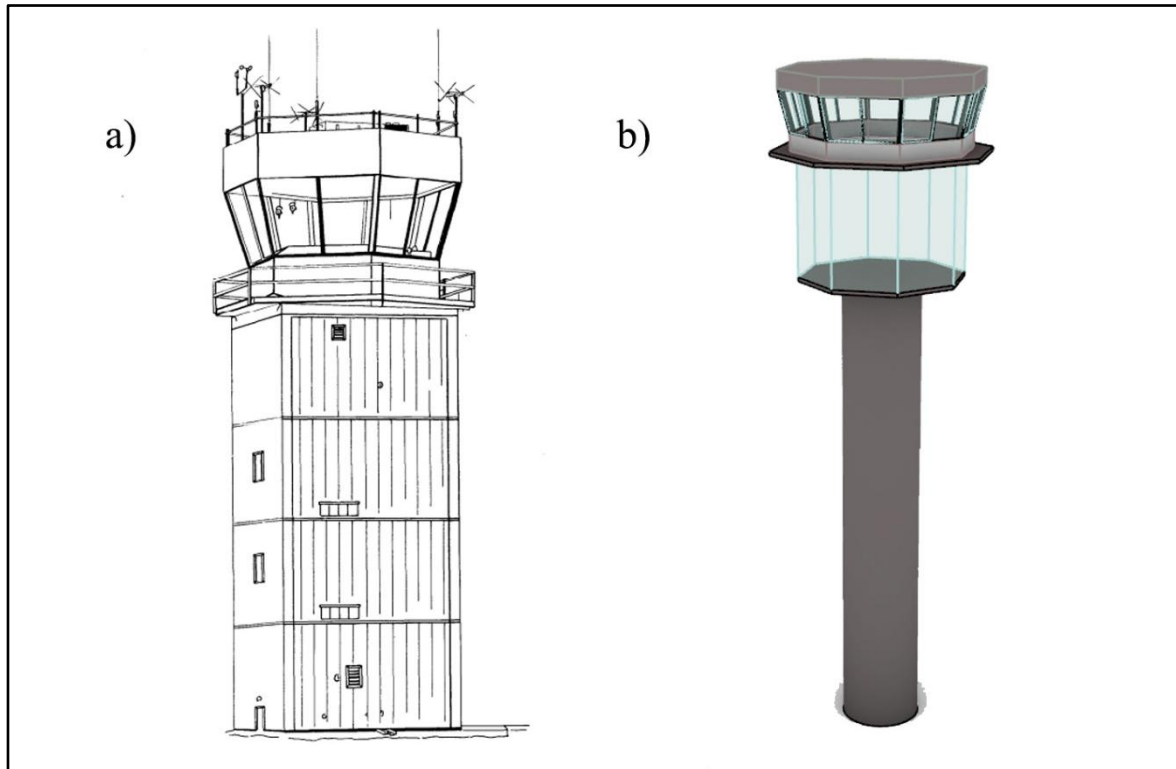


Figure 6.4. a) Perspective of FAA-ICAO sample tower (ICAO, 1984), b) Case building tower designed by author.

The ICAO-FAA standard tower consists of a low activity control cabin design on a rectangular circulation module with a small balcony. In major activity squares, as the area increases, façades and towers become larger and more ATCOs work in this unit, more reflection and visibility loss problems arise. The case building created by the researcher was developed based on a major activity tower design. Whether the circulation module is circular or polygonal has no relevance to the research results and is nowadays usually constructed in curvilinear forms to reduce wind load (see Section 4.2. ATC Towers Nowadays).

Level of activity	Approximate number of personnel simultaneously present in cab	Cab area (square metres)
Low	Not more than 6	21
Intermediate	Between 6 and 12	32
Major	More than 12	50

Figure 6.5. ICAO control cabin area suggestions (ICAO, 1984, pp. I-I-I-2-2-2).

As seen in Figure 6.5, the recommended area for major activity control cabinets is approximately 50 square meters. Figure 6.6 also shows that the recommended geometry for major activity control cabinets is octagonal. Following these recommendations, the case building has a control room with an area of approximately 50 square meters and an interior clear width of 8 meters. Again, the small balcony design is maintained, and the balcony width is accepted as 1 meter. There is no recommendation or rule regarding the width of the balconies, and the balconies are used for cleaning and ventilation of the tower and maintenance of mechanical and electrical equipment.

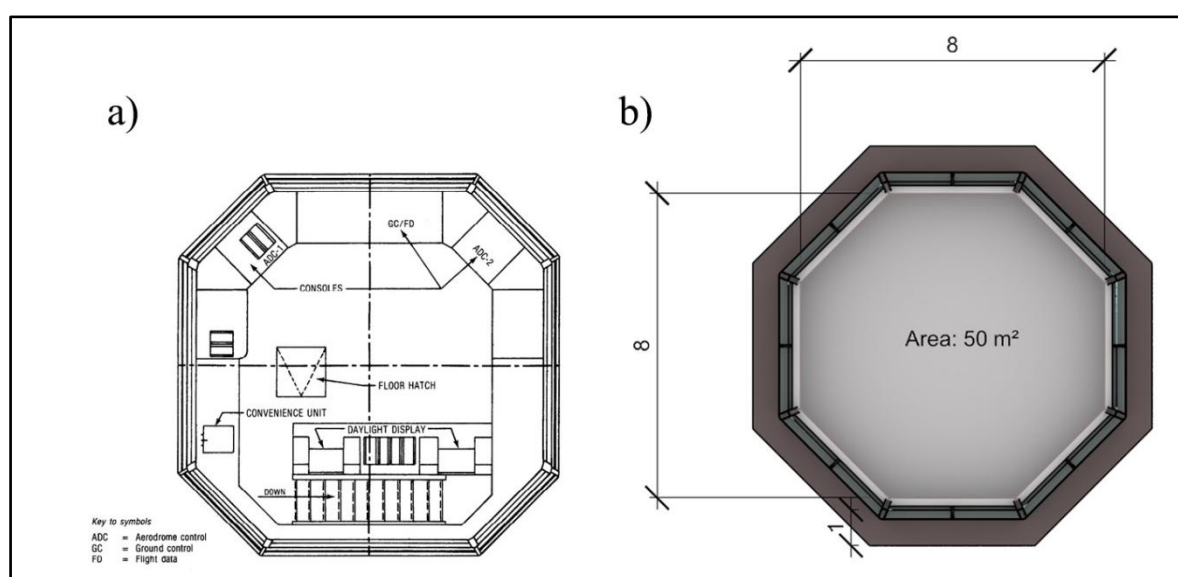


Figure 6.6. a) Major activity cab layout (ICAO, 1984), b) Case building interior layout (source: Author).

In the design of the Case building control cabin, no equipment or stairwells are included in the design. The equipment is located on the runway side or airside, where the operation is actively carried out, while the rest area and stairs are located on the other side. However, each airport has different dynamics, and the position, orientation, and height of the tower are designed accordingly. In this sense, the operation side may correspond to the south side for some squares and the north side for others. The research will analyze the major activity cabin in a hollow form and develop an adaptive façade measure based on the most sunlit façades.

Structural system design is important inside the control cabins. Structural system elements should be designed in a way to minimize visibility (FAA, 2004). Within the scope of the case building, glass joints were considered on the basis of existing tower examples, and the carrier system was prevented from changing the simulation results.

As mentioned in Section 4.3.1. Design Regulations, the net height of the control cabin is 3 meters. For the use of the façade console units, it is designed to continue straight up to a certain level and then slope 15°. Although the level determined as flat varies, it is accepted as 85 cm in terms of FAA recommendation and human ergonomics (see Figure 6.7a).

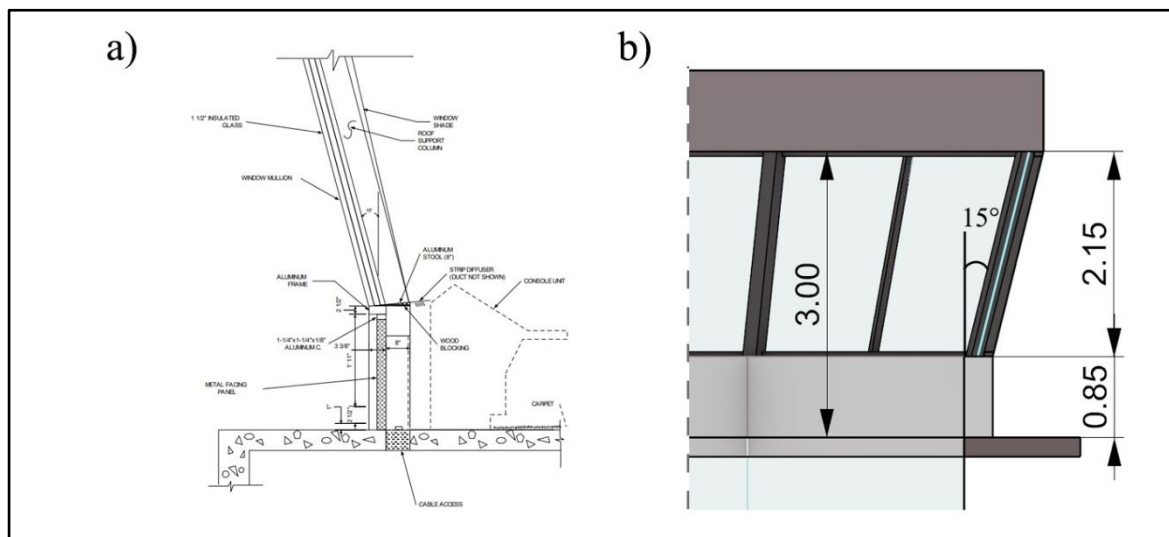


Figure 6.7. a) FAA control cabin façade section, (FAA, 2004) b) Case building façade section (source: Author).

Since it would be very costly to make the façades of ATC towers with circular glazing, almost all towers in the world have façades with more than one piece of glass. Too much glass in the façade will increase the number of joinery and reduce the visibility, while too little will increase the cost and statically strain the façade. In this context, it was decided that each façade should consist of 2 pieces of glass (see Figure 6.8).

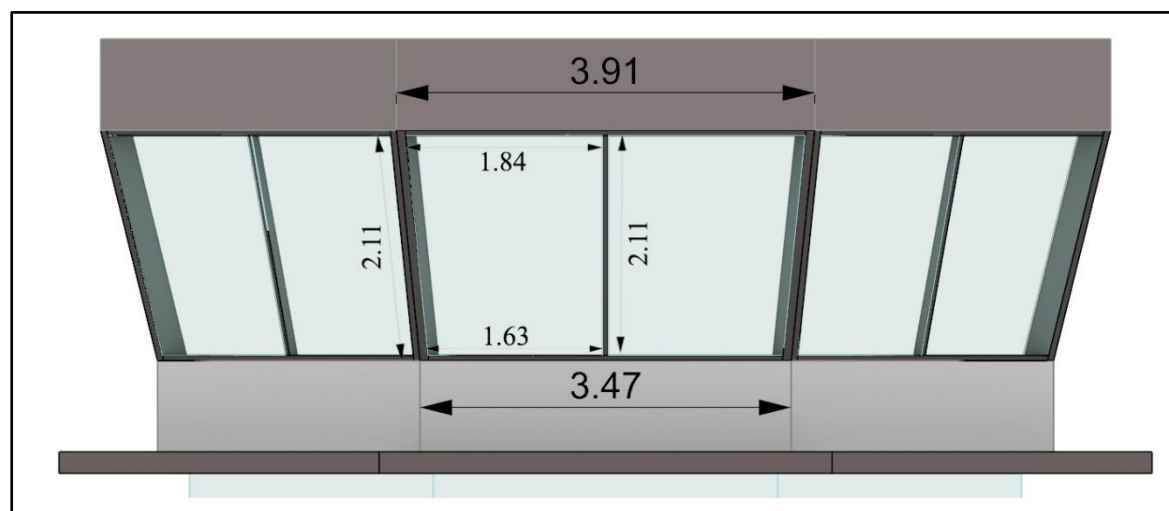


Figure 6.8. Façade dimensions (source: Author).

The 8 façades consist of 16 pieces of glass in total. Since the façades are curvilinear, the upper edge of a façade is 3.91 meters, the lower edge is 3.47 meters, and the length is 2.11 meters. The dimensions of a glass module are upper edge 1.84 meters, lower edge 1.63 meters, and length 2.11 meters. The width of the mullion is 5 cm, and the depth is 10 cm, considering the existing control towers.

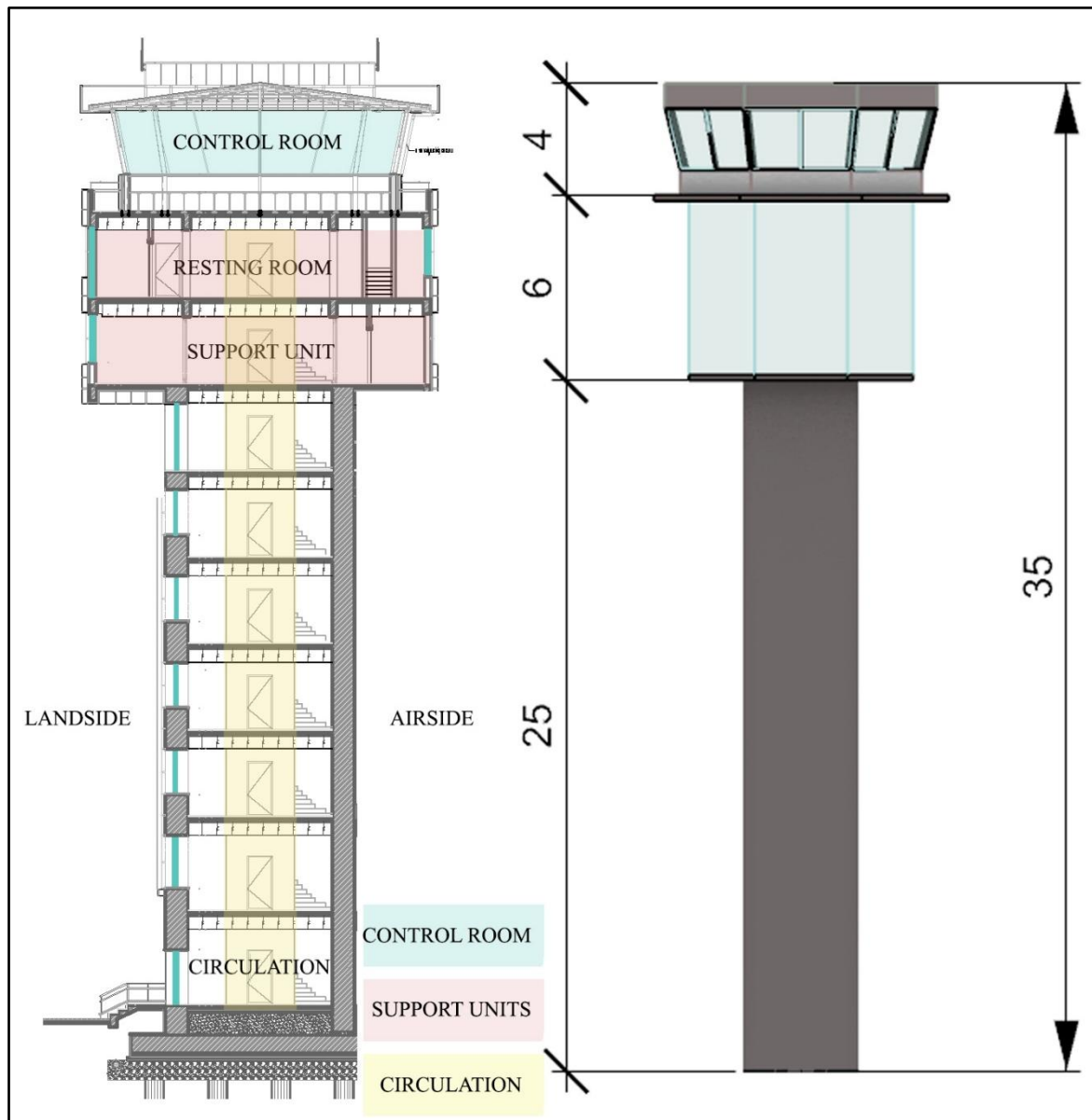


Figure 6.9. Details of the case ATC tower (source: Author).

The height of the tower is another parameter that varies considerably. It is stated that the tower should be high enough to see the operation area, and the eye level of the control room should be 18 meters above the highest point of the runway (FAA, 2004).

The effect of the tower height on the effectiveness of the adaptive façade is minimal because the evaluation compares before and after the adaptive façade. In this sense, the improvement in daylight comfort performance made by the adaptive façade is essential. Towers should not be too low or too high to see the operation area. According to Turkish fire regulations, tall buildings are those exceeding 30.50 meters (Republic of Türkiye, 2007). In this sense, the height of the tower has been accepted as 35 meters to be valid in many places, taking into account the design of existing airports. The 35-meter height includes 25 meters for the circulation module, 6 meters for the support units, 3 meters for the control cabin, and 1 meter for the technical equipment on the control cabin (see Figure 6.9).

6.3. KRF Adaptive Façade

Before proceeding with the façade design, it is important to decide whether the adaptive façade should be applied to the entire control cabin or to a specific part of it. In existing ATC towers, it is known that solar control methods are applied to a certain part of the ATC tower in order to make a cost-effective design, but when they are insufficient, they are applied to all façades. In addition, the use of an active solar control system on all façades would permanently affect visibility in the event of a system failure and pose operational risks. In addition, as mentioned in Section 4.4. Problems of ATC Tower, it is known that each façade module can work independently in existing solar control systems. In this sense, in order to conduct a realistic and original research, an adaptive façade design will be made on half of the control cabin, each of which can have an independent design.

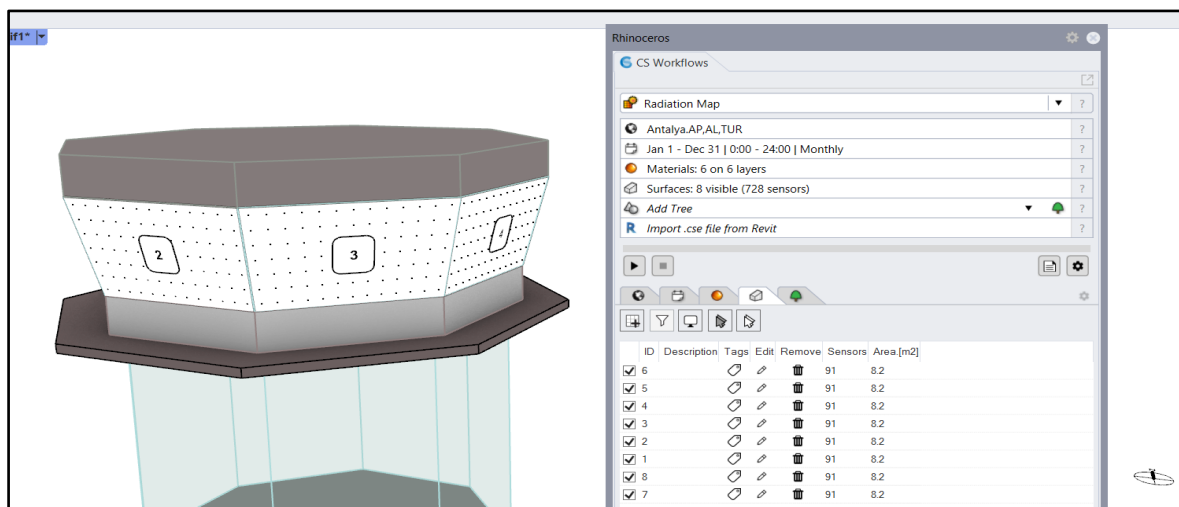


Figure 6.10. Façade radiation map analysis process on Rhinoceros 3D viewport (source: Author).

As seen in Figure 6.10, the ATC tower modeled on the Rhinoceros 3D program will be analyzed for the radiation map through the ClimateStudio. All façades are defined and numbered in the ClimateStudio interface. The numbers were placed in a counterclockwise direction as Southwest 1, South façade 2, Southeast façade 3, East Façade 4. Sensors were added on the façades at 0.5 m intervals, and the simulation was finalized.

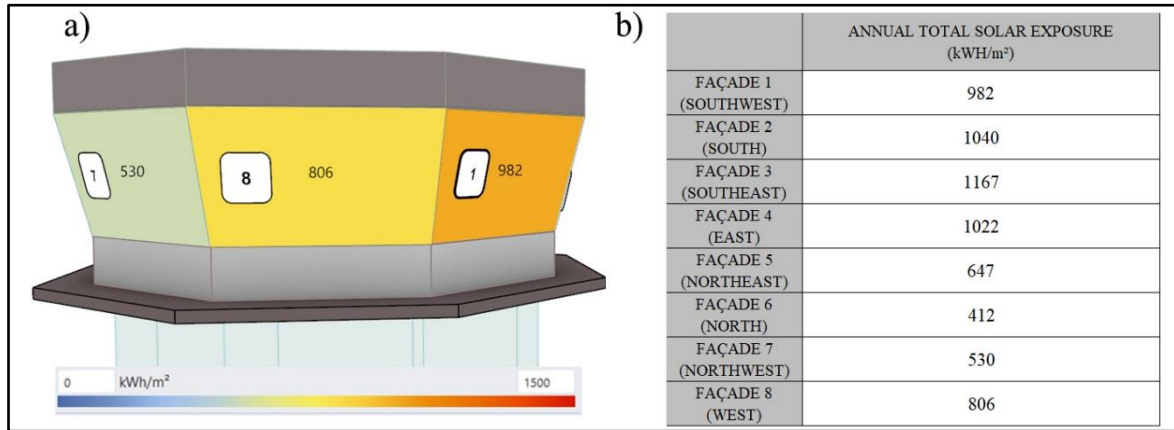


Figure 6.11. a) Radiation map analysis results on Rhinoceros 3D viewport, b) Annual total solar exposure values (source: Author).

