RESEARCH ARTICLE OPEN ACCESS

Analytical and Comparative Study on the Design of Kinetic Facades and their Daylight Performance in Buildings

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ABSTRACT

Due to the issue of climate change and global warming in addition to the constantly increasing demand for energy, the building skin is considered to be a rigid system with fixed characteristics which is unable to adapt to the ever-changing climate conditions. Here rises the need to design building skins that are more intelligent, climate aware and able to react properly to the constant outdoor environment changes. One of the main advantages of the rapid technology evolution, that we are witnessing nowadays, is the development of systems that can react to change by collecting data, evaluating it and then efficiently responding to it accordingly. Kinetic façade systems can not only decrease the need for mechanical systems such as HVAC and artificial lighting but also add to the occupants' comfort.

The aim of this paper is to give an overview of the main elements that are involved in the design of a kinetic façade. Also, a comparative analysis is performed, in which precedents of recent kinetic façade applications are compared, in terms of their design and daylight performance.

Keywords — kinetic façades, daylight performance.

I. INTRODUCTION

From the beginning of human existence, building shells have always provided a shelter that protected its occupants from negative impacts caused by various environmental conditions. However, ever since the twentieth century along with its artificial lighting and HVAC systems developments, buildings were not only separated from the outdoor environment where spaces became dimmer and consumed a lot of energy, but they also created a major negative impact on our environment. Buildings were found to be one of the main provocateurs of global warming as they are responsible for one third of the total greenhouse gas emissions. However, buildings can also play a major role in minimizing emissions through drastically reducing their energy consumption. In order to achieve this, buildings need to change. Buildings need to become more efficient, cost effective, sustainable and able to adapt and respond to the environment changes and user needs throughout their entire duration.

Kinetic facades are described as a macroscale climate adaptive building shells. These facades can adjust their shape, form, orientation or openings in order to respond to the variable climatic environment such as daylight, wind and heat. Along with the constant changes in the environmental conditions and user needs, kinetic facades are capable of undergoing significant deformation. Kinetic skins can react to these changes through folding, sliding, rotating and scaling the building components, or transforming the material properties. This Paper will concentrate on some of the basic elements of kinetic design and also review and compare recent examples of kinetic façade application.

II. KINETIC DESIGN BASIC ELEMENTS

Fox and Yeh (2006) stated that intelligent kinetic systems arise from three key elements: structural engineering, embedded computation and adaptable architecture. [1]

These three categories are reviewed to better understand the way kinetic façades are designed and applied in order to accomplish a more sustainable and adaptable buildings.

A. *Kinetic structural engineering*

The focus of structural engineering on developing kinetic structure designs is constantly increasing as they have proven to provide useful solutions under extreme environmental conditions and emergencies caused by nature disasters or human actions. Kinetic systems are used as technological strategies in building design as they offer transportable, flexible, producible and adaptable characteristics allowing them to adequately respond to the changing needs. Manufacturing these kinetic systems directly rely on advanced computer technology in addition to high quality fabricated kinetic parts. Kinetic structures can differ from each other not only by their typology, but also by the ways and means of its kinetic motion.

1) ***Kinetic structure typologies*** Generally, kinetic structures in architecture are classified into three general categories: deployable, dynamic and embedded. ***Deployable kinetic structure*** can be described as "transportable" architecture. Michael A. Fox defined deployable kinetic structures as "structures that typically exist in temporary location and are easily transportable". The components of this structure provide the ability to be easily constructed and deconstructed and to preform similar functions in various

locations. This kind of systems are often used for temporary shelters in disaster areas, small pavilions or exhibition areas. Whereas ***Dynamic kinetic structure*** consists of numerous single elements as well as large ones that are installed individually but, in a way, to respect the overall design. They can exist and preform their function regardless of the building type and location they are placed on. Shading systems, ceilings, facades, dynamic furniture elements and many other building components are examples of a dynamic kinetic application. ***Embedded kinetic structures*** is specifically designed for a particular building, location and function it is installed upon. Most of the kinetic façade systems fall into this category of kinetic structures. Embedded kinetic structure is responsible for controlling and adapting the whole architecture system in accordance to the changing environmental factors. This type has the most direct impact on the building users and their comfort by controlling various factors such as light, ventilation and thermal comfort. These structures are usually composed of various small elements coupled with intelligent logic that drives the entire structure to act as a whole and change its form or configuration [1]