According to the analysis results, the façades exposed to the most solar radiation are Façade 3 1167 kWh/m², Façade 2 1040 kWh/m², Façade 4 1022 kWh/m² and Façade 1 982 kWh/m² respectively (see Figure 6.11b). The selection of the study area in the northern hemisphere is effective in these results. South and east façades are the most sun-receiving façades. It is proven that adaptive façade design should be applied on façades 1,2,3 and 4.

As mentioned in Section 3.3.2., with KRF structures it is possible to build a system with different geometric modules. Şenel et al. (2024) in their adaptive façade study with KRF structures states that hexagonal geometries have the highest mobility, have a higher solar control and are more cost effective. In this sense, hexagonal fans will be used for the design of the façades.

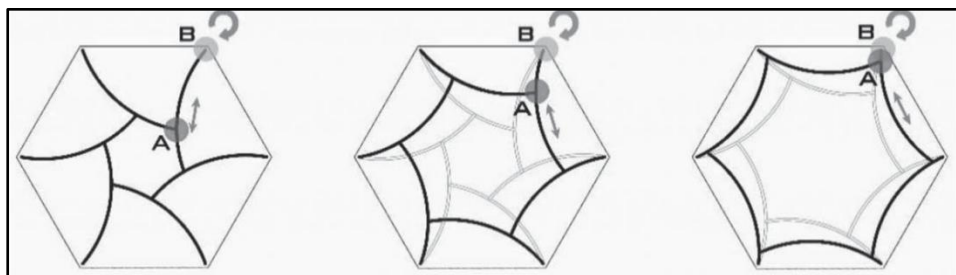


Figure 6.12. Movement path of hexagon fan (Nazarzadeh and Asefi, 2022).

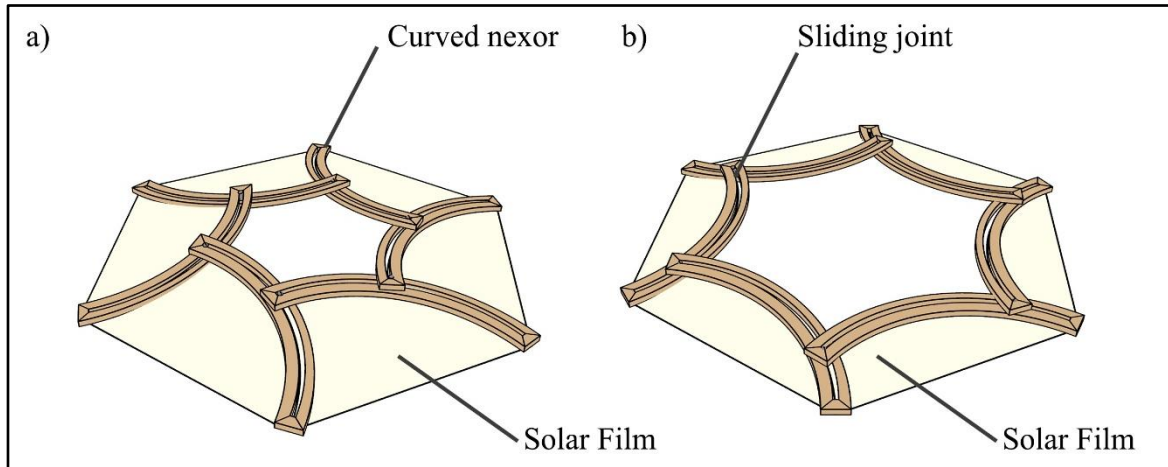


Figure 6.13. a) Open hexagon fan, b) Closed hexagon fan (source: Author).

Figure 6.13 shows a hexagonal fan consisting of 6 nexors and 6 solar films. Solar films are the material used as solar control elements in existing ATC towers. These materials are produced in a flexible form so that they can be stretched between nexor movements. A gap is left in the center of the nexors to accommodate the slide joint. This gap is necessary for mechanical movement but is not included in the simulation as it would not affect the evaluation process.

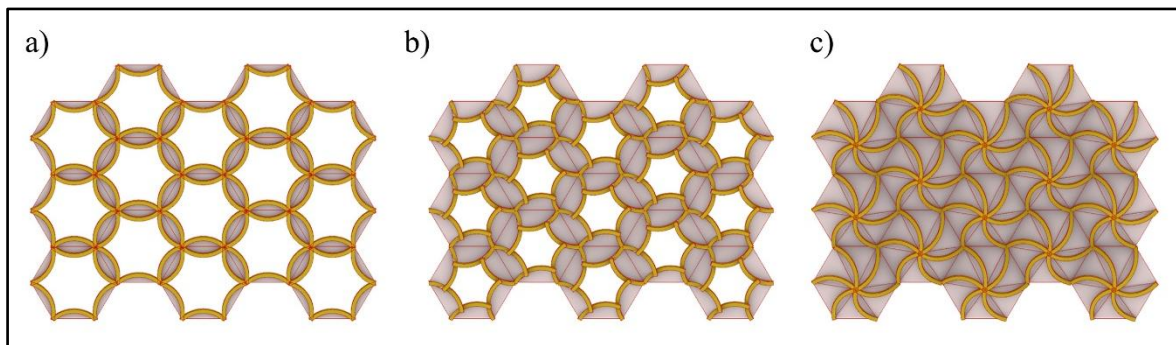


Figure 6.14. Multi-KRF system façade a) Fully closed, b) Half-open, c) Fully Open (source: Author).

The system to be used is the hexagonal fan-based multi-KRF system mentioned in detail in Section 3.3.2. In these systems, one fan moves another fan. Only one nexor can initiate all this movement in the system. The actuators that initiate the movement are not discussed in this study since they will not have any effect on the evaluation of the daylight performance of the system. Figure 6.14 shows the movements that will occur with this system. When the system is fully open, the solar film covers the entire façade between the nexors. However, this film does not obstruct the view as in the existing towers.

6.3.1. Design parameters

Multi-KRF adaptive façade system design consists of many parameters. In the Grasshopper script created by the researcher, these parameters are the rotation angle of the nexors, fan radius, the number of modules, the width of the nexors, the thickness of the nexors, and the height that the system will gain in the z-axis during movement (see Figure 6.15). In the rest of the design, the joint gap in the middle of the nexors or the nexor curvature is not expected to change in the first place, although many parameters are also part of the design. Moreover, due to the nature of KRF structures, these parameters are interdependent, and changing one of them automatically changes the others.

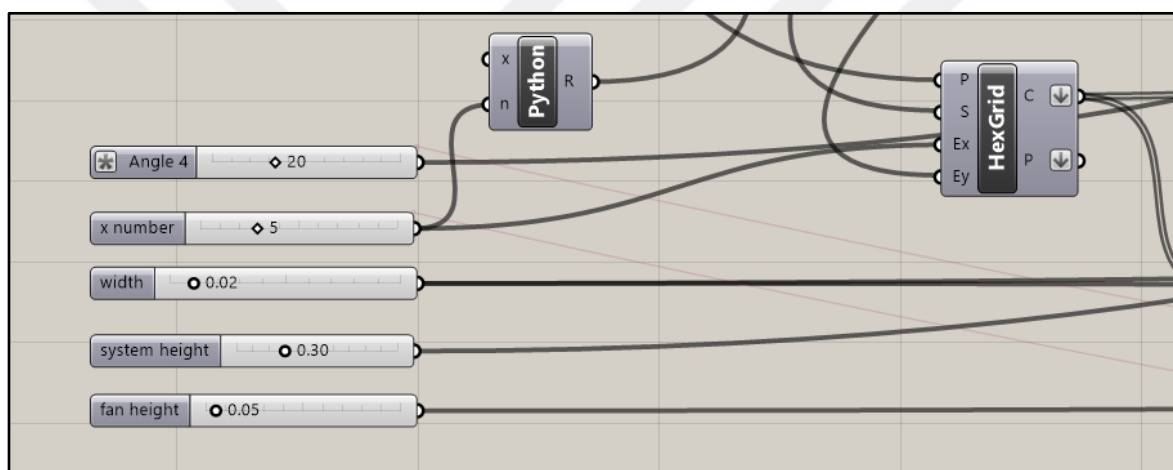


Figure 6.15. Design parameters on Grasshopper canvas (source: Author).

The rotation angle of the nexors, which is one of the most fundamental parameters, is 0° in the fully closed state and 60° in the fully open state due to the geometric structure of the hexagonal modules. Examining each degree increases the number of possibilities to be calculated and will unpredictably extend the optimization time. In this sense, it was decided to analyze the motion in 12 different stages. The rotation angles are coded to increase in multiples of 5, such as 0° , 5° , and 10° .

The height that the system will gain in the z-axis during the movement is designed to be 30 cm in the fully open state at this 12-step degree of movement. When examining fans of different geometries, this is the average height that the system gained. Taking the same study as a reference, the fan width was determined as 5 cm and the thickness as 4 cm (see Figure 6.16). These parameters were accepted as constant parameters.

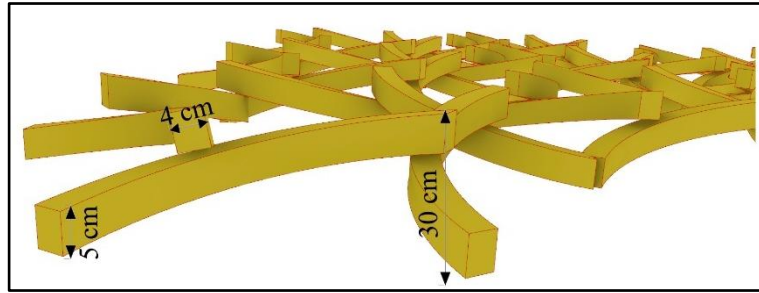


Figure 6.16. System dimensions (source: Author).

In the system, the number of modules on the x and y axis and the fan radius parameters are interdependent parameters. In this sense, the variable parameter is simply determined as the number of modules on the x-axis. A simple script was written in Python, one of the software languages, to find the fan radius value based on the façade dimensions (see Figure 6.17). This code is basically the length of the façade in the x-axis divided by the length of the hexagonal modules in the x-axis to obtain the radius value. The number of modules on the X axis is set to a maximum of 15. When the façade is divided into more than 15 modules, they become inapplicable modules smaller than 20 cm in diameter.

A screenshot of the Grasshopper Python Script Editor window. The window has a menu bar with 'File', 'Edit', 'Tools', 'Mode', and 'Help'. There are 'Test' and 'OK' buttons on the right. The script is as follows:

```

1  if n is None:
2      R = None
3  else:
4      try:
5          n_int = int(n)
6          R = 7.40 / (3 * n_int + 1)
7      except Exception as e:
8          R = None
9          print("Hata:", e)

```

Figure 6.17. Python script to calculate the radius of hexagonal modules (source: Author).

After finding the radius value, it is necessary to find the required number of modules on the y-axis. This code is basically based on finding the number of modules by dividing the length of the façade in the y-axis by the length of the hexagonal modules in the y-axis. The length on the y-axis is assumed to be approximately 2.20 meters and the required number of modules is calculated by rounding the resulting value to the nearest whole number.

6.4. Materials

In order to perform UDI, ASE, and view analysis in Grasshopper environment, the materials inside and outside the control cabinet must be defined. Since the Radiance engine is used, the materials will also be created as Radiance Materials. In this sense, ClimateStudio has a material pool within itself. For an ATC tower control cabin, the materials that comply with the standards and regulations will first be selected from this pool, and if there is no suitable material in the pool, a new material will be created and transferred to the simulation.

The materials to be defined for the interior of the control cabinet will be for the floor, ceiling, wall, glass, and mullion. Outside the control cabin, it is necessary to define materials for nexor and solar film, which are the elements of the adaptive façade. The created materials were assigned to the appropriate models, and the scene data required for simulations was created (see Figure 6.20).

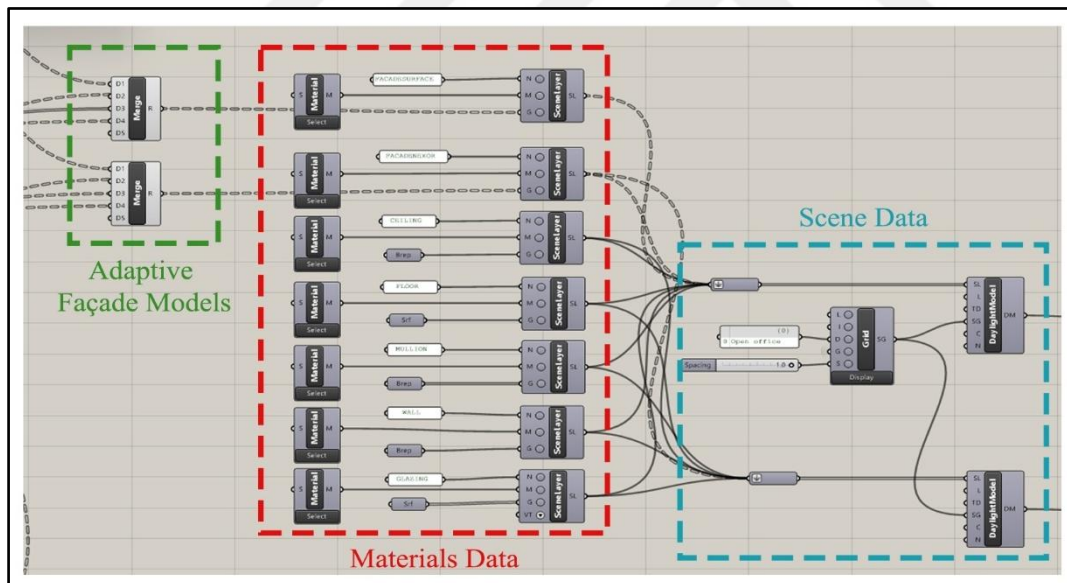


Figure 6.20. Creating scene data on the Grasshopper canvas (source: Author).

Detailed explanations are given in Section 4.3.1. regarding the qualifications of the materials assigned. In general, dark colored, low-reflective, noise-blocking, and sustainable materials were preferred. Firstly, 'Dark Carpet' material was assigned as the floor material. The reflectance value of this material is 5% (see Figure 6.21). This material is compatible with modular structure control cabinets and is suitable for operations with noise-blocking.

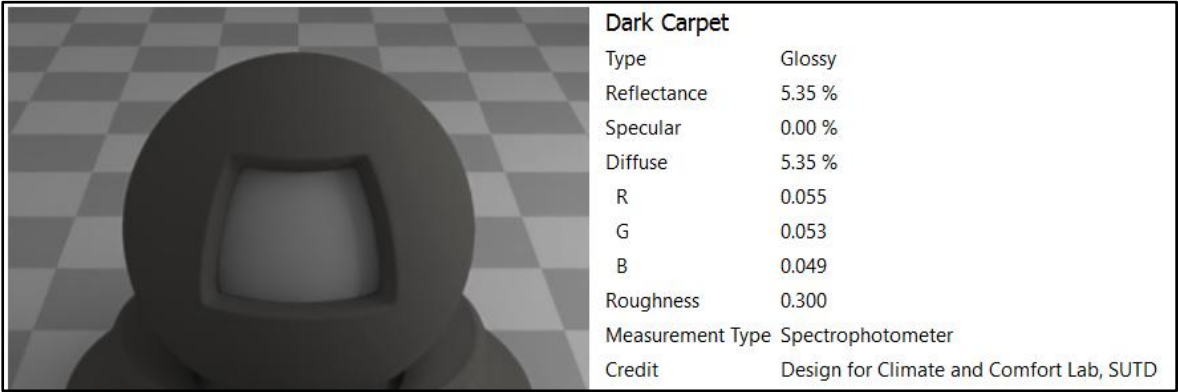


Figure 6.21. Dark Carpet material detail.

Since the floor and ceiling are the surfaces where reflections occur the most, material choices are very critical. The ceiling material was also selected as 'Black Ceiling' material from dark-toned materials in order to reduce reflections as much as possible. The reflectance value of this material is 5.07% (see Figure 6.22). It is known that many airports have subsequently painted their ceilings black due to reflection problems (see Section 4.4.1. Visibility limitation).

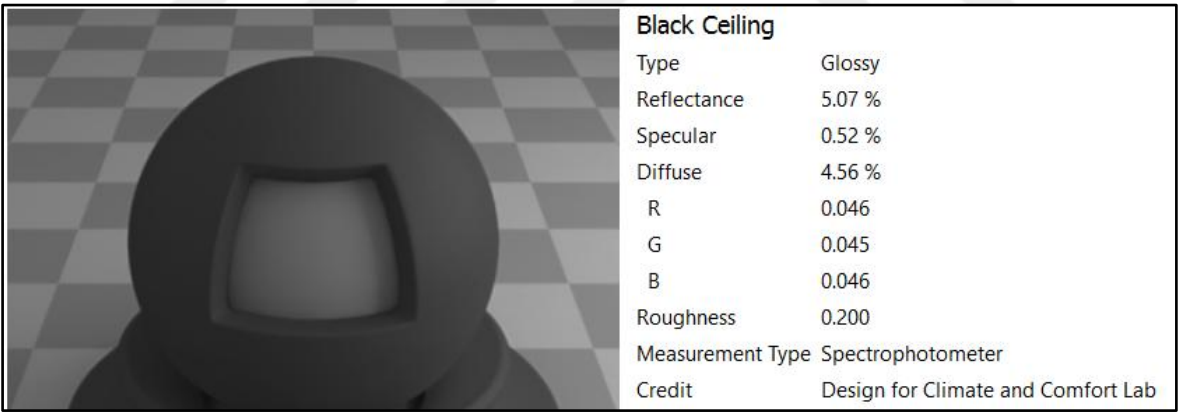


Figure 6.22. Black Ceiling material detail.

The other most important material is the choice of glass to be used for façades. Low-e glass is important for daylight performance, while insulating glass is important for energy performance. The VLT (Visible Light Transmittance) value of the preferred glass material is 61%. If this value is 0, it means that the light does not pass through, and 100 means that the light passes through completely. In this sense, the controlled transmittance of light is very important for operations.

As seen in Figure 6.23 VLR (Visible Light Reflectance) value is 10% and which means the reflection of light from the glass surface. A high reflection value means that the glass works like a mirror, and the VLT and solar gain values decrease, while a value of 10% means clear float glass (Thermosash, n. d.). FAA (2004) recommends that the glass be clear. UVal means insulation. It is important that this value is high for energy conservation. Finally, the SHGC (Solar Heat Gain Coefficient) value is the ability of the glass to absorb heat. An example of this is the use of glass as a heat source in winter. It is important that this value is in balance for energy conservation.

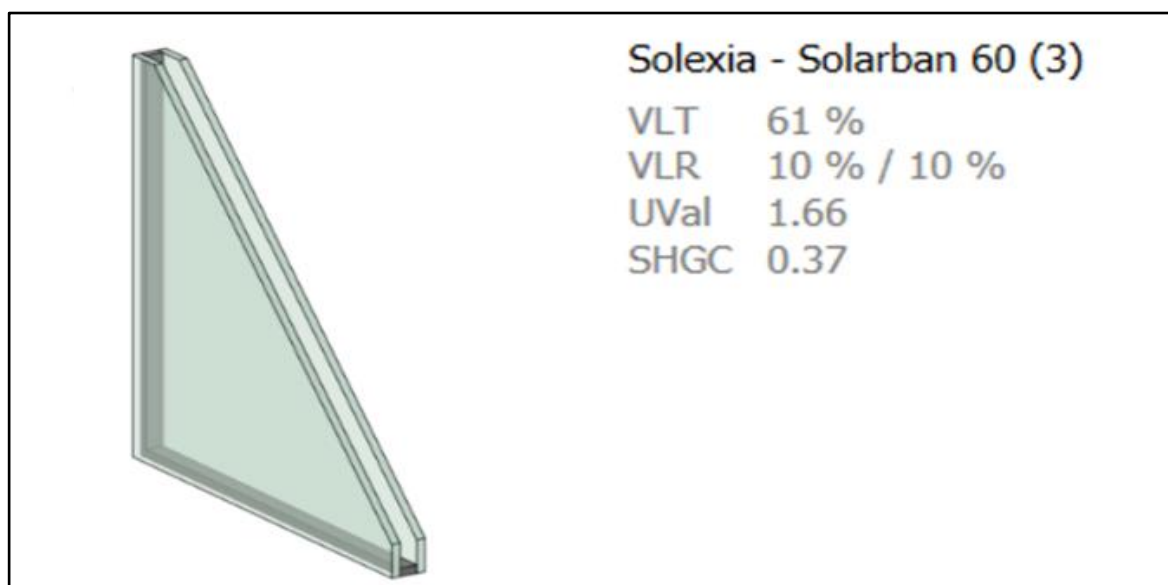


Figure 6.23. Façade glass material detail.

'Black Wall' material was preferred for the 85 cm high walls under the curved glass façades designed for the consoles. The reflectance value of this material is 4.55% (see Figure 6.24).

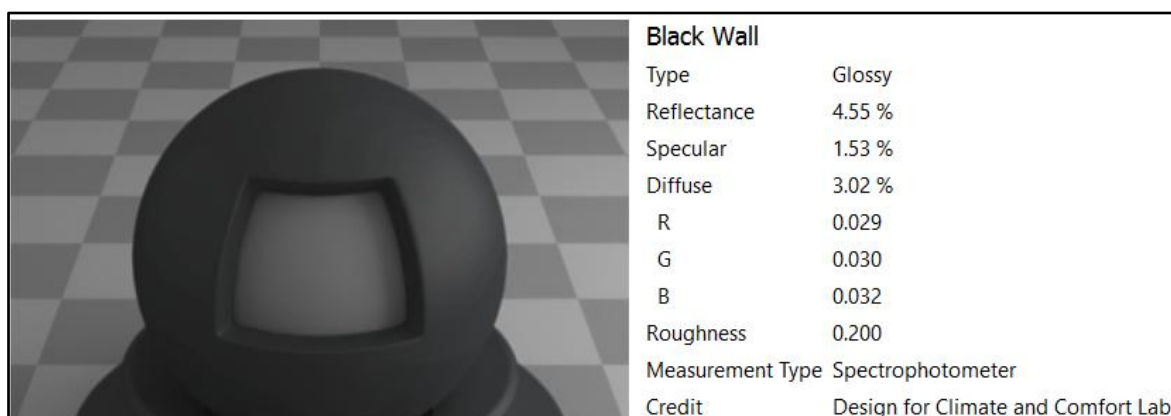


Figure 6.24. Black wall material detail.

The last material in the control cabinet is the mullion material. It affects both internal and external reflections. For the mullion, 'Grey Mullion' material with a reflectance value of 10.75% is assigned (see Figure 6.25).



Figure 6.25. Mullion material detail.

For the nexors that form the construction of the adaptive façade, a wood material was considered inspired by the FAA sustainable ATC towers projects (FAA, 2023b). In this context, 'Aged Redwood' material, which is both sustainable, economical and has a low reflectance value (8.69%), was assigned for the nexors (see Figure 6.26).

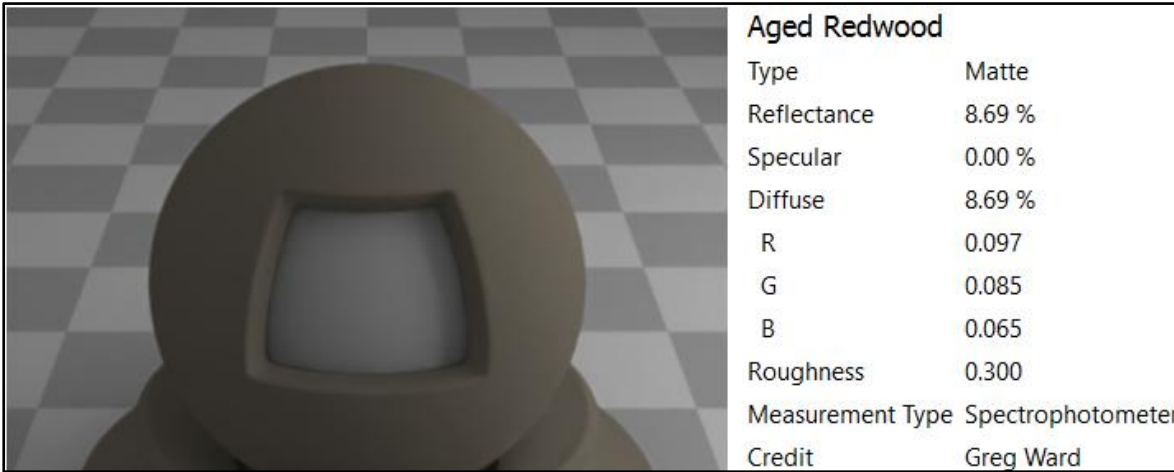


Figure 6.26. Nexor material detail.

Finally, it is necessary to assign the solar film material, which is a flexible material among nexors. In this sense, there is no material belonging to or close to this material in the ClimateStudio material pool. In order to obtain the technical specifications of this material, manufacturers of motorized solar screens for existing ATC towers were contacted and technical information was obtained from them.

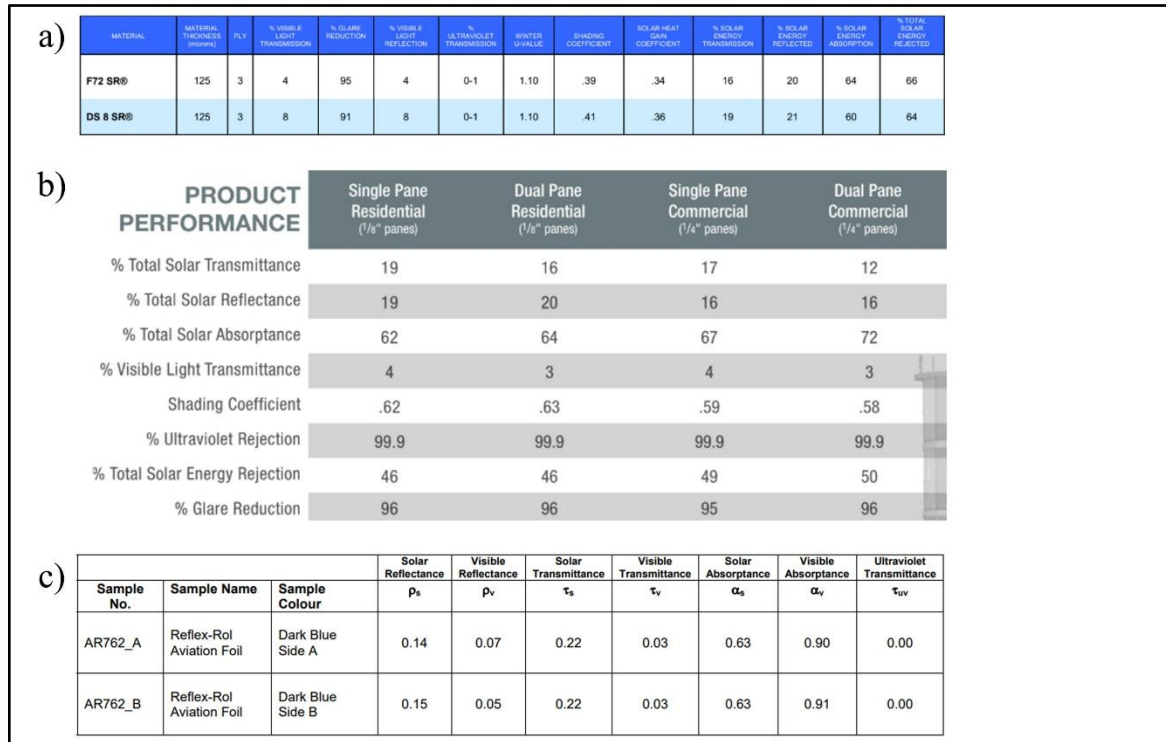


Figure 6.27. Technical details of received solar film material a) Sent by Plastic-View Company (Plastic-View, 2025), b) Sent by Solar-Screen Company (Solar-Screen AB, 2025), c) Sent by Reflex-Rol UK. Company (Hutchins, 2009).

As seen in Figure 6.27, both materials have close values in terms of technical values. However, when they are focused on a specific purpose, there are decreases or increases in some values. For example, when higher shading is desired, for example to reduce the indoor temperature, the solar reflectance value is kept lower in some materials. When all these materials were evaluated, the values of the solar film material to be created for simulation were taken as visible light transmittance 0.03, solar transmittance 0.22, visible light reflectance 0.07, solar reflectance 0.14 and specular reflection 0.00. Then, these values were transformed into radiance material, coded and transferred to the simulation (see Figure 6.28).

```
void trans solar_film
0
0
7 0.03 0.03 0.03 0.22 0.07 0.14 0.0
```

Figure 6.28. Custom Solar Film radiance material data (source: Author).

6.5. Simulation

Daylight models with materials and scene files were prepared and connected to the necessary simulations. For ASE and UDI data, simulations were performed to obtain two different outputs from a single analysis (see Figure 6.29.). This is expected to speed up the simulation and optimization processes. For the simulation, the sensors were placed 1 meter apart and 0.762 meters above the ground. A total of 52 sensors were used for the analysis.

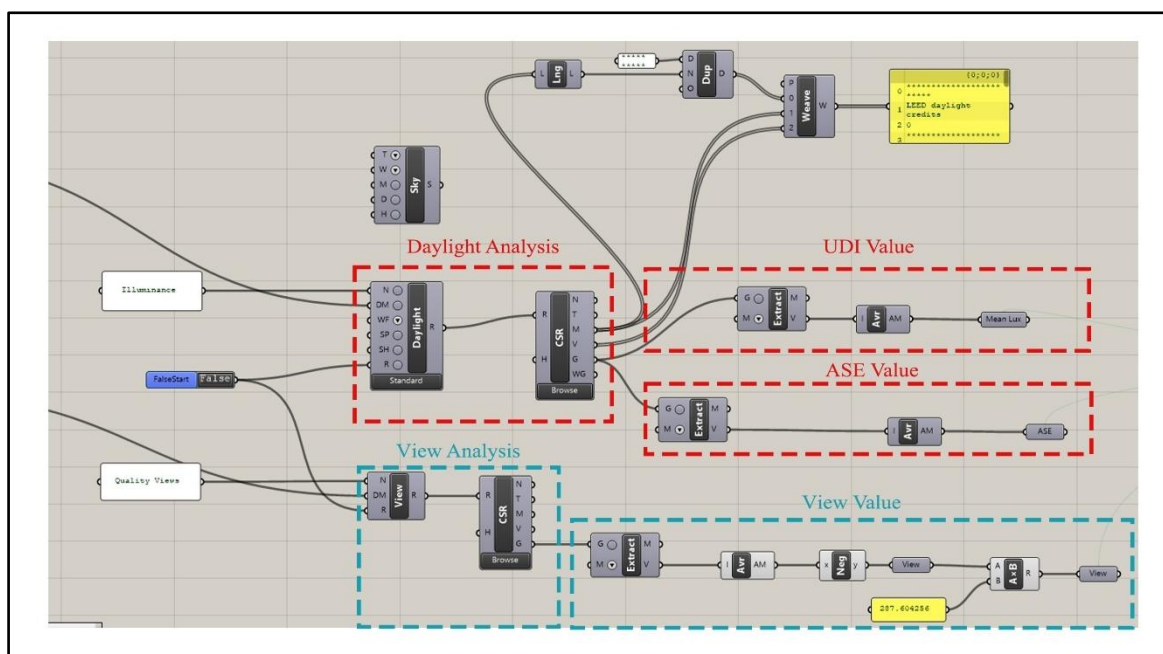


Figure 6.29. ClimateStudio analysis setting on Grasshopper canvas (source: Author).

6.6. Multi-Objective Optimization

There are two commands to connect to the optimization plugin Octopus. These are the goal and the genome. Goal is expected to connect and optimize values such as ASE, UDI, and view in this research, while genome values are expected to change the design and produce different ASE, UDI, and view values. Therefore, a bridge is required to enable Octopus and ClimateStudio simulation commands to work together. The Ladybug False Start command was used for this. With this command, a change in any of the Octopus genomes will trigger the False Start command and restart the simulations. This way, every time the evolutionary algorithm wants to test a result, the simulation will run again and give the result.

Since ASE and mean lux values will be transferred directly to Octopus, no action is taken, while the view value is multiplied by minus one. Because Octopus always tries to minimize the incoming goal values as a working principle. Giving a negative value to the view value means that it will try to increase it. The research aims to increase the view value while decreasing the ASE and UDI values (see Figure 6.30.).

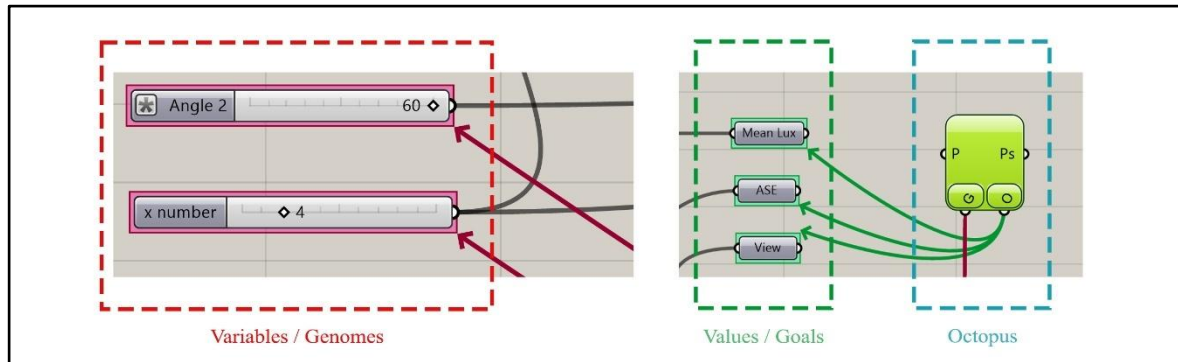


Figure 6.30. Genomes and goals of optimization (source: Author).

Adaptive façade is designed on 4 façades, and it is aimed that all 4 façades can work and be designed independently of each other like the solar control elements in the existing towers (see Figure 6.31). With a total of 3 goals and 8 genomes, the optimization is ready to run. The working settings for Octopus were set as elitism 0.5, mutation probability 0.2, mutation rate 0.9, crossover rate 0.8 and population size 100 and set to run for 60 generations. Academic studies on façade optimization are known to vary similar settings according to the simulation difficulty (Jalali et al., 2020; Kızılörenli and Maden, 2023).

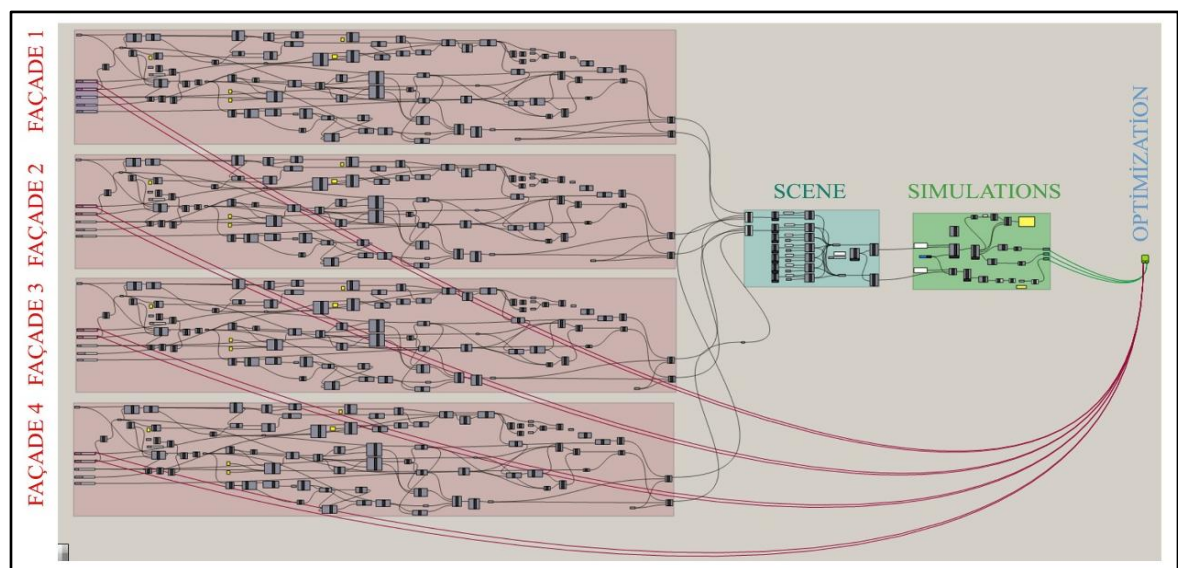


Figure 6.31. Whole Grasshopper script connected to Octopus (source: Author).

7. RESULTS

In this section, the performance analysis of the kinetic façade system developed for an air traffic control (ATC) tower within the scope of a multi-objective optimization process is presented and a before-and-after comparison is made. An evolutionary algorithm using the Octopus plugin in Grasshopper was applied to solve the design problem; UDI, ASE and View-Out values were set as objectives.

7.1. Current Performance Before Optimization

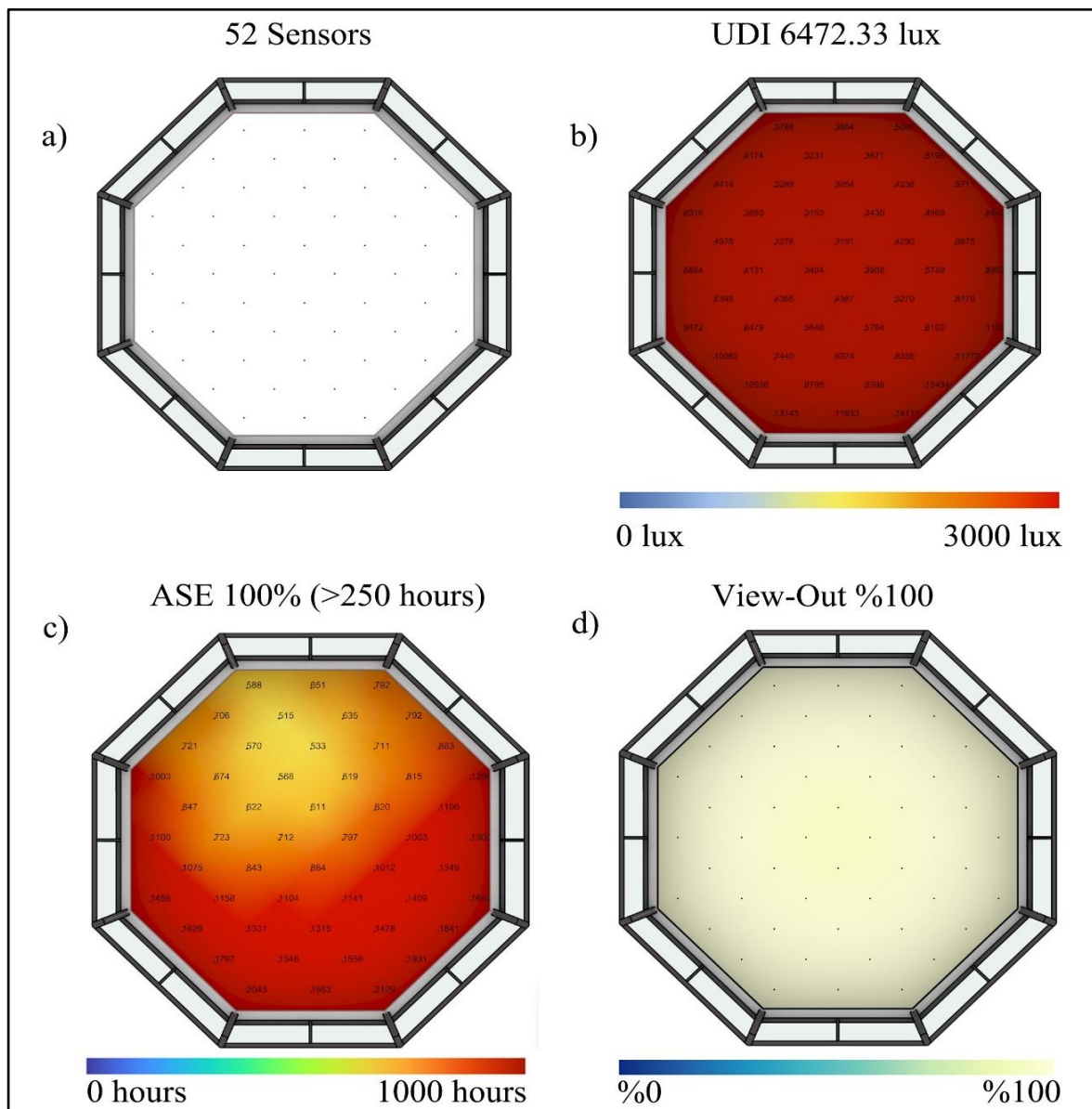


Figure 7.1. Simulation results of a sample ATC tower built with existing regulations and Standards, a) Sensor map, b) UDI value, c) ASE value, d) View-Out value (source: Author)

In order to objectively evaluate the daylight performance of the adaptive façade, it is necessary to evaluate the daylight performance of the case ATC tower, which was built in accordance with the existing standards and regulations before the adaptive façade was applied. In Figure 7.1, the daylight performance values of this building are evaluated through UDI, ASE, and View goals.

When the data of 52 sensors placed 1 meter apart inside the Case ATC tower are analyzed, it is seen that the UDI value is 6472.33 lux. The fact that all sensors are colored red in Figure 7.1b shows that the comfort limit of 3000 lux is seriously exceeded in all sensors. The values read on the sensors show that the highest value is on the southeast façade (façade 3) with 12433 lux, and the lowest value is on the northwest façade with 3788 lux. The UDI value of 6472.33 lux indicates that the comfort limit is exceeded more than 2 times. In addition, this orientation of the sensor values confirms the decisions made in Section 6.3. on which façades the adaptive façades will be applied.