2) ***Ways of kinetic motion:*** There are various motion types used in kinetic façade systems since each kinetic façade is unique and different in terms of shape, movement, complexity and function. However, there are five general motion categories that are frequently used in kinetic facades: sliding, folding, layering, rotating, and scaling.

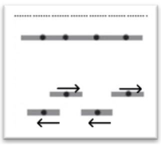
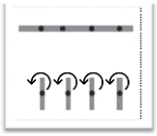
Ways of kinetic motion		
Façade type	**Illustration**	**Description**
Sliding		These façades contain certain elements such as shutters or louver systems that have the ability to slide either horizontally or vertically thus, creating a playful and dynamic sun shading design.
Folding		Folding façade elements change the appearance of the façade dramatically by giving it a third dimension. This type is more complex and requires a management system in order to control the movement of the shading elements installed on the façade.
Layering		This type of façade doesn't include changes in its original perimeters. It can contains from one to several movable layers. It is this motion that makes these facades act as shading systems. Kinetic parts can be installed between two glass panels which makes the façade very compact comparing to other types of kinetic facades.
Rotating		In this type of kinetic façade certain elements such as shutters, louvers, lamellae etc. has the ability to rotate either vertically or horizontally at specified angles and thus acting as shading systems. Rotating façade is one of the more common and used kinetic façades.
Scaling		Scaling facades have the ability to scale certain elements in the facade by expanding and shrinking its specified patterns, thus creating devices that prevents direct light from entering the space.

Table 1: Ways of kinetic motion in kinetic facades

3) ***Means of kinetic motion:***

The "means" of kinetic motion refers to the driving mechanism behind the ways of kinetic motion.
So, in order for motion to occur in kinetic systems, their elements need to have some kind of actuation. Generally, there are four different methods for actuation in kinetic architecture: pneumatic, hydraulic, electrical and chemical actuation.

Pneumatic actuators convert the energy from compressed air into motion. Generally, these actuators are composed from a piston within a cylinder. When compressed air is pumped into the cylinder either by external compressor or a manual pump, the pistons move inside the cylinder creating a motion. This motion can be either linear or rotary depending on the type of the actuator. [7]

Hydraulic actuators are very similar to pneumatic actuators with the difference that they use fluid pressure instead of air to generate motion. They are mainly composed of a reservoir that stores the fluid; a pump that pressures the fluids through the system; valves that control the flow; and a piston within a cylinder chamber that converts the flued pressure into motion. [8]

Electrical actuators convert electrical energy into mechanical energy. They are typically composed of an outer casing called a stator that through its north and south magnetic poles provide a strong magnetic field; an armature which is cylindrical core that rotates within the stator; a commutator that rotates with the armature; fixed brushes that are in contact with the commutator and carry the direct current resulting in the necessary motion. When the electric current passes through the armature placed within the magnetic field of the stator, a force is created and causes the armature to move. [9]

Chemical actuators do not require any type of energy to create motion. The motion in this type of actuators is caused by change in the density of the contained chemicals. These actuators are mostly found in passive solar tracking devices and are based on the thermal expansion of chemicals within them. When there is equal illumination, the solar tracking systems will be stable. When the actuators are illuminated, the solar heat creates a gas pressure in the chemicals resulting in the movement of the solar tracking device in order to establish equal illumination again.