ASE is recorded at 100% and is well away from the comfort limit of 10%. This means that all sensor points are exposed to over 1000 lux of direct sun for at least 250 hours a year. The intense red tones in the ASE map and the yellow areas in the center indicate that the light distribution is extremely uncontrolled. This situation both disrupts visual comfort and may cause secondary effects such as an increase in indoor temperature. When the data on the sensor is analyzed, it is seen that the sun exposure hours are similar to the UDI data, with the most hours on the southeast façade with 2129, and the least hours on the northwest façade with 588 hours. This means that the greatest reflections and visibility losses will occur on the southeast front, and conducting air traffic operations on this front involves high risks.

A view-out value of 100% does not mean that there is no reflection, glare, or obstruction of vision in this building. This value only means that in the 360° visual field in the horizontal plane and a 60° visual field in the vertical plane, there are no obstructive elements such as columns or daylight control elements such as curtains. In this sense, the ATC tower design has been designed to provide high visibility value by paying attention to FAA (2004) and ICAO (1987) regulations. ATC towers give high values in view-out analyses because they are buildings with glass on all façades however, ATCO visibility decreases due to frequent and high levels of visibility-obstructing events such as glare and reflection.

7.2. General Findings from the Optimization Process

The optimization process started on 28 March 2025 at 18:20 and was completed on 10 April 2025 at 20:00. The process took a total of 313 hours and 40 minutes, or approximately 13 days. Optimizing 4 different façades with different designs is the main reason for the long optimization time. During this time, the Octopus evolutionary algorithm calculated a total of 11845 probabilities over 60 generations and found 2975 Pareto-front results (see Figure 7.2b).

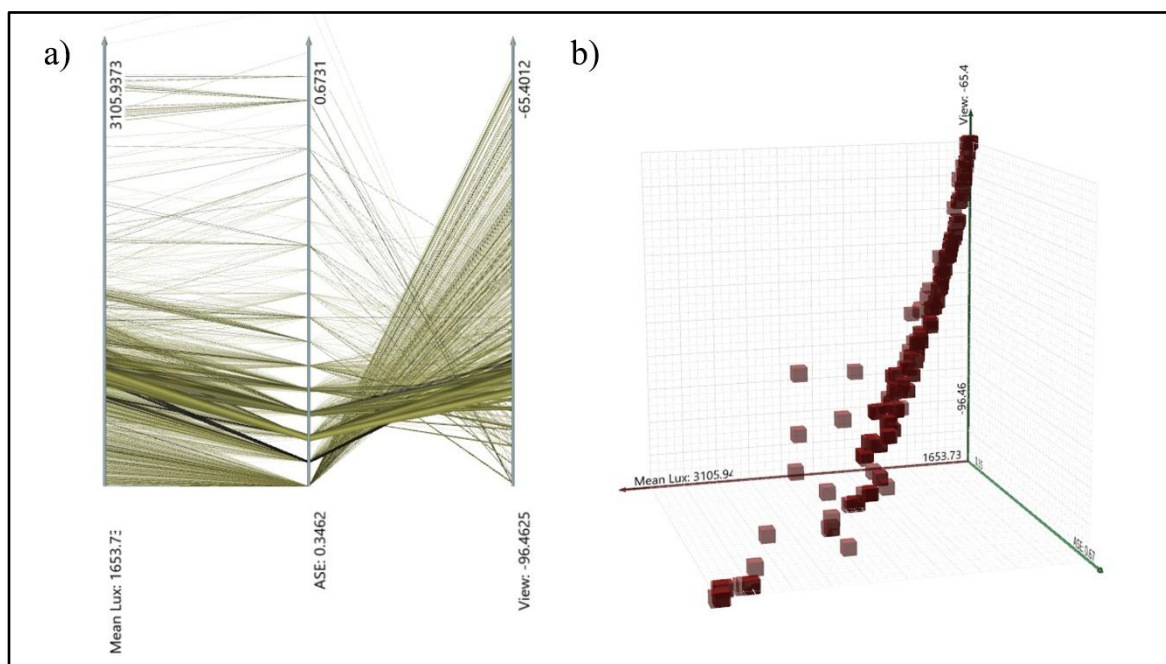


Figure 7.2. Optimization results a) Relationship of generations to value as a multi-axis view, b) Pareto-Front results at generation 60 (source: Author).

When the ASE values in the generations are analyzed, while the minimum ASE value was above 60% in the first generation, this value decreased to 34.6% towards the last generations. The average ASE value stabilized at 38% by the 40th generation, meaning that although the 10% threshold stipulated in LEED v4 could not be reached, a significant improvement was achieved.

In the initial generations, UDI values were very high; the number of individuals above 4000 lux was quite high. However, as the algorithm progresses, UDI averages decrease to the range of 2000-2300 lux, and a more comfortable indoor lighting level is reached. It is seen

that this metric reaches stability, especially between the 20th and 30th generations. This shows that the problem of excessive glare is reduced.

This metric, which is critical in terms of visual comfort, has shown a rapid increase, especially as of the 10th generation, and individuals above 90% have started to be produced. Average View-Out values did not fall below 85% after the 50th generation (see Figure 7.3c). While the minimum View-Out rate hovered around 60% in the first generation, it stabilized above 70% with optimization.

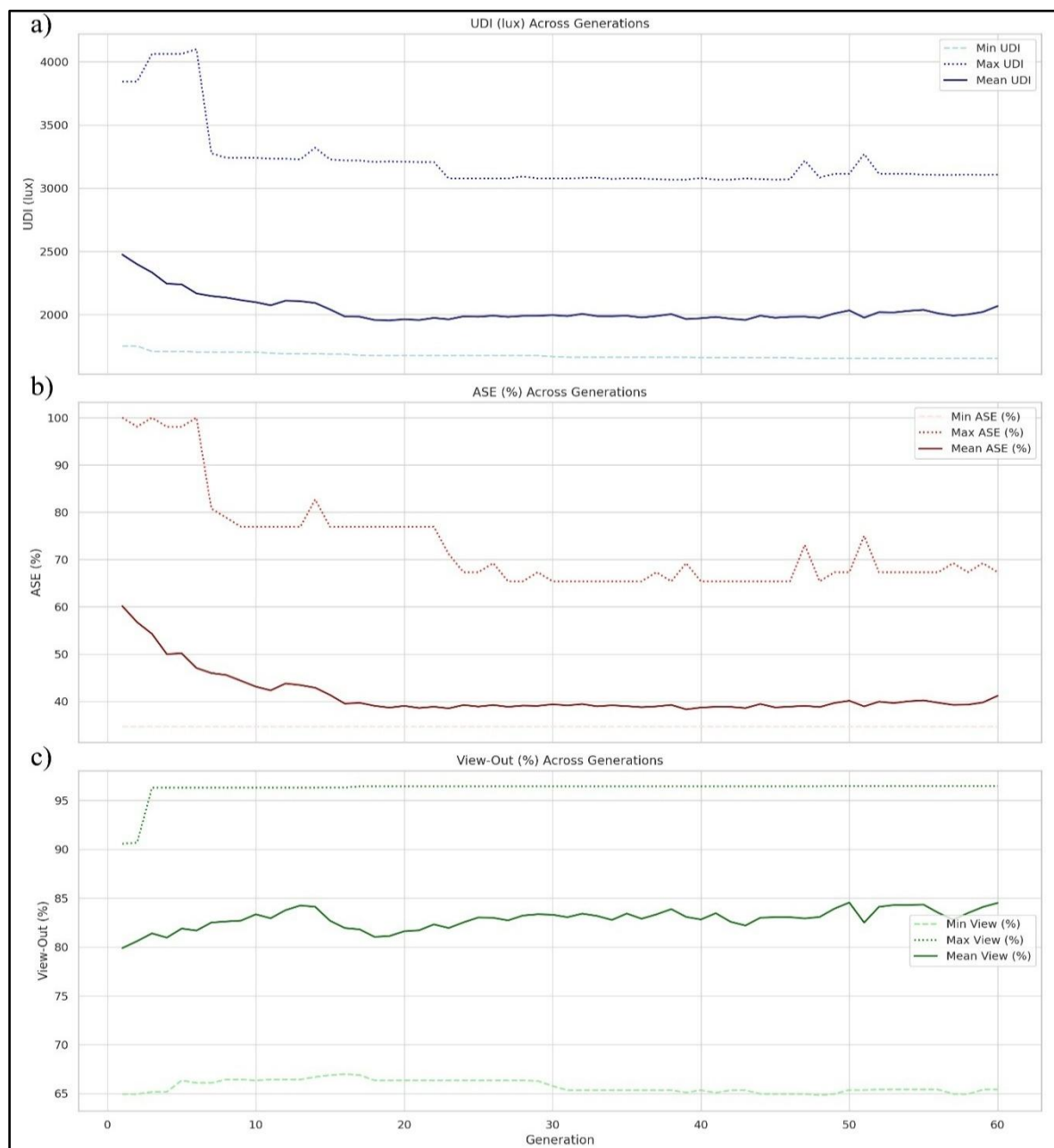


Figure 7.3. Minimum and maximum goal values across generations: a) UDI, b) ASE, c) View-Out (source: Author).

The box plot showing the performance distribution of all results of the optimization process is important for visualizing systematic trends and relationships between metrics. The UDI data is positioned in the optimum illumination range with a median value of around 2200 lux, while only a few individuals exceed 4000 lux, indicating a risk of excessive glare (see Figure 7.4). In terms of ASE, a significant improvement was achieved throughout the process; while values close to 100% were observed at the beginning, the distribution stabilized in the range of 35-41%, and the median value was 38%. In terms of the View-Out metric, the majority of individuals were concentrated in the 80-90% band, and the median value was 85%, indicating that the system preserved the perception of outdoor space.

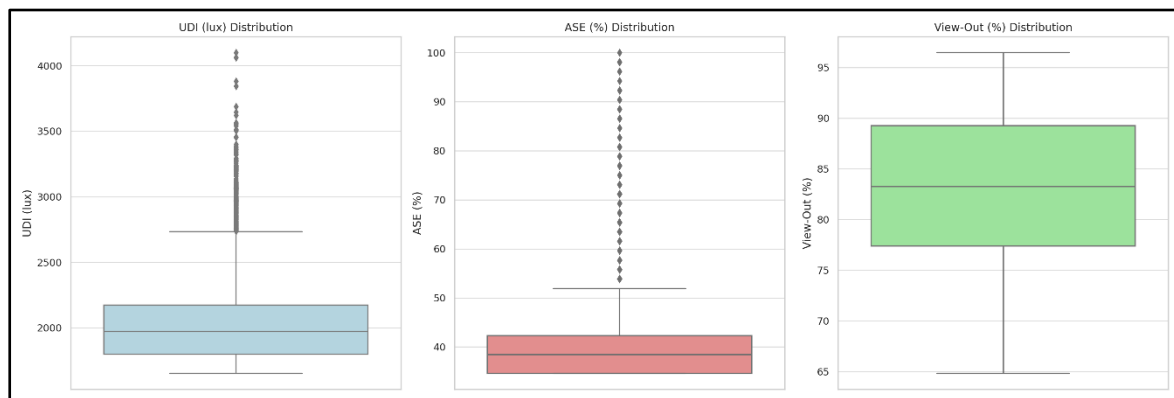


Figure 7.4. Box plot showing the performance distribution of all results (source: Author).

7.3. Pareto-Optimum Designs

The solutions produced in the multi-objective optimization process performed with the Octopus algorithm reveal a set of Pareto-optimal individuals that cannot be directly compared with each other but stand out in different performance areas. These individuals are defined as solutions where one performance metric cannot be improved without further improvement of the others. In other words, an individual's UDI can be reduced, but this reduction will result in an increase in ASE or a loss of View-Out.

In this context, Pareto-optimum individuals, which represent architecturally meaningful and feasible ranges of solutions, can be chosen for different purposes and in the context of different geographical and operational requirements. For all these reasons, an ATC tower may be more suitable for ASE, UDI, or any of the View priority designs. The evolutionary algorithm produces a small number of results with a lot of variation in the first generations,

but as the generations progress, it produces a large number of similar results. In this context, a Pareto-front analysis was performed for all generations to find optimum designs that can be used for different purposes. In this context, 5 Pareto-optimum design solutions were selected.

Table 7.1. Pareto-Optimum design solutions and their parameters (source: Author).

		DESIGN 1	DESIGN 2	DESIGN 3	DESIGN 4	DESIGN 5
GENERATION		37	59	60	60	13
INDEX		168	192	176	187	60
UDI (lux)		1924.47	1894.48	2137.95	2220.43	2174.12
ASE (%)		36.54	34.62	38.46	40.38	38.46
View-Out (%)		85.16	83.43	89.91	93.47	85.13
FAÇADE 1	Module Rotation Angle (°)	55	60	55	55	35
	Module Count (X-Axis)	1	5	1	1	1
FAÇADE 2	Module Rotation Angle (°)	55	60	55	55	40
	Module Count (X-Axis)	7	5	1	1	6
FAÇADE 3	Module Rotation Angle (°)	55	55	55	55	45
	Module Count (X-Axis)	7	7	6	1	8
FAÇADE 4	Module Rotation Angle (°)	60	60	55	55	50
	Module Count (X-Axis)	5	5	5	5	5

As seen in Table 7.1 optimum designs emerged in Generation 13, Generation 17, Generation 59, and Generation 60. When module count (x-axis) parameters are analysed, the value ‘1’ is used for façade 1-Southwest. The highest module count value was used for façade 3 – South-east façade. For façade 4- east, many Pareto-optimum solutions have a module count value of 5. Façade 2 is the façade whose design parameters change the most.

7.3.1. Solution design-1

The first of the 5 Pareto-optimum solution designs is the 37th Generation 168 index design. When this design was applied to the ATC Tower façades and daylight performance simulation was performed, UDI 1924.47 lux, ASE 36.54%, and view-out 85.16% values were obtained. The façade module count and module rotation angle parameters that give these values are 1 and 55° for façade 1, 7 and 60° for façade 2, 7 and 60° for façade 3, 5 and 60° for façade 4, respectively (see Figure 7.5).

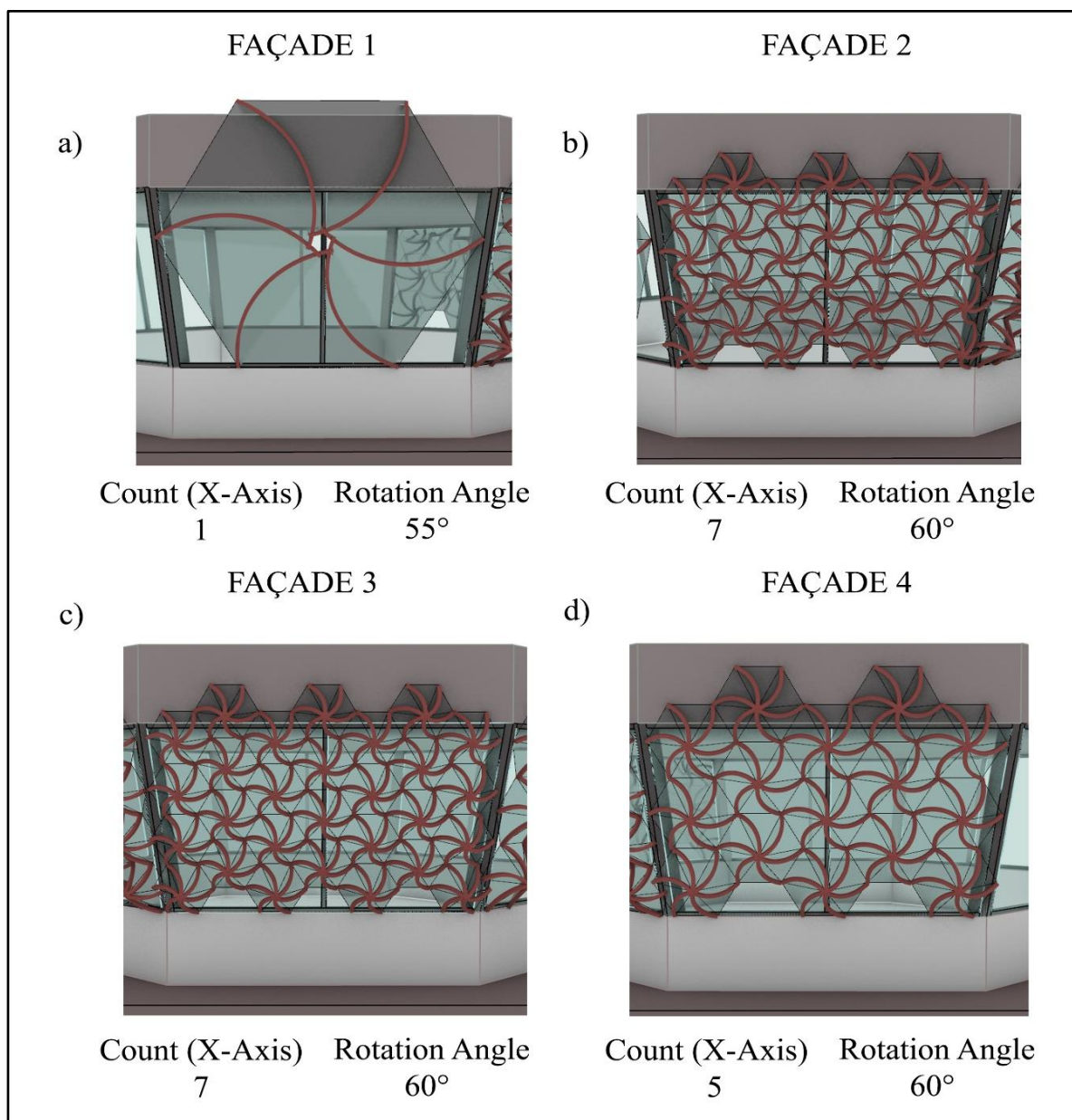


Figure 7.5. Façade views and their parameters of design 2: a) Façade 1, b) Façade 2, c) Façade 3, d) Façade 4 (source: Author).

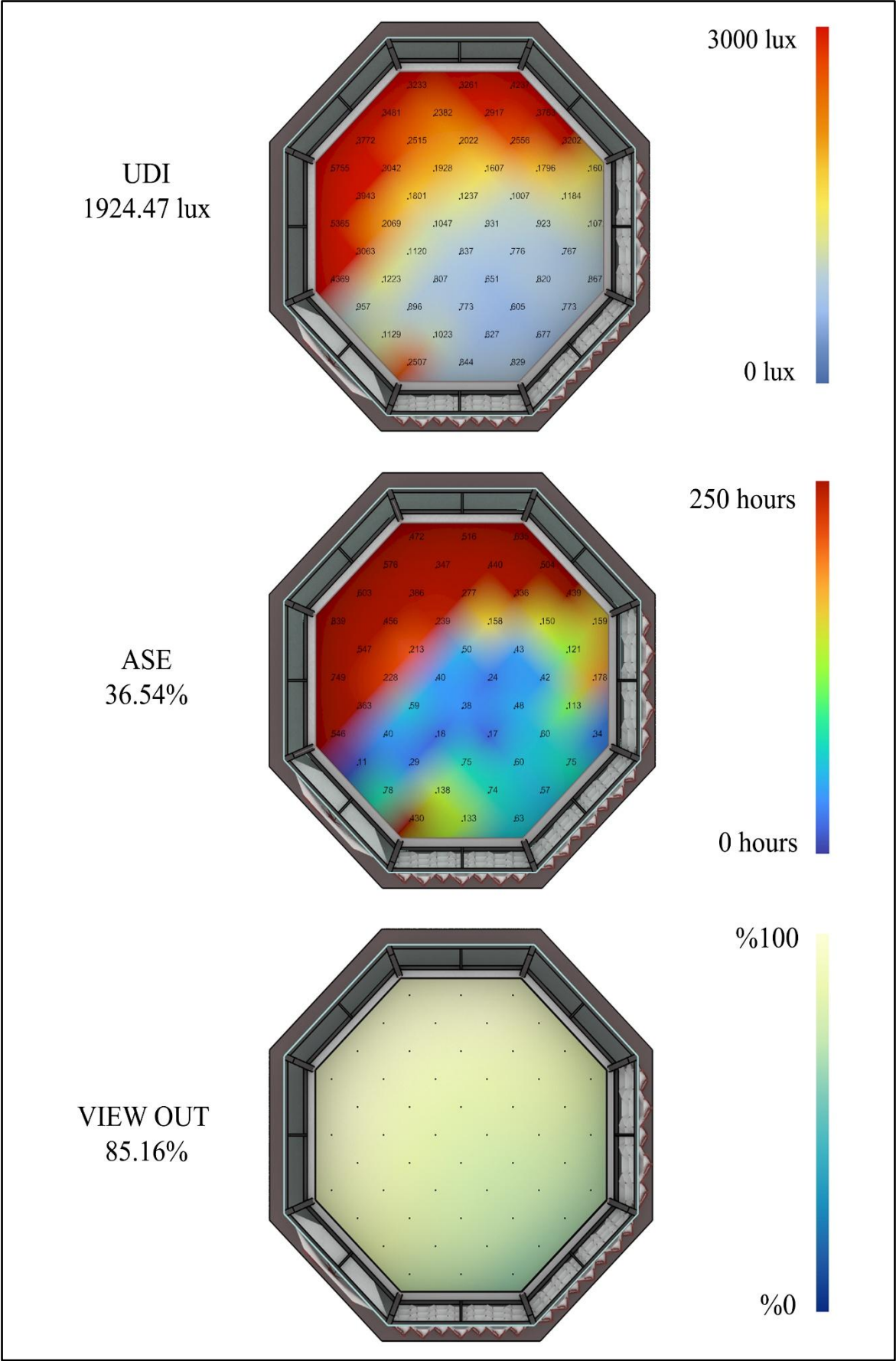


Figure 7.6. Design 1 goals and sensor values (source: Author).

7.3.2. Solution design-2

The second of the 5 Pareto-optimum solution designs is the 59th Generation 192 index design. When this design was applied to the ATC Tower façades and daylight performance simulation was performed, UDI 1894.48 lux, ASE 34.62%, and view-out 83.43% values were obtained. The façade module count and module rotation angle parameters that give these values are 5 and 60° for façade 1, 5 and 60° for façade 2, 7 and 55° for façade 3, 5 and 60° for façade 4, respectively (see Figure 7.7).

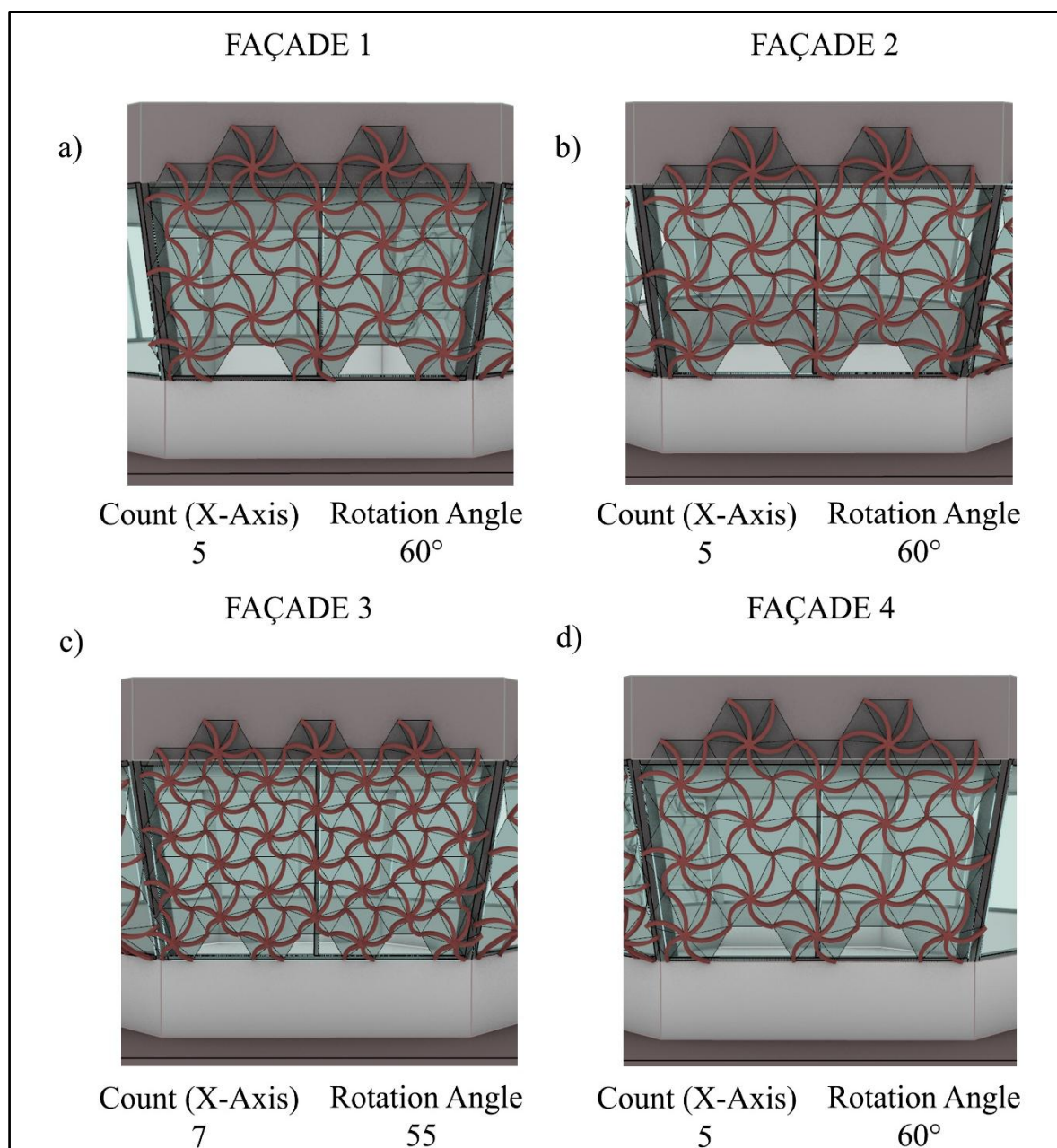


Figure 7.7. Façade views and their parameters of design 2: a) Façade 1, b) Façade 2, c) Façade 3, d) Façade 4 (source: Author).

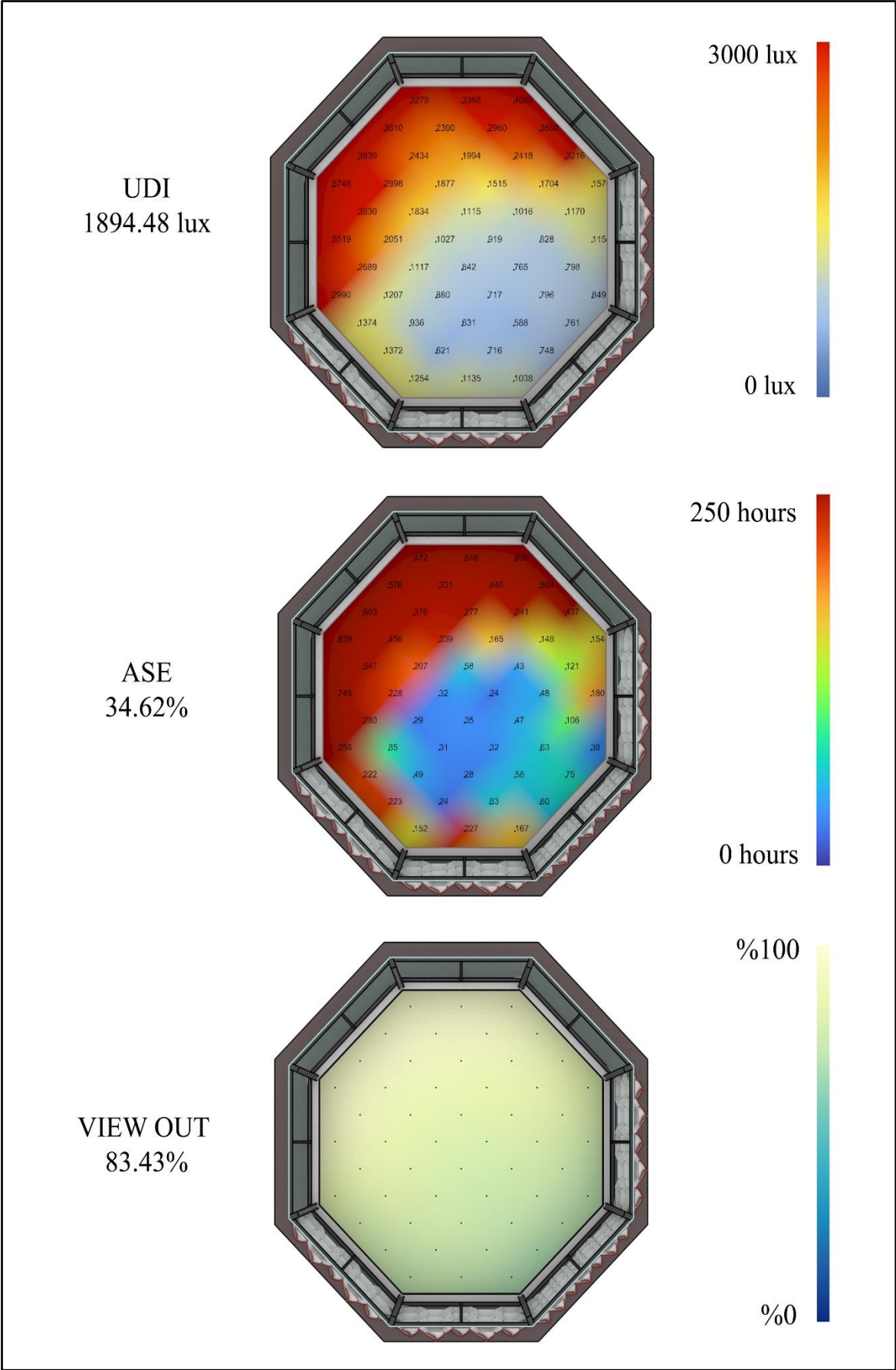


Figure 7.8. Design 2 goals and sensor values (source: Author).

7.3.3. Solution design-3

The third of the 5 Pareto-optimum solution designs is the 60th Generation 176 index design. When this design was applied to the ATC Tower façades and daylight performance simulation was performed, UDI 2137.95 lux, ASE 38.46%, and view-out 89.91% values were obtained. The façade module count and module rotation angle parameters that give these values are 1 and 55° for façade 1, 1 and 55° for façade 2, 6 and 55° for façade 3, 5 and 55° for façade 4, respectively (see Figure 7.9).

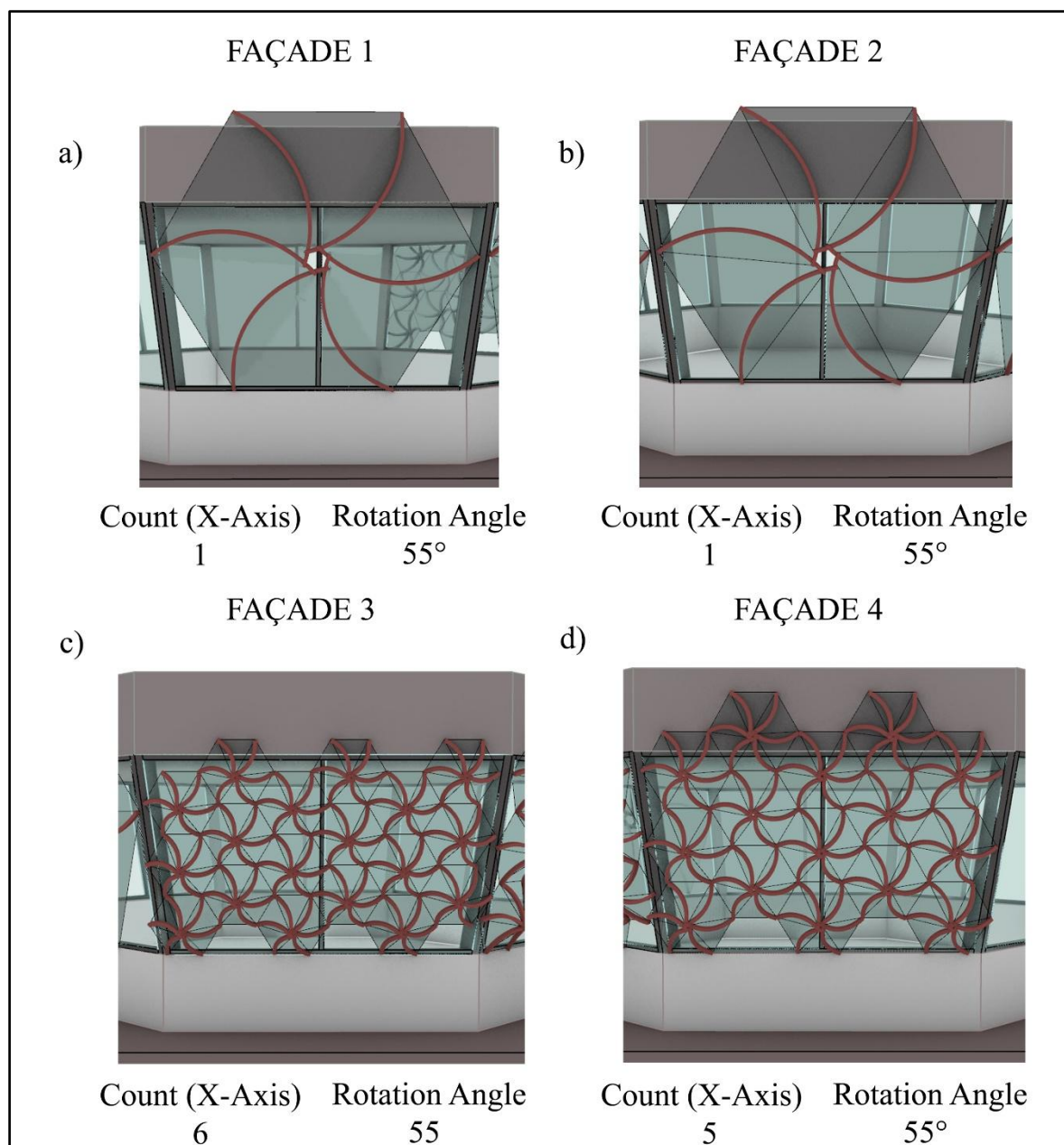


Figure 7.9. Façade views and their parameters of design 3: a) Façade 1, b) Façade 2, c) Façade 3, d) Façade 4 (source: Author).

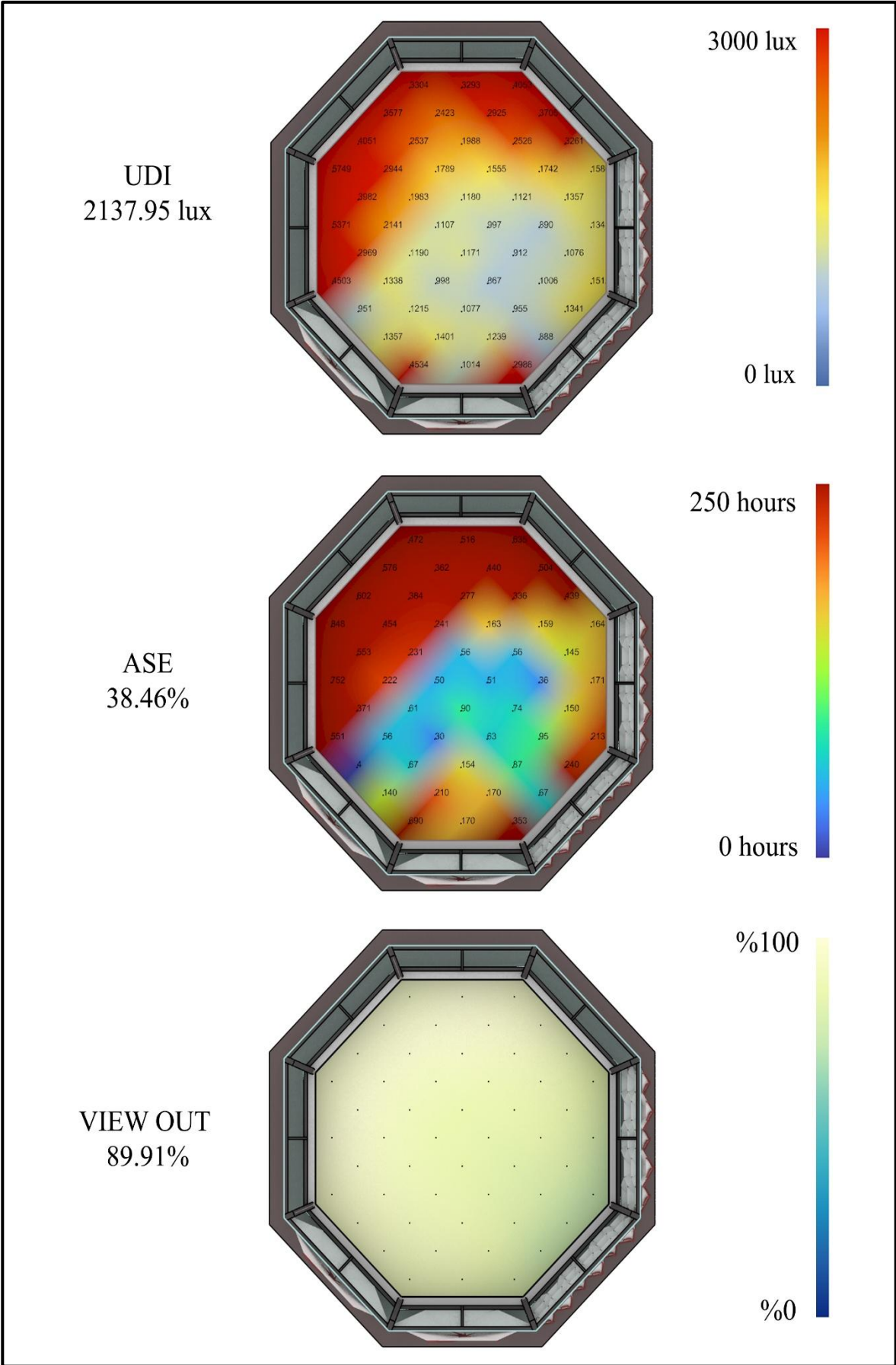


Figure 7.10. Design 3 goals and sensor values (source: Author).

7.3.4. Solution design-4

The fourth of the 5 Pareto-optimum solution designs is the 60th Generation 187 index design. When this design was applied to the ATC Tower façades and daylight performance simulation was performed, UDI 2220.43 lux, ASE 40.38%, and view-out 93.47% values were obtained. The façade module count and module rotation angle parameters that give these values are 1 and 55° for façade 1, 1 and 55° for façade 2, 1 and 55° for façade 3, 5 and 55° for façade 4, respectively (see Figure 7.11).

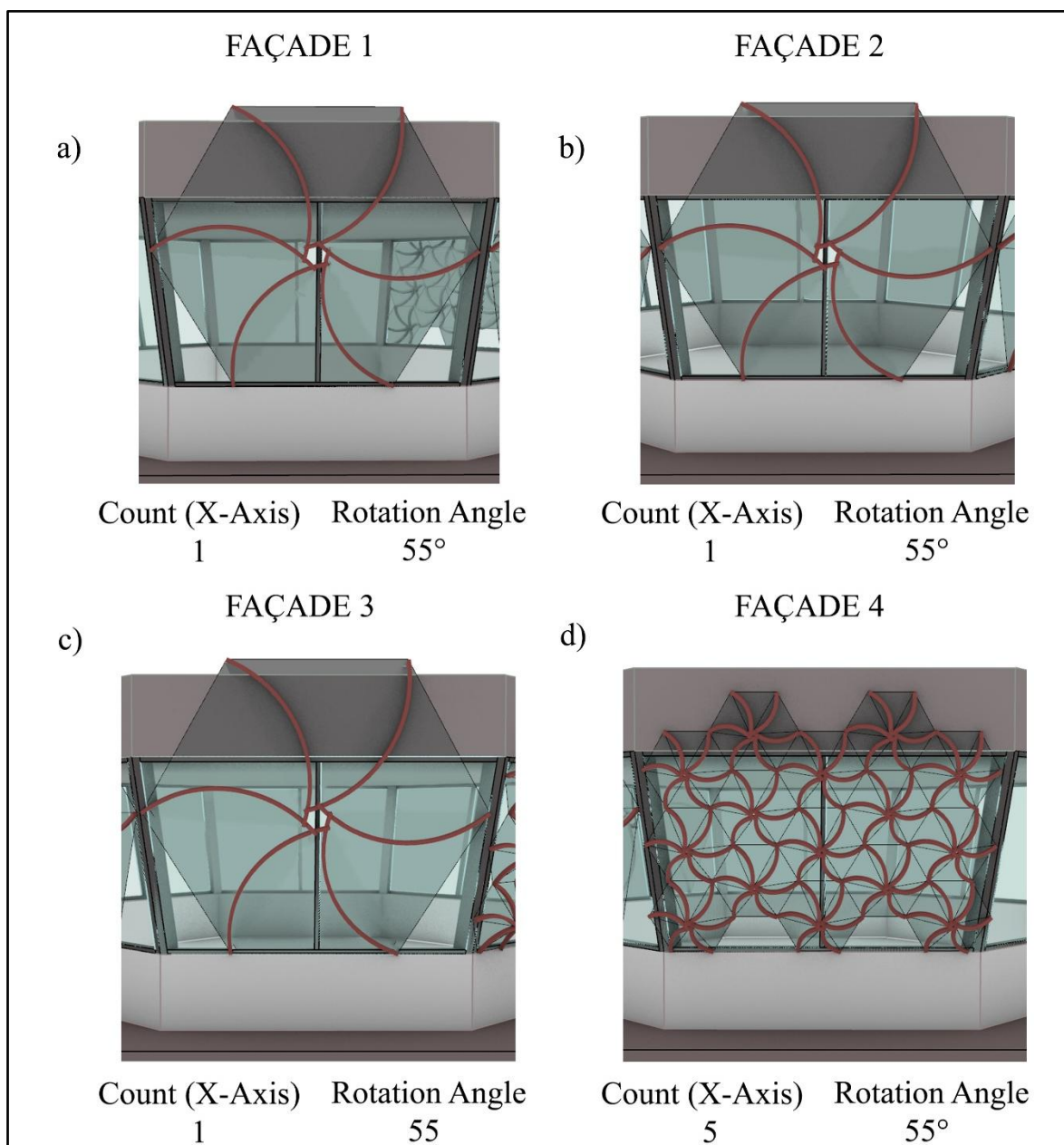


Figure 7.11. Façade views and their parameters of design 4: a) Façade 1, b) Façade 2, c) Façade 3, d) Façade 4 (source: Author).