Means of kinetic motion	**Advantages**	**Disadvantages**
Pneumatic actuation	- Simplicity in manufacturing - Provides accurate motion - Low in cost - Lightweight and require minimum maintenance - Explosion and fire safety	-Pressure losses, air compressibility - Performance difficulties at low speed - Does not give uniform and constant speed of motion - Requires additional regulates and valves for more accurate control
Hydraulic actuation	- Rugged, suitable for high force applications - Higher horsepower to weight ratio - Provides constant motion without additional fluids Supplying	- Requires many additional parts such as: reservoir, pumps, noise reduction equipment, etc. - Possible flued leak - Liquid pollution, necessity for high cleanness service - Large and difficult to transport
Electrical actuation	- Higher control accuracy - Suitable for any force Requirement - Quiet, smooth, repeatable - Low operating costs - Easy to program and control - Low maintenance	- Not suitable for all environments - Complex structure - Overheating problems - Hight cost of its components
Chemical actuation	- Completely passive - No energy required - less expensive - low in maintenance	- requires direct sunlight contact - slow to react - imprecise in performance - should be manually adjusted several times a year - expensive shipping and installing

Table 2: Means of kinetic motion in kinetic facades

B. *Embedded computation*

It should be noted that the term kinetic envelope refers to the building's components that have the ability to set their mechanical parts in motion i.e., actuated. The motion in all the previously mentioned kinetic typologies should have some kind of control method. Actuators need a control system that understands incoming data from climate change and user interaction and converts it into actuation commands.

Embedded computation refers to computational control mechanism known as sensor technology which is responsible for analysing the various changing conditions and responding to them, by giving orders to the structural parts of the kinetic system. Embedded computation is based on actuators, computational processors and various information collectors such as sensors, cameras and microphones. ***Sensors*** are the devices that collects data and information from the physical environment whether inside or outside the building. ***Sensors*** can sense and record different changes depending on their type such as temperature, light levels, humidity, wind speed, noise, pressure, etc. They send the collected data to the processors and then monitor all the changes in the structures that occurs as a response to this data. ***Computational processors*** are the computer systems that receive the data from the sensors, analyse it and convert it into an adequate response with respect to the primary design requirements and then send commands to the actuators. ***Actuators*** are the devices that convert the energy that is usually pneumatic, electrical or hydraulic into motion creating changes in the configuration of the kinetic geometry as a result to the stimuli perceived by the sensors and triggered by the computational processor.

1) **Control Mechanisms**

Various level of machines may exist in different kinetic systems. Zuk (1970) classified level of machines according to their ability to adapt to different needs into: [2]

Single variable man control This is the first developed type. It was basically designed to execute repetitive procedures such as turning the machine on or off or increasing and decreasing its speed. These operations were performed by human control and in some cases the motive power of the machine was provided by men.

Multi variable-man control It was basically originated in 19th century. This type of machines is more sophisticated than the previous as it is more complex and can execute several operations at the same time or in sequence. These machines are also controlled by humans.

With Multi variable- automatic control, human control is replaced by computers where they have partial or full control of multi and various operations. The essential component in these machines are sensors as they are responsible for detecting various factors such as light, heat, pressure, sound, current etc. Computer controls are installed with backup systems and the ability to switch into human control in case of emergencies.

Multi variable- heuristic control has the ability to not only perform multivariable and automatic operations but also to learn from its previous experiences. Here computer controls are installed with heuristic capability and can perform adaptation. For instance, these machines are able not only to construct whole building completely but also to repair and reproduce themselves automatically.

2) Types of movement control

There are several types of control systems based on the intelligent device placement in relation to the movement mechanisms and motors. Each one of these systems has its own advantages, and the decision of which system should be used, depends on the transformation and movement features desired in the building. Fox and Bryant (2006) have categorized control mechanisms into six general types:

Internal control These systems have the ability to move mechanically by sliding or rotating due to their constructional configuration. They do not have any direct control device or mechanism as these systems totally rely on their internal constructional control. Deployable and transportable architecture belongs to this category.