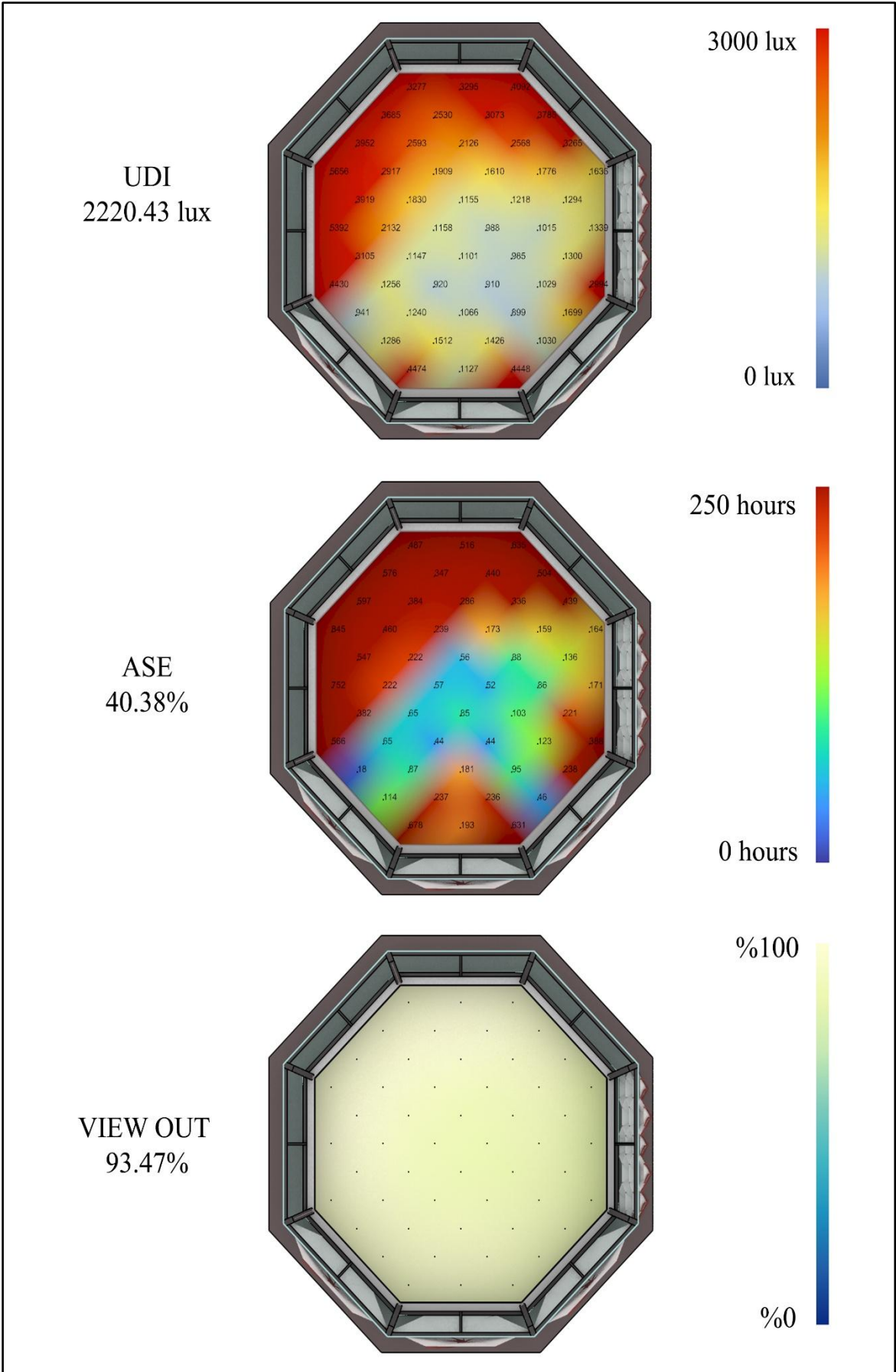


Figure 7.12. Design 4 goals and sensor values (source: Author).

7.3.5. Solution design-5

The last of the 5 Pareto-optimum solution designs is the 13th Generation 60 index design. When this design was applied to the ATC Tower façades and daylight performance simulation was performed, UDI 2174.12 lux, ASE 38.46%, and view-out 85.13% values were obtained. The façade module count and module rotation angle parameters that give these values are 1 and 35° for façade 1, 6 and 40° for façade 2, 8 and 45° for façade 3, 5 and 50° for façade 4, respectively (see Figure 7.13).

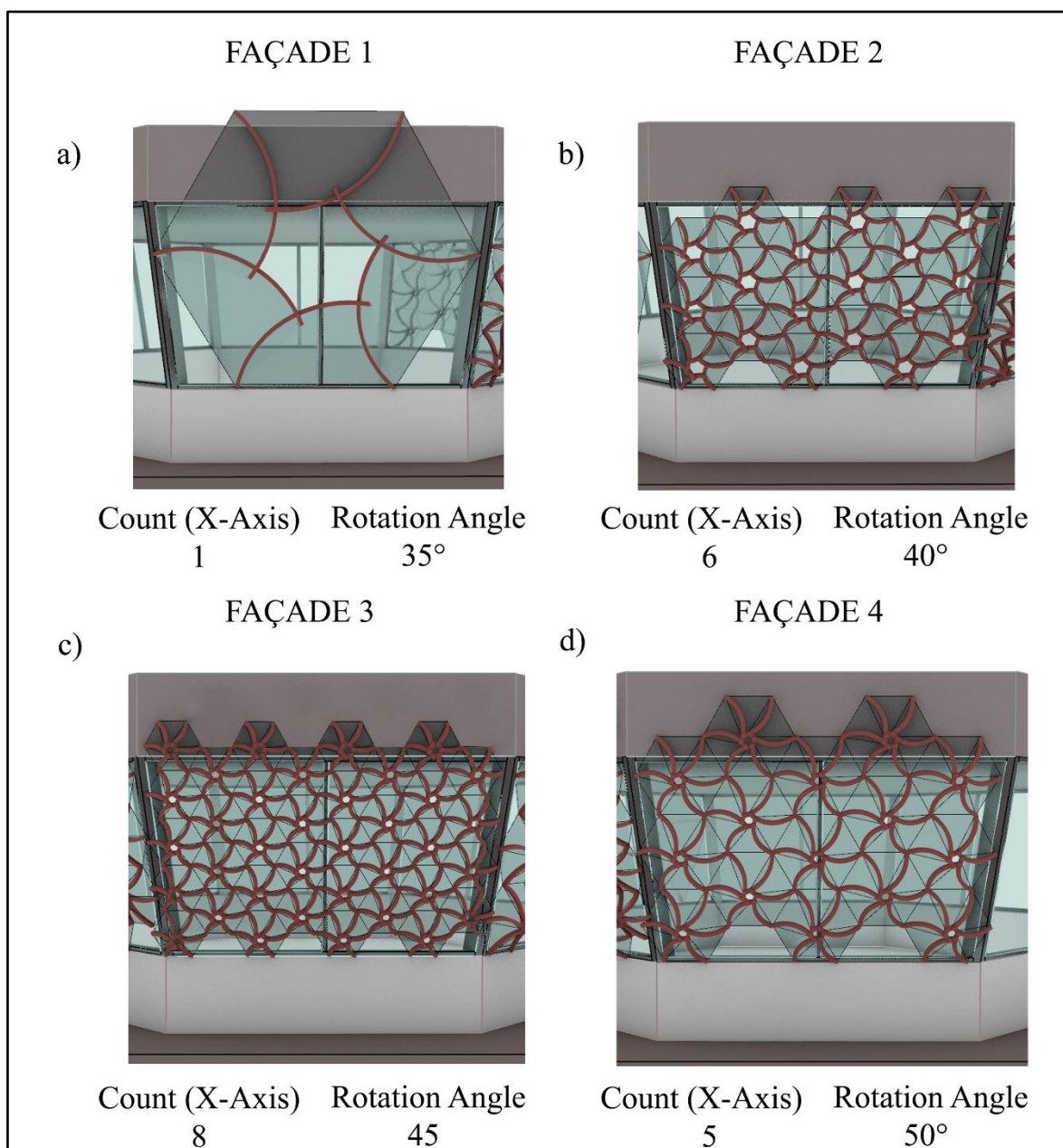


Figure 7.13. Façade views and their parameters of design 5: a) Façade 1, b) Façade 2, c)

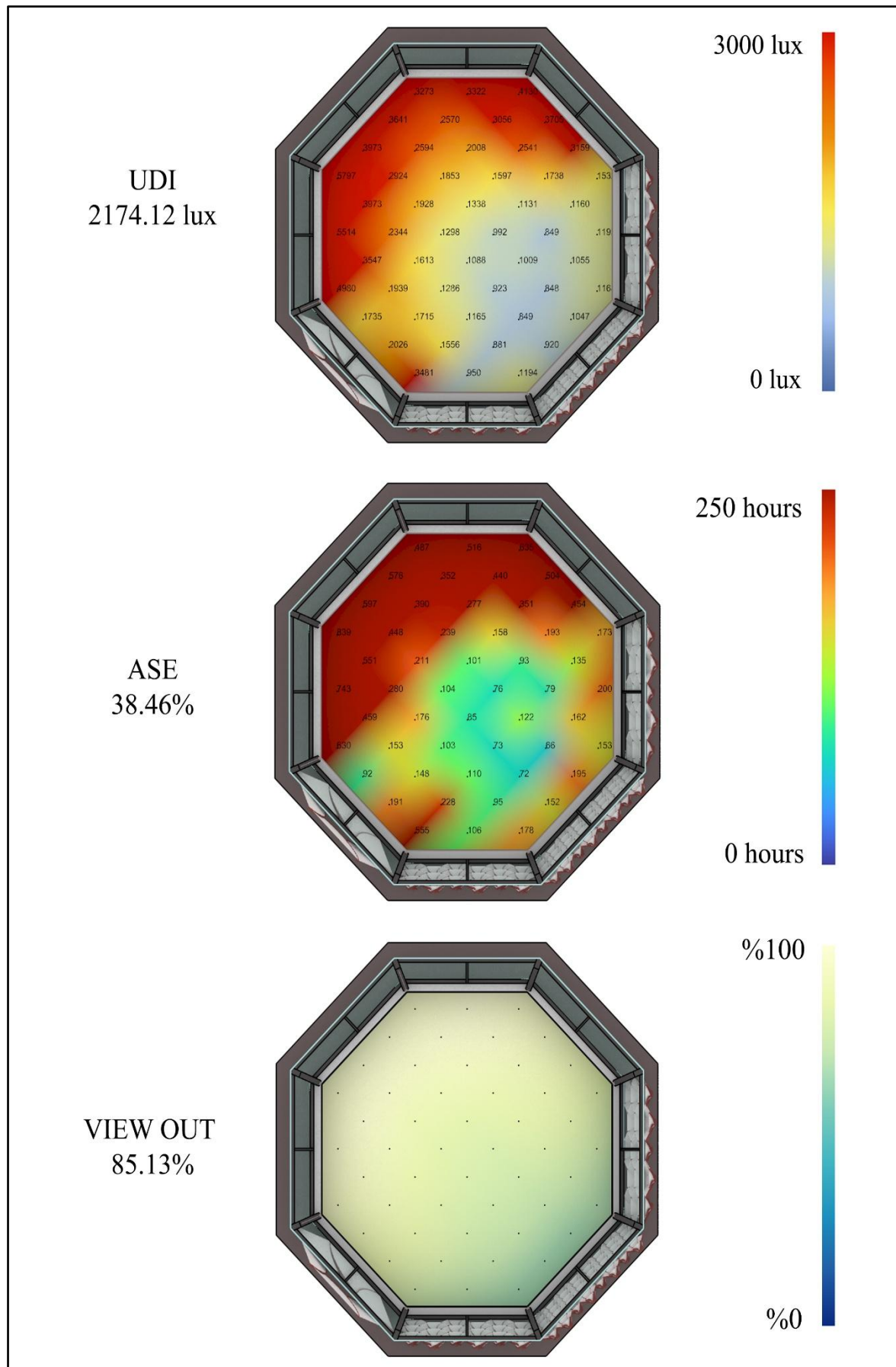


Figure 7.14. Design 5 goals and sensor values (source: Author).

7.4. Evaluation Results

The performance evaluation of the five Pareto-optimum individuals selected as a result of the optimization process provided meaningful outputs in terms of both environmental metrics and morphological variations. This evaluation was done not only between the five individuals, but also in comparison to the overall solution space generated by the algorithm.

The Case ATC tower, which was built in accordance with the standards and regulations, performed poorly when the daylight performance analysis was performed, exceeding the 3000 lux limit more than 2 times with a UDI value of 6472.33 lux, and exceeding the 10% limit 10 times with an ASE value of 100%. These data show that the problems mentioned in the study are caused by these data. These results confirm that problems such as excessive daylight exposure and visual discomfort can only be solved by filtering and adaptive systems.

After the optimization process, the average performance of 11,845 solution designs in the overall solution pool decreased to UDI = 2038.53 lux, ASE = 41.25%, View = 82.85%. On the other hand, the five selected designs outperformed these average values; ASE was reduced to 34.62%, UDI was stabilized between 1894.48 and 2220.43 lux, and View was achieved up to 93.47%.

Among the design parameters, the module rotation angle value is predominantly 55°, 60°, and 50°. This is related to the selection of sunny and warm climate cities like Antalya as the study area. Modules were used in fully open or almost fully open conditions to increase daylight performance. The module count value for Façade 1 is predominantly 1. It can be seen that the effect of this façade on ASE and UDI control is less than the effect on View-Out value, and evolutionary development has reduced the number of nexors in this façade to achieve a higher view-out value. Façade 3 is the façade with the highest module count value. Since this façade is exposed to the sun more, more modules are needed. Façade 2 is the most different in this respect. It is seen that high module count values are used if the design is focused on ASE reduction, and lower module count values are used if the design is focused on view.

Although the five selected Pareto-optimum designs produced very similar values in terms of environmental performance indicators, each of them offers unique solutions representing different architectural priorities. For example, Design 2, which stands out by improving the lowest ASE value by 63.46% and the UDI value by 70.73%, provided the most successful daylight control with its high angle (60°) and dense number of modules. In contrast, Design 4, although 5.76% less successful than Design 2 in terms of ASE value, maintained the highest view-out of 93.47%, reducing the module density and making the façade more permeable.

As seen in Figure 7.15, Design 1 provided a balanced configuration with 85.15% view-out and 36.54% ASE, providing visual comfort and daylight control simultaneously. Compared to the baseline scenario, the ASE value was reduced by 63.46% and the UDI value by 70.27% to 1924.47 lux. This design follows a balanced graph in terms of all evaluation parameters. It has increased the amount of view by reducing the number of modules in Façade 1, and has succeeded in reducing UDI and ASE values by using a large number of modules on façades that are more exposed to the sun and generally using these modules at degrees close to fully open. This balanced design can be rearranged to specifically increase visibility by reducing the number of modules on the façades where the operation is managed. This makes the adaptive façade generally applicable to ATC towers in hot climate regions that experience glare and reflection problems.

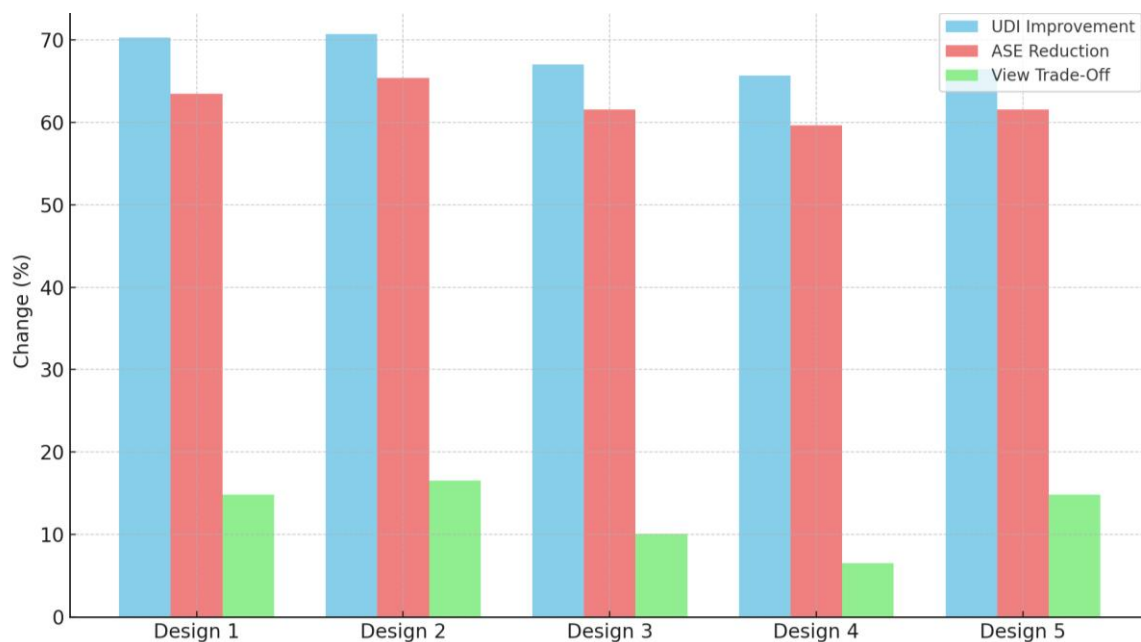


Figure 7.15. Performance evaluation of selected designs compared to the initial situation (source: Author).

Solution design 2 As shown in Figure 7.15, the Pareto-optimal result provides the best improvement in ASE value. Even in Façade 1, where a small number of modules are typically preferred in other designs, the best improvement in ASE value is achieved by using a large number of modules that are almost completely open. However, this module usage has resulted in the lowest view trade-off value of 16.67% among other solution designs, making it the Pareto-optimal result with the lowest view. This type of solution design is more suitable for use in regions such as Antalya, which have problems with glare, reflection, and excessive heating. Although adaptive façade designs were developed for only four façades within the scope of the methodology, adaptive façades can also be used on other façades to ensure that the ASE value complies with standards. However, since this will result in a decrease in the view-out value, the design must be developed in conjunction with simulations.

Solution design 3 made the balanced design view-oriented by setting the module count value to 1 in Façade 1 and Façade 2. This individual offers high visual clarity with a View-Out value of 89.91% and successfully limits glare with an ASE value of 38.46%. It is seen that the Southwest and South façades are the priority façades where the number of modules should be reduced in order to increase visibility for the specified study area. This design will be suitable for ATC towers where the view-out parameter is more important than the balanced daylight performance parameters and where the use of adaptive façades is required, especially on the sides of air traffic operations.

Solution design 4 provides significant improvement in ASE and UDI values among other Pareto-optimal results and emerges as the result with the highest view-out value of 93.47%. This was achieved by using the module count value as 1 and the rotation angle value almost completely open in Façade 1, Façade 2 and Façade 3. Solar radiation analysis shows that the East façade, which is the second most exposed to the sun, is the most critical façade for the improvement in ASE and UDI values. This design is suitable for ATC towers where reflection and glare issues do not affect a large part of the operational process and where visibility requirements are more prominent.

Solution design 5 is a successful example selected from Generation 13 with different variations. Thanks to the diversity in the first generations of the optimization process, these types of variations can yield optimal results with unique parameters. It stands out with a high

view-out value of 85.13% while improving the ASE value by 61.54% and UDI value by 66.42% by keeping the module rotation angle value in the range of 35°-50°, unlike other designs. The use of semi-open modules, which offer daylight performance improvements similar to other solution designs, shows that it is sufficient for the systems to be opened and closed only at certain times of the day, and that the static form of the existing adaptive façade design can have a positive effect on daylight performance in a passive manner during the remaining hours. These types of designs are suitable for general ATC towers that need improvement in daylight comfort and visual comfort.

As there is no best design or perfect design, each ATC tower should be designed in accordance with the most appropriate adaptive façade design by evaluating many parameters such as the façades where operations are carried out, climatic conditions, geographical conditions, surrounding building heights, control room sizes and geometry. In addition, new regulations and standards to be developed in terms of architectural requirements will facilitate the determination of the most optimum façades.

8. CONCLUSION AND RECOMMENDATIONS

This study aims to address daylight performance-based environmental problems encountered in air traffic control towers. Problems such as visual discomfort, visibility-limiting reflection, and glare cause difficulties for air traffic controllers during operations. As a result of the literature analysis, it is aimed to investigate how Kinetic Reciprocal Frame (KRF) adaptive systems that can respond to environmental performance criteria specific to the air traffic control tower can be developed through a multi-objective optimization process and to evaluate the daylight performance of these façades.

The methodology was carried out in three phases. Phase 1 - Problem Identification and Literature Analysis phase, kinetic façades, KRF structures, air traffic control towers, and related regulations and standards were researched. In the Phase 2- Modeling and Simulation phase, the case ATC tower was modeled with Rhinoceros 3D, the most sun-exposed façades and the annual sunlight exposure (ASE), useful daylight illuminance (UDI), and view-out values were analyzed with ClimateStudio. The façades to be designed are the southwest, south, southeast, and east façades. Then, a KRF structure-based adaptive façade design script with Grasshopper and Python was created for these four façades. Finally, in Phase 3 - Optimization and Pareto-front Analysis, the multi-objective optimization process was completed with Octopus, and 2975 Pareto-optimum solutions were found among 11845 results. Finally, a Pareto-front analysis was performed with ASE, UDI, and view-out values among the solution designs, and the 5 most optimum results were determined.

All of the Pareto-optimum solution designs achieved by the optimization resulted in significant improvements compared to the ATC tower design recommended by the standards. In the baseline scenario, the UDI value was 6472.33 lux, the ASE value was 100%, and the View-Out value was 100%, indicating that excessive glare and uncontrolled light penetration create serious comfort problems. Solution designs have been successful in their goal to reduce the UDI value below LEED 3000 lux limit by keeping it in the range of 1894-2220 lux. Although it reduced the ASE value to 34.62%, it did not reach the LEED 10% target, but it showed a positive approach by achieving an improvement of 65.38%. The view-out ratio was kept above 85% (highest 93.47%), ensuring balanced optimization and façade designs that would not restrict operational activities.

The following is a list of the key findings:

- As a result of the literature analysis, it is determined that the studies on the architecture of air traffic control towers are quite limited. Academic studies are mainly related to the engineering aspects of towers, and the architectural design remains in the background.
- The existing standards (ICAO, FAA, and EASA) mentioned in Section 7.1 are inadequate at the design and evaluation stage in terms of daylight performance, visibility, height, and daylight control elements, façade design. The daylight performance analysis of the case ATC tower, which was built following the standards and regulations, proved this inadequacy and the need for the use of additional daylight control elements.
- In Pareto-front analysis, it is important to evaluate solutions in all generations to reach the right conclusion, because few different solutions emerge in the first generations, while many similar results emerge in the last generations.
- When the parameters in the Pareto-optimum solution designs are analyzed, the module count value for Façade 1 - Southwest is predominantly 1. It is seen that the effect of this façade on ASE and UDI control is less than the effect on View-Out value, and evolutionary development has gone to reduce the number of nexors in this façade to achieve a higher view-out value.
- Kinetic Reciprocal Frame adaptive façade is found to be successful against the environmental issues of glare, reflection, and daylight comfort reduction with 65.38% improvement in ASE, 70.73% improvement in UDI, and only 6.53% loss in view-out.

Although only the problems that cause daylight comfort are addressed in this research, issues such as energy losses due to heating and cooling loads, noise problems, control cabinet geometries, and façade geometries can be used for the development of optimum ATC towers. In addition, although this study focused on hot arid climates, it can be extended to other climatic regions. Finally, there is a pressing need for the development of international guidelines and standards that encourage the integration of adaptive systems in aviation infrastructure.

REFERENCES

- A Elnawawy, M., A Mandour, M., Farag, M., and Kamal, M. (2023). Pneumatic Modular System as Adaptive Skin to Enhance Daylighting and energy efficiency in Workspace. *Engineering Research Journal*, 178, 322-321.
- Addington, M., and Schodek, D. (2005). Smart materials and technologies. *Archit. Urbanism*, 5(3), 8-13.
- Al-Imam, A. R. K. (2024). *Daylight optimization with kinetic façades: A parametric design for a sustainable campus library building* (Master's Thesis). Bahçeşehir University, Türkiye.
- Alakavuk, E., and Sarisayin, N. H. (2024). The Effect Of Using Kinetic Façades In Increasing The Daylighting Performance Of Buildings. *Light and Engineering*, 32(6).
- Alizade, R. (2019). Structural synthesis of robot manipulators by using screw with variable pitch. *Universal Journal of Mechanical Engineering*, 7(2), 50-63.
- Anderson, J. D., and Bowden, M. L. (2005). *Introduction to flight* (Vol. 582). McGraw-Hill Higher Education New York, NY, USA.
- Apriliawan, I., Alkadri, M. F., and Dewi, O. C. (2024). Interactive Kinetic Façade with Design for Disassembly (DfD) strategy: improving energy efficiency and circularity of building materials in tropical climate. *Intelligent Buildings International*, 1-19.
- Arvidsson, I., Arvidsson, M., Axmon, A., Hansson, G. A., Johansson, C. R., and Skerfving, S. (2006). Musculoskeletal disorders among female and male air traffic controllers performing identical and demanding computer work. *Ergonomics*, 49(11), 1052-1067.
- Athienitis, A. K., Barone, G., Buonomano, A., and Palombo, A. (2018). Assessing active and passive effects of façade building integrated photovoltaics/thermal systems: Dynamic modelling and simulation. *Applied Energy*, 209, 355-382.
- Attia, S. (2017). Evaluation of adaptive façades: The case study of Al Bahr Towers in the UAE. *QScience Connect*, 2017(2), 6.
- Attia, S., Lioure, R., and Declaude, Q. (2020). Future trends and main concepts of adaptive façade systems. *Energy Science and Engineering*, 8(9), 3255-3272.
- Avinç, G. M., Koç, S. N., and Selçuk, S. A. (2024). Biomimetic Façade Design Proposal to Improving Thermal Comfort in Hot Climate Region. *International Journal of Built Environment and Sustainability*, 11(2), 27-39.
- Ayçam, İ., and Ceylan, O., (2017). *Analysis of Daylight Control in Advanced Façade Systems for Office Module in Ankara* . 3rd International Sustainable Buildings Symposium (ISBS), (359-377). , U. Arab Emirates.

- Aydın, S. S. (2009). *Meydan Kontrol Kulelerinin ve Donanımlarının Tasarımına Ergonomik Bir Yaklaşım A. Ü. Hava Alanı Meydan Kontrol Kulesi Üzerine Bir Uygulama* (Master's Thesis). Anadolu University, Türkiye.
- Balderrama, A., Kang, J., Prieto, A., Luna-Navarro, A., Arztmann, D., and Knaack, U. (2022). Effects of Façades on urban acoustic environment and soundscape: A systematic review. *Sustainability*, 14(15), 9670.
- Barnes, C. F., Jr. (2009). *The portfolio of Villard de Honnecourt: A new critical edition and color facsimile*. Routledge.
- Başar, C. (2014). *Mekan Hareketlerinin Fiziksel, Topolojik Ve Deneyimsel Bağlamlar Üzerinden İncelenmesi* (Master's Thesis). İstanbul Technical University, Türkiye.
- Baverel, O., and Saidani, M. (1999). The multi-reciprocal grid system. *Journal of the International Association for Shell and Spatial Structures*, 40(1), 33-41.
- Baverel, O. L. (2000). *Nexorades: a family of interwoven space structures*. University of Surrey (United Kingdom).
- Bedon, C., Honfi, D., Machalická, K. V., Eliášová, M., Vokáč, M., Kozłowski, M., Wüest, T., Santos, F., and Portal, N. W. (2019). Structural characterisation of adaptive façades in Europe – Part I: Insight on classification rules, performance metrics and design methods. *Journal of Building Engineering*, 25, 100721.
- Bianca, S. (2000). *Urban form in the Arab world: past and present* (Vol. 46). vdf Hochschulverlag AG.
- Bilstein, R. E. (2001). *Flight in America: From the Wrights to the astronauts*. Johns Hopkins University Press.
- Chellappa, S. L., Gordijn, M. C., and Cajochen, C. (2011). Can light make us bright? Effects of light on cognition and sleep. *Progress in brain research*, 190, 119-133.
- Chen, P., and Tang, H. (2024). A Framework for Adaptive Façade Optimization Design Based on Building Envelope Performance Characteristics. *Buildings*, 14(9), 2646.
- Chilton, J. (2009). *Development of timber reciprocal frame structures in the UK*. In A. Domingo and C. Lázaro (Eds.), *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009: Evolution and trends in design, analysis and construction of shell and spatial structures (1877–1884)*.
- Chilton, J. C., and Choo, B. S. (1992). *Reciprocal frame long span structures*. In N. K. Srivastava, A. N. Sherbourne, and J. Roorda (Eds.), *Innovative large span structures (100–109)*. Toronto, Canada.
- Chilton, J. C., Choo, B. S., and Coulliette, P. (1994). Retractable roofs using the reciprocal frame. *Proceedings of the IABSE Symposium Birmingham 1994: Places of Assembly and Long-Span Building Structures*, 71, 49–54.

- Darwin, C. (1968). On the origin of species by means of natural selection. 1859. *London: Murray Google Scholar*, 16.
- Dastoum, M., Guevara, C. S., and Arranz, B. (2024). Efficient daylighting and thermal performance through tessellation of geometric patterns in building façade: A systematic review. *Energy for Sustainable Development*, 83, 101563.
- DeLucia, P. R., Ott, T. E., and Palmieri, P. A. (2009). Performance in nursing. *Reviews of human factors and ergonomics*, 5(1), 1-40.
- Diarce, G., Urresti, A., García-Romero, A., Delgado, A., Erkoreka, A., Escudero, C., and Campos-Celador, A. (2013). Ventilated active façades with PCM. *Applied Energy*, 109, 530-537.
- Donnelly, M. C. (1992). *Architecture in the Scandinavian countries*. MIT Press.
- Douthe, C., and Baverel, O. (2009). Design of nexorades or reciprocal frame systems with the dynamic relaxation method. *Computers and Structures*, 87(21-22), 1296-1307.
- European Union Aviation Safety Agency (EASA). (2022). *Certification specifications and guidance material for aerodrome design (CS-ADR-DSN)*.
- Elguezabal, P., Lopez, A., Blanco, J. M., and Chica, J. A. (2019). New Concept Of Solar Collector Integrated Into A Sandwich Panel As An Active Façade; Cfd Based Parametric Assessment And Case Study. *Dyna*, 94(6), 691-697.
- Elmokadem, A., Ekram, M., Waseef, A., and Nashaat, B. (2018). Kinetic architecture: Concepts, History and applications. *International Journal of Science and Research (IJSR)*, 7(4), 750-758.
- Fathy, H. (1986). *Natural energy and vernacular architecture: Principles and examples with reference to hot arid climates*. University of Chicago Press.
- Etman, O., Tolba, O., & Ezzeldin, S. (2013, September). Double-Skin façades in Egypt between parametric and climatic approaches. In *eCAADe 2013: Computation and Performance—Proceedings of the 31st International Conference on Education and research in Computer Aided Architectural Design in Europe, Delft, The Netherlands, September 18-20, 2013*.
- Favoino, F., Jin, Q., and Overend, M. (2017). Design and control optimisation of adaptive insulation systems for office buildings. Part 1: Adaptive technologies and simulation framework. *Energy*, 127, 301-309.
- Federal Aviation Administration (FAA). (2004). *Order 6480.7D: Airport Traffic Control Tower and Terminal Radar Approach Control Facility Design Guidelines* (Order No. 6480.7D), U.S. Department of Transportation. Facility Design Guidelines. In: U.S. Department of Transportation.
- Federal Aviation Administration (FAA). (2018). *FAA 6480.4 – Airport traffic control tower siting process*.

- Fernando, D., Navaratnam, S., Rajeev, P., and Sanjayan, J. (2023). Study of Technological Advancement and Challenges of Façade System for Sustainable Building: Current Design Practice. *Sustainability*, 15(19), 14319.
- Fox, M. A., and Yeh, B. P. (2000). *Intelligent kinetic systems in architecture. Managing Interactions in Smart Environments: 1st International Workshop on Managing Interactions in Smart Environments (MANSE'99), Dublin, December 1999* (91-103). Springer London.
- Gediri Gökçen, G. Ş. (2023). Uyum gösteren (adaptif) cepheler: Hareketli güneş kontrol elemanlarının ısı enerji performansının değerlendirilmesi (Master's Thesis), Middle East Technical University, Türkiye.
- Gelez, S., Aubry, S., and Vaudeville, B. (2011). Nexorade or reciprocal frame system applied to the design and construction of a 850 m² archaeological shelter. *International Journal of Space Structures*, 26(4), 303-311.
- Giedion, S. (2009). *Space, time and architecture: the growth of a new tradition*. Harvard University Press.
- Giovanardi, M., Baietta, A., Belletti, F., Magnani, S., Casadei, O., and Pracucci, A. (2024). Exploiting the value of active and multifunctional façade technology through the IoT and AI. *Applied Sciences*, 14(3), 1145.
- Glassman, E. J., and Reinhart, C. (2013). Façade optimization using parametric design and future climate scenarios. *Proceedings of the 13th Conference of the International Building Performance Simulation Association*, 1585–1592.
- Goharian, A., Daneshjoo, K., Mahdavinejad, M., and Yeganeh, M. (2022). Voronoi geometry for building façade to manage direct sunbeams. *Journal of Sustainable Architecture and Civil Engineering*, 31(2), 109-124.
- Gombrich, E. H. (1979). *The sense of order: A study in the psychology of decorative art*. Oxford, England: Phaidon.
- Gong, F. F., Ma, Y. C., Shi, F., Chen, C., Tian, L. L., and Huang, J. J. (2024). Environmental and Energy Performances of the Nearly Net-Zero Energy Solar Decathlon House with Dynamic Façades: A Comparison of Four Climate Regions. *Buildings*, 14(12), 4053.
- Gustafsson, J. (2016). *Connections in Timber Reciprocal Frames* (Master's Thesis). Chalmers University of Technology, Sweden.
- Günay, M. (2021). Design in visual communication. *Art and Design Review*, 9(02), 109.
- Güney, N. N., and Arpacioğlu, Ü. (2024). Examining Façade Adaptability: A Study of Adaptive Façade Classification Criteria. *Kent Akademisi*, 17(5), 1925-1938.

- Habibi, S., Valladares, O. P., and Peña, D. M. (2022). Sustainability performance by ten representative intelligent Façade technologies: a systematic review. *Sustainable Energy Technologies and Assessments*, 52, 102001.
- Hachem, C., and Elsayed, M. (2016). Patterns of façade system design for enhanced energy performance of multistory buildings. *Energy and Buildings*, 130, 366-377.
- Hafizi, N., and Vural, S. M. (2022). New Taxonomy of Climate Adaptive Building Shell Office Buildings: Focus on User-Façade Interaction Scenarios. *Energies*, 15(14), 5268.
- Helmis, C. G., Assimakopoulos, V. D., Flocas, H. A., Stathopoulou, O. I., Sgouros, G., and Hatzaki, M. (2009). Indoor air quality assessment in the air traffic control tower of the Athens Airport, Greece. *Environmental monitoring and assessment*, 148, 47-60.
- Hinkle, L. E., Wang, J., and Brown, N. C. (2022). Quantifying potential dynamic façade energy savings in early design using constrained optimization. *Building and Environment*, 221, 109265.
- Hong, W., Laurenzi, M. P., and Council, A. B. (2007). *Building Energy Efficiency: Why Green Building are Key to Asia's Future*. Asia Business Council.
- Hosseini, S. M., Heidari, S., Attia, S., Wang, J. L., and Triantafyllidis, G. (2024). Biomimetic kinetic façade as a real-time daylight control: complex form versus simple form with proper kinetic behavior. *Smart and Sustainable Built Environment*.
- Hosseini, S. M., Mohammadi, M., Rosemann, A., Schröder, T., and Lichtenberg, J. (2019). A morphological approach for kinetic façade design process to improve visual and thermal comfort: Review. *Building and Environment*, 153, 186-204.
- Houlsby, G. T. (2014). John Wallis and the numerical analysis of structures. *Nexus Network Journal*, 16, 207-217.
- Hutchins, M. G. (2009). *The optical properties of De Leeuw Ltd Reflex-Rol (UK) sample AR760* (Report No. 09/312). Sonnergy Ltd, Solar Energy Materials Research Laboratory.
- Ibrahim, M., and Fayed, S. (2024). Solar radiation analysis: computational performance analysis for the foldable axis of a responsive external skin on the south façade. *Innovative Infrastructure Solutions*, 9(6), 202.
- International Civil Aviation Organization (ICAO). (2005). *Annex 2: Rules of the Air*.
- International Civil Aviation Organization (ICAO). (2016). *Annex 14 – Volume I (Aerodromes)*.
- International Civil Aviation Organization (ICAO). (1984). *Air Traffic Services Planning Manual*. In. Montreal, Canada.

International Civil Aviation Organization (ICAO). (1987). *Doc 9184: Airport planning manual – Part 1 master planning*.

International Civil Aviation Organization (ICAO). (1993). *Human Factors in Air Traffic Control (Circular 241)*. In. Montreal, Canada.

Internet: Altensis. (2023). *İstanbul Havalimanı Hava Trafik Kontrol Kulesi*. Web: <https://www.altensis.com/proje/istanbul-havalimani-hava-trafik-kontrol-kulesi/> Last Access Date: 23.03.2025

Internet: Alyn, G. (2017). *AAU Anastas and GSA Research Laboratory use digital technologies to create self-supporting stone pavilion*. Web: <https://www.dezeen.com/2017/05/07/aa-u-anastas-gsa-research-laboratory-stone-pavilion-jericho-palestine/> Last Access Date: 13.02.2025

Internet: Archdaily. (2014). *Breath Box / NAS Architecture*. Web: <https://www.archdaily.com/535107/breath-box-nas-architecture> Last Access Date: 27.01.2025

Internet: Archdaily. (2017). *Bund Finance Centre / Foster + Partners + Heatherwick Studio*. Web: <https://www.archdaily.com/881511/bund-finance-centre-foster-plus-partners-plus-heatherwick-studio> Last Access Date: 28.01.2025

Internet: Archdaily. (2019). *Apartment Building for Four Friends / Lussi+Halter Partner AG + Lola Domenech*. Web: <https://www.archdaily.com/929295/apartment-building-for-four-friends-lussi-plus-halter-partner-ag-plus-lola-domenech> Last Access Date: 28.01.2025

Internet: Archello. (2010). *Heathrow Air Traffic Control Tower*. Web: <https://archello.com/project/heathrow-air-traffic-control-tower> Last Access Date: 23.02.2025

Internet: ClimateStudio. (2024). *SKY*. Web: <https://climatestudiodocs.com/docs/sky.html> Last Access Date: 06.05.2025

Internet: Controltowers. (2018). *Croydon*. Web: <https://web.archive.org/web/20181023130243/http://www.controltowers.co.uk/C/Croydon.htm> Last Access Date: 22.02.2025

Internet: Designboom. (2012). *Brisbane airport kinetic parking garage façade by ned kahn + UAP*. Web: <https://www.designboom.com/art/brisbane-airport-kinetic-parking-garage-façade-by-ned-kahn-uap/> Last Access Date: 23.02.2025

Internet: DHMI. (2019). *Antalya - Teknik Bilgiler ve Kolaylıklar*. Web: <https://www.dhmi.gov.tr/Sayfalar/Havalimani/Antalya/TeknikBilgilerveKolayliklar.aspx> Last Access Date: 05.05.2025

Internet: Eurocontrol. (2024a). *European Aviation Overview*. Web: <https://www.eurocontrol.int/publication/eurocontrol-european-aviation-overview> Last Access Date: 07.01.2025

- Internet: Eurocontrol. (2024b). *Remote towers - the Skeyes DiTo project*. Web: <https://www.eurocontrol.int/article/remote-towers-skeyes-dito-project> Last Access Date: 22.02.2025
- Internet: Federal Aviation Administration (FAA). (2021). Air Traffic Control. Web: https://www.faa.gov/about/history/photo_album/air_traffic_control Last Access Date: 25.01.2025
- Internet: Federal Aviation Administration (FAA). (2023a). *Sustainable and adaptive air traffic control tower design initiatives*. Web: <https://www.faa.gov/tower-design> Last Access Date: 07.01.2025
- Internet: Federal Aviation Administration (FAA). (2023b). *Sustainable Tower Design Initiative*. Web: <https://www.faa.gov/tower-design> Last Access Date: 22.02.2025
- Internet: Flightradar24. (2025). *Statistics*. Retrieved 07 January from Web: <https://www.flightradar24.com/data/statistics> Last Access Date: 07.01.2025
- Internet: International Air Transport Association (IATA). (2023). *Global Outlook for Air Transport*. Web: <https://www.iata.org/en/iata-repository/publications/economic-reports/global-outlook-for-air-transport---june-2023/> Last Access Date: 08.01.2025
- Internet: IMA. (2023). Architecture. Imarabe. Web: <https://www.imarabe.org/en/architecture> Last Access Date: 07.01.2025
- Internet: Infinitive Data Expert (IDE). (2022). *Façade Market Size, Industry Analysis By Type (Ventilated, Non-Ventilated, and Others), By Application(Commercial, Residential, and Others) – Global, Trends, Share And Forecast 2023-2030*. Web: <https://www.infinitivedataexpert.com/industry-report/façade-market#description> Last Access Date: 07.01.2025
- Internet: Karataş, Z. (2020). *Göbeklitepe, ekonomi ve İbni Haldun*. Web: <https://www.indyturk.com/node/235171/t%C3%BCrkiyeden-sesler/g%C3%B6beklitepe-ekonomi-ve-ibni-haldun> Last Access Date: 11.01.2025
- Internet: Krymsky, Y. (2011). *CJ RandD Center Kinetic Façade*. Web: <https://yazdanistudioresearch.wordpress.com/2011/11/15/cj-rd-center-kinetic-façade/> Last Access Date: 28.01.2025
- Internet: LadybugTools. (2024). *EPW Map*. Web: <https://www.ladybug.tools/epwmap/> Last Access Date: 17.03.2025
- Internet: McNeel, R. (2010). *Rhinoceros 3D*. Robert McNeel and Associates. Web: <https://www.rhino3d.com> Last Access Date: 04.05.2025
- Internet: Memon, O. (2023). *History: How Have Air Traffic Control Towers Evolved Over The Years?* Web: <https://simpleflying.com/atc-towers-history-guide/> Last Access Date: 22.02.2025