Direct control the movement of this systems is resulted by applying one of the various sources of energy such as human energy, electrical motors or mechanical changes in response to environmental conditions. Each component of the direct control system is responsible for its own movement depending on its own set of desired parameters. In this system, various components do not work in conjunction with each other as they are only responsible for themselves. For instance, a system with two movable openings on different walls may not open or close at the same time. In this case each opening is responsible for its movement.

In-direct control the movement is actuated indirectly through a sensor feed-back system. These systems depend on a sensor that detects change and then sends a massage to a control device. The control device then gives an on/off instruction to an energy source to induce the movement. Indirect control system is a singular self-controlled response to a unique stimulus. These systems are more advanced than the direct control systems as each one of their components sends information into a centralized control device that analyses the data and then instructions to each component.

Responsive in-direct control is similar to the indirect control system, but in this system the device control can receive input data from numerous sensors. After the control device processes the information obtained from the inputs, it makes an optimized decision and sends it to the energy source to induce the movement of a singular object.

Ubiquitous responsive in-direct control movement in this system is actuated by several autonomous sensor/motor (actuator) pairs that act together as a networked whole. The control system in this type requires a feedback algorithm that is predictive and auto-adaptive and will enable individual components to react respectively one to another.

Heuristic responsive in-direct control the main difference between this type and the other indirect control types is that here the control mechanism has learning capacity. This system has the ability to learn from previous successful experimental adaptation to optimize a system in response to environmental changes. It gathers information to respond efficiently to changing environment patterns while learning the most effective response of the system components.

C. Adaptable architecture

Adaptation in architecture can be defined as the ability of buildings and their components to adjust and reconfigure themselves in response to the various human needs and climate changes. Since kinetic architecture is a combination of flexible structure and intelligence (embedded computation), it allows buildings incorporated with kinetic systems to sense environmental and occupant need changes and respond to them by performing physical modifications in their structure i.e., adapt. Computer systems will receive and interpret the environmental circumstances and induce structure movement. Through rotating, folding, scaling and translation of building components, the kinetic building façade can anticipate and react to environmental condition changes. Architectural application for adaptive kinetic facades varies according to the initial reason for adopting kinetic system in the building. For instance, kinetic facades may be adaptable to one or several climate sources such as solar radiation, daylight, airflow, etc. Most of the adaptive kinetic facades fall into two main categories: solar and airflow adaptable kinetic facades. [3]

1) Solar adaptable kinetic facades

Solar adaptable kinetic facades can be categorized into three types: solar heat, solar light and heat, and solar electricity adaptable facades.

Solar heat adaptable kinetic facades: aim to maximize the admission of solar heat during cold months and decrease solar heat gains during summer. Whereas Solar light and heat adaptable kinetic facades: regulate the quantity and the quality of the light entering the building. These facades control indoor illuminance levels, light distribution, glare and outside views. They are equipped with properties that allows them to sense and respond to the outdoor lighting conditions by providing the space with adequate amount of daylight and solar heat. Solar electricity adaptable kinetic facades are incorporated with active solar energy techniques that aim to generate electricity from solar energy. This type involves building integrated photovoltaics that have kinetic characteristics often called heliotropic sun tracking systems. These systems have the ability to move according to the sun position in order to catch maximum amount of solar energy.

2) ***Airflow adaptable kinetic facades***

These facades can be categorized into two types: Natural ventilation and wind electricity adaptable kinetic facades.

Natural ventilation adaptable kinetic facades aim to provide indoor environments with adequate outside air. This type of kinetic facades regulates the quality of the entered air in terms of temperature, moisture, smell, etc. It offers adequate indoor air quality, better thermal comfort and in some cases, it may enhance the daylight performance of the building too. Whereas Wind electricity adaptable kinetic facades: are usually incorporated with small wind turbines that produce electricity from converting wind's kinetic energy into electrical power.

III. LITERATURE BASED CASE STUDIES

After demonstrating the kinetic design key elements which included structural engineering, embedded computation and adaptive architecture, seven case studies are presented and analysed in terms of their kinetic design. The chosen case studies are famous examples of the recent developments in kinetic façade design. They were chosen based on their main way of motion, in order to cover most of the kinetic types used around the world and under different climates.

A. *Criteria of analysis*

The analysis of each case study will be conducted through the following criteria:

General information: that includes the project's location, architects, construction year, main function, total floor area, floor levels and building cost.

Building description: which includes information about the building (such as the purpose of its construction) and a brief overview of the type of spaces exciting in the project.

Location and climate description: which includes the precise location of the project and a general overview of the location's climate in order to understand the purpose of the kinetic façade and the way it works within these specific environmental conditions.

Building concept: which demonstrates the concepts and the ideas that stands behind the design of the project and its kinetic facade.

Kinetic façade description: that describes in detail the structure of the kinetic facade and its various components. It also describes the way the kinetic façade works and the main purpose and outcome of its use.

Kinetic design key elements: in this part, the key elements of each project's kinetic facade will be examined and it will include:

Structural engineering: including the kinetic structure type, ways of kinetic motion and means of kinetic motion.

Embedded computation.

Adaptive architecture.

B. *Descriptive Analysis of the case studies*

1) ***Arab World Institute***

Fig.1: The Arab World Institute

General information

Location: Paris, France

Architect: Jean Nouvel

Year of construction: 1987

Main usage: Multi-functional cultural centre

Total floor area: 16, 894 m²

Stories: 12

Building cost: 100,000,000 €

Building description

The building was constructed from 1981 to 1987 and was funded by both Arab states and France. The design of Arab World Institute came as a result to a design competition called by the French Government as a means to strengthen the connection between Arab culture and French people. The design competition was won by Jean Nouvel, who concentrated on combining the traditional Arabic architecture with the modern architecture style of France. The building contains museum of Arab art and civilization, library, auditorium, conference hall, restaurant, meeting rooms cafeteria and other support facilities and offices.

Location and climate description

The Institute is located on Rue des Fosses Saint Bernard in Paris, France. Its south façade faces the Saint-Louise island and follows the curve shape of the river waterway. While its north façade faces la Cite the old settlement of Lutece and l'Ile St. Louis.

The climate of Paris is mild and generally warm and temperate. The average annual hours of sunshine in Paris is 1779 hours. As a result, a shading system was needed to be installed on the building's south facades.

Building concept

The design of the building's south façade was inspired by the traditional Arabic screen called "Mashrabiya". The mashrabiya is an oriental opening composed of carved wood latticework and it is used ever since the Middle Ages. The main purpose of these traditional screens was to provide the indoor spaces with light and air while in the same time gives privacy to the occupant. In the design of the Institute, Jean Nouval mimics this traditional Mashrabya screens by transforming its lattice components into glass and steel construction patterns.

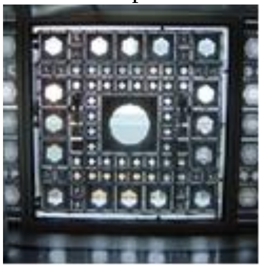


Fig.2: The Mashrabya concept

Fig.3: The traditional Mashrabya

Kinetic façade description

The Institute's south façade is divided into 240 sub grids which contains photosensitive mechanical devices operating on the principle of camera lens. Each sub grid consists of a small grid of shutters with various shapes and sizes, and a circular large shutter that is set in the centre of the grid. The large and the small shutters can expand and contract through rotational movement creating the scale effect. Depending on the light intensities in the building, shutters open or close gradually. Throughout the different phases of the shutters movement, a shifting geometric pattern is formed with squares circles and octagonal shapes. The smaller the openings on the diaphragms are, the less light will enter the space. The building contains approximatively 25.000 light sensitive diaphragms on 1600 elements which are all connected to a central computer. The Façade is considered to be an innovative and successful shading system. However, it received several critiques due to mechanical problems and expansive maintenance of the shutters additionally heat load was not reduced as much as it was expected.