- Internet: Museum, N.A.A.S. (2022). *Air Traffic Control*. Web: <https://airandspace.si.edu/explore/stories/air-traffic-control> Last Access Date: 23.02.2025
- Internet: Plastic-View. (2025). *Two ATCT Window Shade Systems*. Web: www.pvatc.com Last Access Date: 05.04.2025
- Internet: Rutten, D. (2013). *Grasshopper: Generative Modeling for Rhino*. Web: <https://www.grasshopper3d.com> Last Access Date: 04.05.2025
- Internet: Santiye. (2021). *Rize-Artvin Havalimanı Projesinin de Tercihi PERI Kalıp ve İskele Sistemleri Oldu*. Web: <https://www.santiye.com.tr/rize-artvin-havalimani-projesinin-de-tercihi-peri-kalip-ve-i-skele-sistemleri-oldu-1857.html> Last Access Date: 22.02.2025
- Internet: Sharp, C. J. (2007). *Saqqara pyramid of Djoser in Egypt*. https://en.wikipedia.org/wiki/Pyramid_of_Djoser#/media/File:Saqqara_pyramid_ver_2.jpg Last Access Date: 11.01.2025
- Internet: Solar-Screen AB. (2025). *Spec for Roler Blind Film*. Web: <https://solarscreen.se/en/startpage/> Last Access Date: 02.04.2025
- Internet: Solemma LLC. (2021). *ClimateStudio*. Solemma LLC. Web: <https://www.climatestudio.com> Last Access Date: 04.05.2025
- Internet: Thermosash. (n. d.). *Glass Performance*. Web: <https://www.thermosash.co.nz/materials/glass/glass-performance/> Last Access Date: 05.05.2025
- Internet: Transportheritage. (2018). *Croydon Airport*. Web: <https://web.archive.org/web/20180925180501/http://www.transportheritage.com/find-heritage-locations.html?sobi2Task=sobi2Detailsandcatid=91andsobi2Id=273> Last Access Date: 22.02.2025
- Internet: USGBC. (2018). *LEED v4 for Building Operations and Maintenance - current version*. Web: <https://www.usgbc.org/resources/leed-v4-building-operations-and-maintenance-current-version> Last Access Date: 05.05.2025
- Internet: Vierlinger, R. (2013). *Octopus for Grasshopper: A Multi-objective Optimization Tool Based on Evolutionary Algorithms [Computer software]*. Web: <https://www.food4rhino.com/en/app/octopus> Last Access Date: 05.05.2025
- Internet: Walshgroup. (2017). *O'Hare International Airport – South Air Traffic Control Tower*. Web: <https://www.walshgroup.com/ourexperience/building/aviation/ohareinternationalairportsouthairtrafficcontroltower.html> Last Access Date: 23.02.2025
- Internet: Metalyapı. (2013). *Istanbul New Airport - Air Traffic Control Tower 1*. Web: <https://www.metalyapi-eng.com/projects-istanbul-new-airport-air-traffic-control-tower-1.html> Last Access Date: 23.02.2025

- Internet: Michler, A. (2012). *CJ Research Center's Kinetic Folding Façade / Yazdani Studio*. Web: <https://www.evolo.us/cj-research-centers-kinetic-folding-façade-yazdani-studio/> Last Access Date: 28.01.2025
- Jafari, M., and Alipour, A. (2021). Review of approaches, opportunities, and future directions for improving aerodynamics of tall buildings with smart façades. *Sustainable Cities and Society*, 72, 102979.
- Jalali, Z., Noorzai, E., and Heidari, S. (2020). Design and optimization of form and façade of an office building using the genetic algorithm. *Science and Technology for the Built Environment*, 26(2), 128-140.
- Jamsari, E. A., Nawi, M. A. M., Sulaiman, A., Sidik, R., Zaidi, Z., and Ashari, M. (2013). Ibn Firnas and his contribution to the aviation technology of the world. *Advances in Natural and Applied Sciences*, 7(1), 74-78.
- Javanmard, Z., & Mangano, G. (2024). A review of sustainable pathways to climate-neutral buildings: Technological synergy of advanced cladding systems and building integrated photovoltaics. In F. Calabrò, L. Madureira, F. C. Morabito, & M. J. Piñeira Mantiñán (Eds.), *Networks, markets and people. NMP 2024* (Lecture Notes in Networks and Systems, Vol. 1189, 293–305. Springer.
- Juaristi, M., and Monge-Barrio, A. (2016). *Adaptive façades in temperate climates. An in-use assessment of an office building. 11th conference on advanced building skins*.
- Jung, H., Kim, Y., and Kim, S. (2015, August). A Study on Transformable Façade Design Using Scissors system. In *Proceedings of IASS Annual Symposia* (Vol. 2015, No. 6, 1-10). International Association for Shell and Spatial Structures (IASS).
- Kahne, S., and Frolow, I. (1996). Air traffic management: evolution with technology. *IEEE Control Systems Magazine*, 16(4), 12-21.
- Karakoç, Z. (2017). *Yapı örtüsü olarak mütekabil elemanların incelenmesi* (Master's Thesis). Fatih Sultan Mehmet Vakıf University, Türkiye.
- Karakuş, G. (2016). *Doha Tower On-site Review Report*.
- Kazda, A., and Caves, R. E. (2010). *Airport design and operation*. Emerald Group Publishing Limited.
- Kim, D. H., Luong, H. T., and Nguyen, T. T. (2024). Optimizing the Shading Device Configuration of Kinetic Façades through Daylighting Performance Assessment. *Buildings*, 14(4), 1038.
- Kim, H., Asl, M. R., and Yan, W. (2015, September). Parametric BIM-based energy simulation for buildings with complex kinetic façades. In *Proceedings of the 33rd eCAADe Conference* (Vol. 1, 657-664).
- Kim, M.-J. (2002). A Study on the Scythian gold plaques. *Journal of Fashion Business*, 6(3), 1-14.

- Kitajima, S., and Suehiro, K. (2023). 平面から曲面へ展開可能な測地線グリッドを用いたレシプロカルフレームのモデル化 [Modeling of a reciprocal frame using a geodesic grid deployable from a plane to a curved surface]. *AIJ Journal of Technology and Design*, 29(73), 1653–1658.
- Kızılörenli, E., and Maden, F. (2023). Modular responsive façade proposals based on semi-regular and demi-regular tessellation: Daylighting and visual comfort. *Frontiers of Architectural Research*, 12(4), 601-612.
- Kolarevic, B., and Parlac, V. (2015). Architecture of Change: Adaptive Building Skins. In *The Routledge Companion for Architecture Design and Practice* (223-238). Routledge.
- Konstantzos, I., and Tzempelikos, A. (2017). A Holistic Approach for Improving Visual Environment in Private Offices. *Procedia Environmental Sciences*, 38, 372-380.
- Krisman, M. R., Putriekapuja, R. A., and Amir, E. (2024). The Influence of Noice Levels in The Cabin Tower on The Work Environment of Air Traffic Controllers at Airnav Indonesia Subbranch Gorontalo. *Kontribusi: Research Dissemination for Community Development*, 7(2), 70-76.
- Kutlu, M. (2020). Orta Asya'da Tütekli (Kırlangıç) örtünün kökeni ve tarihî gelişim aşamaları üzerine bir değerlendirme. *Journal of History Studies*.
- Lim, Y.-W., Kandar, M. Z., Ahmad, M. H., Ossen, D. R., and Abdullah, A. M. (2012). Building façade design for daylighting quality in typical government office building. *Building and Environment*, 57, 194-204.
- Loonen, R. C., Rico-Martinez, J. M., Favoino, F., Brzezicki, M., Ménézo, C., La Ferla, G., and Aelenei, L. L. (2015, November). Design for façade adaptability: Towards a unified and systematic characterization. In *10th Conference on Advanced Building Skins, 3-4 November 2015, Bern, Switzerland* (1284-1294). Economic Forum.
- Loonen, R. C., Trčka, M., Cóstola, D., and Hensen, J. L. (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews*, 25, 483-493.
- Mahmoud, A. H. A., and Elghazi, Y. (2016). Parametric-based designs for kinetic façades to optimize daylight performance: Comparing rotation and translation kinetic motion for hexagonal façade patterns. *Solar Energy*, 126, 111-127.
- Martokusumo, W., Koerniawan, M. D., Poerbo, H. W., Ardiani, N. A., and Krisanti, S. H. (2017). Algae and building façade revisited. a study of façade system for infill design. *Journal of Architecture and Urbanism*, 41(4), 296-304.
- Matheou, M., Couvelas, A., and Phocas, M. C. (2020). Transformable building envelope design in architectural education. *Procedia Manufacturing*, 44, 116-123.
- Metwally, W. M., and Ibrahim, V. A. R. (2024). The Integration of Bio-Active Elements into Building Façades as a Sustainable Concept. *Buildings*, 14(10), 3086.

- Mohamed, N. A. G., and Ali, W. H. (2014). Traditional residential architecture in Cairo from a green architecture perspective. *Arts and Design studies*, 16(6), 6–26.
- Mohtashami, N., Fuchs, N., Fotopoulou, M., Drosatos, P., Streblow, R., Osterhage, T., and Müller, D. (2022). State of the Art of Technologies in Adaptive Dynamic Building Envelopes (ADBEs). *Energies*, 15(3), 829.
- Moloney, C. (2016). *Realizing an aesthetics of movement for architecture*. 267-278.
- Moloney, J. (2011). *Designing kinetics for architectural façades: state change*. Routledge.
- Nadiri, P., Mahdavinejad, M., and Pilechiha, P. (2019). Optimization of Building Façade to Control Daylight Excessiveness and View to Outside. *Journal of Applied Engineering Sciences*, 90(2).
- Nazarzadeh, F., and Asefi, M. (2022). Geometric feasibility of kinetic reciprocal frame structures with linear and curved elements and a constant perimeter. *Journal of Architectural Engineering*, 28(2), 04022014.
- Özen, G. (2022). *Design and analysis of deployable reciprocal frames* (Doctoral dissertation). İzmir Institute of Technology, Türkiye.
- Özen, G., and Korkmaz, K. (2022). Mobility Analysis of Reciprocal Frames. *International Journal of Digital Innovation in the Built Environment (IJDIBE)*, 11(2), 1-14.
- Özen, G., Korkmaz, K., and Kiper, G. (2024). Design of Rollable Reciprocal Frame Network. *Journal of the International Association for Shell and Spatial Structures*, 65(1), 15-26.
- Paech, C., Göppert, K., and Wilbrenninck, S. (2014). Fast-track design and build of a FIFA compliant stadium. *Stahlbau*, 83(6), 394-399.
- Panya, D. S., Kim, T., and Choo, S. (2020). A methodology of interactive motion façades design through parametric strategies. *Applied sciences*, 10(4), 1218.
- Parigi, D. (2021). The Parigi mechanism: A novel 1-DOF mechanism and its application as a kinetic reciprocal system (KRS) adaptive façade. *Nexus Network Journal*, 23(3), 629-646.
- Parigi, D., & Sassone, M. (2010). The design of a planar kinetic reciprocal frame. In Q. Zhang, L. Yang, & Y. Hu (Eds.), *Proceedings of the IASS Symposium 2010: Spatial Structures – Permanent and Temporary (1979–1990)*. Shanghai, China: China Architecture & Building Pres
- Parigi, D., & Sassone, M. (2011). Morphogenesis of kinetic reciprocal frames. In *Proceedings of the Structural Engineering World Congress (SEWC) 2011*.
- Park, W., Park, K.-S., Koh, H.-M., and Ha, D.-H. (2006). Wind-induced response control and serviceability improvement of an air traffic control tower. *Engineering structures*, 28(7), 1060-1070.

- Parliament of the Commonwealth of Australia. (2021). *Report 2/2021: Referrals made in November and December 2020*. Parliamentary Standing Committee on Public Works.
- Pellegrino, S., and Calladine, C. R. (1986). Matrix analysis of statically and kinematically indeterminate frameworks. *International Journal of Solids and Structures*, 22(4), 409-428.
- Pérez-Valcárcel, J., Muñoz-Vidal, M., López-César, I. R., Freire-Tellado, M. J., and Suárez-Riestra, F. (2024). Analysis of Deployable Cylindrical Space Bar Structures of Reciprocal Linkages with Frustoconical Ends. *Designs*, 8(3), 46.
- Pérez-Valcárcel, J., Muñoz-Vidal, M., Suárez-Riestra, F., López-César, I. R., and Freire-Tellado, M. J. (2021). A new system of deployable structures with reciprocal linkages for emergency buildings. *Journal of Building Engineering*, 33, 101609.
- Petrescu, R. V., Aversa, R., Akash, B., Bucinell, R., Corchado, J., Apicella, A., and Petrescu, F. I. (2017). History of aviation-a short review. *Journal of Aircraft and Spacecraft Technology*, 1(1).
- Platzer, W. J., and Platzer, W. (2003). Switchable façade technology—energy efficient office buildings with smart façades. In *Proceedings of the Solar World Congress* (14-19).
- Polat, H., and İlerisoy, Z. Y. (2020). A Geometric Method on Façade Form Design with Voronoi Diagram. *Modular Journal*, 3(2), 179-194.
- Popovic Larsen, O. (1996). *Reciprocal frame structures* (Doctoral dissertation). University of Nottingham, England.
- Popovic Larsen, O. (2007). *Reciprocal frame architecture*. Routledge.
- Popovic Larsen, O. (2014). Reciprocal Frame (RF) Structures: Real and Exploratory. *Nexus Network Journal*, 16(1), 119-134.
- Popovic Larsen, O., and Lee, D. S.-H. (2013). Reciprocal Frames (RFs) used for quick-built deployable emergency shelters. In *Proceedings of IASS Annual Symposia* (Vol. 2013, No. 9, 1-7). International Association for Shell and Spatial Structures (IASS).
- Pugnale, A., and Sassone, M. (2014). Structural reciprocity: critical overview and promising research/design issues. *Nexus Network Journal*, 16, 9-35.
- Republic of Türkiye. (2007). *Binaların Yangından Korunması Hakkında Yönetmelik* (Sayı: 26735). Resmî Gazete.
- Republic of Türkiye Ministry of Transport and Infrastructure. (2018). *Earthquake regulations for airfield structures in Türkiye (THMYDY)*.

- Rezakhani, M., & Kim, S.-A. (2020). Using virtual reality to evaluate the impact of dispersion of elements on kinetic façade. In *Proceedings of the 20th International Conference on Construction Applications of Virtual Reality (CONVR 2020)*. Teesside University Press.
- Romano, R. (2021). Kinetic Adaptive Façades. A Systematic Review of Technological and Adaptive Features. In G. Chiesa (Ed.), *Bioclimatic Approaches in Urban and Building Design* (499-519). Springer International Publishing.
- Romano, R., Aelenei, L., Aelenei, D., and Mazzucchelli, E. S. (2018). What is an adaptive façade? Analysis of Recent Terms and definitions from an international perspective. *Journal of Façade Design and Engineering*, 6(3), 65-76.
- Rutledge, A., Romero, M., and Benton, E. (2024). Exploring Mental Health Disorders Among Air Traffic Controllers. *The Collegiate Aviation Review International*, 42(2).
- Sadeghi, J., and Maden, F. (2024). Status Quo of Multi-Objective Design Optimization of Kinetic Façades: A Quantitative Review. *Gazi University Journal of Science*, 37(4), 1616-1631.
- Salleh, M. R. (2008). Life event, stress and illness. *Malaysian Journal of Medical Sciences*, 15(4), 9-18.
- Schleicher, S., Lienhard, J., Poppinga, S., Masselter, T., Speck, T., and Knippers, J. (2011, March). Adaptive façade shading systems inspired by natural elastic kinematics. In *Proceedings of the International Conference on Adaptive Architecture*.
- Secchi, S., Fausti, P., Cellai, G., Parente, M., Santoni, A., and Zuccherini Martello, N. (2022). The acoustic and daylighting effects of external façade sun shading systems. *Journal of Façade Design and Engineering*, 10(1), 155-172.
- Seyrek, C. I., Widera, B., and Woźniczka, A. (2021). Sustainability-Related Parameters and Decision Support Tools for Kinetic Green Façades. *Sustainability*, 13(18), 10313.
- Sharaidin, K., Burry, J., and Salim, F. (2012, September). Integration of digital simulation tools with parametric designs to evaluate kinetic façades for daylight performance. In *Digital Physicality-Proceedings of the 30th eCAADe Conference* (Vol. 2, 701-709).
- Sonati, J., De Martino, M., Vilarta, R., Maciel, É., Moreira, E., Sanchez, F., De Martino, G., and Sonati, R. (2015). Quality of Life, Health, and Sleep of Air Traffic Controllers with Different Shift Systems. *Aerosp Med Hum Perform*, 86(10), 895-900.
- Sureshkumar Jayakumari, S. D., Imalka, S. T., Yang, R. J., Liu, C., Yang, S., Marschall, M., Corradini, P. S., Benito, A. F., and Williams, N. (2024). Energy and Daylighting Performance of Kinetic Building-Integrated Photovoltaics (BIPV) Façade. *Sustainability*, 16(22), 9739.

- Şenel, H. A., İlerisoy, Z. Y., and Soyluk, A. (2024). Using KRF Structures As An Adaptive Façade And Evaluation of Daylight Performance Based on Geometry: A Case Study in Ankara. *International Journal of Built Environment and Sustainability*, 11(1), 1-13.
- Tabadkani, A., Shoubi, M. V., Soflaei, F., and Banihashemi, S. (2019). Integrated parametric design of adaptive façades for user's visual comfort. *Automation in Construction*, 106, 102857.
- Talaei, M., Mahdavinejad, M., Azari, R., Prieto, A., and Sangin, H. (2021). Multi-objective optimization of building-integrated microalgae photobioreactors for energy and daylighting performance. *Journal of Building Engineering*, 42, 102832.
- Taveres-Cachat, E., Grynning, S., Almas, O., and Goia, F. (2017). Advanced transparent façades: market available products and associated challenges in building performance simulation. *Energy Procedia*, 132, 496-501.
- Ulular, I. B. (2022). *Kinetic façades for maximizing human comfort and increasing space use efficiency in highly glazed building interiors* (Master's thesis). Middle East Technical University, Türkiye
- Uluslan, Ş. (2021). İstikbal Göklerdedir: Türk Tayyare Cemiyeti (1925-1938)(Türk Tayyare Cemiyeti'nden Türk Hava Kurumu'na). *Uluslararası Atatürk Kongresi*, 1(8), 2330-2370.
- United Nations Environment Programme (UNEP). (2022). *2022 Global Status Report for Buildings and Construction*. UNEP.
- Velasco, R., Brakke, A. P., and Chavarro, D. (2015). Dynamic Façades and Computation: Towards an Inclusive Categorization of High Performance Kinetic Façade Systems. In G. Celani, D. M. Sperling, and J. M. S. Franco, *Computer-Aided Architectural Design Futures. The Next City - New Technologies and the Future of the Built Environment* Berlin, Heidelberg.
- Verderame, L. (2021). Animal agents in Sumerian literature. In *Fierce lions, angry mice and fat-tailed sheep: Animal encounters in the ancient Near East* (15-22). McDonald Institute for Archaeological Research, University of Cambridge.
- Voigt, M. P., Chwalek, K., Roth, D., Kreimeyer, M., and Blandini, L. (2023). The integrated design process of adaptive façades—A comprehensive perspective. *Journal of Building Engineering*, 67, 106043.
- Wagiri, F., Shih, S.-G., Harsono, K., and Wijaya, D. C. (2024). Multi-objective optimization of kinetic façade aperture ratios for daylight and solar radiation control. *Journal of Building Physics*, 47(4), 355-385.
- Wagiri, F., Shih, S. G., Harsono, K., and Wijaya, D. C. (2024). Multi-objective optimization of kinetic façade aperture ratios for daylight and solar radiation control. *Journal of Building Physics*, 47(4), 355-385.

- Wallis, J. (1972). *Opera mathematica* (Vol. 1). Theatro Sheldoniano.
- Webb, M., Aye, L., and Green, R. (2018). Simulation of a biomimetic façade using TRNSYS. *Applied Energy*, 213, 670-694.
- Wienold, J., and Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*, 38(7), 743-757.
- Zeier, H. (1994). Workload and psychophysiological stress reactions in air traffic controllers. *Ergonomics*, 37(3), 525-539
- Zhang, X., Zhang, H., Wang, Y., and Shi, X. (2022). Adaptive Façades: Review of Designs, Performance Evaluation, and Control Systems. *Buildings*, 12(12), 2112.





Gazili olmak ayrıcalıktır