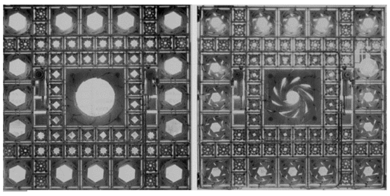


Figure 4: The scaling movement of the shutters.

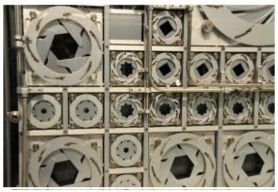


Figure 5: Detail of the movable shutters

Kinetic design key elements

1) Structural engineering

   Kinetic structure type: this kinetic system falls under the embedded kinetic structure type as the system is specifically designed for this building and it is responsible for adapting the whole building to the changing environment factors.

   Ways of kinetic motion: this façade can be classified as a scaling façade because as the shutters of the kinetic system open and close, the shape and the size of the opening changes through shrinking and expanding similarly to the lens of a camera.

   Means of kinetic motion: this kinetic system uses electrical actuation as the shutters movement is operated by electronically controlled servomotors that receives commands by the computer to either open or close the shutters.

2) Embedded computation

   The type movement control used in this facade is ubiquitous responsive in-direct control.

   This kinetic system is composed of high-tech photosensitive mechanical devices that sense the intensity of the sunlight incident on the facade. All the shutters are connected and controlled by a computer system that gives order depending on the data collected from the sensors.

3) Adaptive architecture

   This is a solar and heat adaptable kinetic façade, as the kinetic shutters control the amount of light and heat that enters the space. Solar intensity is the stimuli used to control the shutters. If sunlight levels are too high compared to the initial defined setpoint, the shutters are commanded by the central computer to close. However, the computer ignores the solar radiation condition and command all the shutters to open in case the outside temperatures falls below 5°C to maximize the solar heat gain indoor. These shutters are electronically controlled to permit only 10 to 30% of daylight, thus preventing the occurrence of glare or visual discomfort and maintain the indoor temperature within the favourable limits.

2) Kiefer Technic Showroom

Figure 8: Kiefer technic showroom

General information

Location: Bad Gleichenberg, Austria
Architect: Ernst Giselbrecht Partner ZT GmbH
Year of construction: 2007
Main usage: Commercial
Total floor area: 545 m²
Stories: 2

Building description

Kiefer Techinc is a company that manufactures functional furniture, cooling and heating devices, door systems and other. The building is designed as a showroom for the equipment produced by this company. The construction started in the spring of 2006 and finished in the summer of 2007.
The building is composed of two floors that includes offices and exhibition spaces.

Location and climate description

The Kiefer showroom is located in Bad Gleichenberg, Austria. Bad Gleichenberg is a small town in the south of Austria. Its climate is familiar to be warm and temperate with average temperature between -1 in winter and 20 degrees in summer. The average annual sunshine hours is around 1820 hours per year.

Building concept

Previously, facades were characterized by their window configuration and number of axes creating some kind of hierarchy as the number of axis were determined depending on the importance of the worker in that space e.g. the director have more windows than the ordinary workers. As the facades nowadays can be entirely transparent, this type of hierarchy vanished. Although this transparency represents modern character where all workers are equally treated, the perception of indoor comfort varies between the different workers. For this reason, the architects designed the Kiefer showroom with dynamic façade that adapt and change its configuration depending on the outside changing conditions and the user needs. Thereby optimizing the indoor climate while allowing the users to control the amount of light they desire to enter the space.

Kinetic façade description

The south façade of the building is composed of two layers: inner static one made of glass and an outer dynamic skin. The dynamic shell consists of 112 metals covered with white plaster panels that run with electric motors responding not only to exterior conditions but also to user control. These panels fold and unfolds by sliding up and down when converting between different states of openness. As the sun moves throughout the day, the building constantly changes its configuration depending on the direction of the solar rays fallen on the façade. Additionally, the users can control all the panels as they please. Thus, the façade becomes a kinetic sculpture called “dancing façade” that changes and continuously presents new faces.

Figure 7: The different configuration of the kinetic facade.

Kinetic design key elements

1) Structural engineering

Kinetic structure type: this kinetic system falls under the embedded kinetic structure type as the system is specifically designed for this building and it is responsible for adapting the whole building to the changing environment conditions and user needs.

Ways of kinetic motion: this façade is a folding façade as its panels fold and unfold by sliding up and down creating a third dimension.

Means of kinetic motion: this kinetic system uses electrical actuation as the movement of the 112 panels is powered by 56 electrical engines

2) Embedded computation

The type movement control used in this Kiefer showroom facade is ubiquitous responsive in-direct control. The kinetic system has an electronic control that gives commands to the 56 electrical engines which are connected together but can act individually in respect to one another. The command from the electronic control can be override by users as they can give commands depending on their comfort needs.

3) Adaptive architecture

Kiefer showroom façade is also a solar and heat adaptable kinetic façade as the kinetic panels control the amount of light and heat that enters the space. The panels change their configuration in response to the intensity of the solar light fallen on the façade. It also allows the user to control movement of the panels, for example, users can close the panels if they feel disturbed by the intensity of the light. However, the building was criticised with the claim that the façade is more a showcase for the company products than a responsive shading system. Additionally, the sustainability of this building might be questioned as the 56 electrical motors requires a large amount of electrical power within the favourable limits.

3) Al Bahr Towers

Figure 8: Al Bahr tower

General information

Location: Abu Dhabi, UAE
Architect: Aedas Architects
Year of construction: 2012
Main usage: Office building
Total floor area: 56,000 m²
Stories:26
Building cost: 195,000,000 €

Building description

Abu Dhabi Investment Council (ADIC) made an international competition to design a new headquarters of the Council board. The project submitted by Aedas architects together with Arup company was selected. The construction began in March 2009 and was completed in 2012.

The project is composed of two 26-storey towers with height of 145m that are designed based on traditional Arabic architecture. The towers mainly contain office spaces in addition to some supplementary spaces such as auditoria, gymnasium, catering, prayer rooms and plantrooms. A two-level basement connects the towers and provides car parking spaces, large green areas, a secure vault and various storage and catering spaces.

Location and climate description

Al Bahr towers are located in the capital of the United Arab Emirates, Abu Dhabi. They are positioned at the south-east part of the city at the intersection of Al Saada street and Al Salam street. Abu Dhabi is familiar with its hot desert climate where the average temperatures during the summer months are above 38 °C whereas the average temperatures during the cooler period are around 18 °C. Abu Dhabi is considered to be one of the sunniest countries on earth where the average annual hours of sunshine per year is 3609 hours with an average of 9.9 hours of sunshine per day. [10]

Building concept

The two towers have a cylindrical form with circular plans which grants maximum usage of floor area and allows outside view in all direction. However, this type of design causes a large amount of heat gain under the climate of Abu Dhabi as the façade is open in all directions. For this reason, the architects designed an innovative external responsive shading systems. Similarly to the Arab World Institute, the design of this shading system was derived from the traditional solar screen "Mashrabiya". The steel lattice work sunscreens are placed over the entire glass facades except for the north facing parts

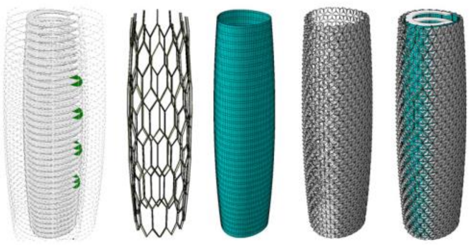


Figure 9: The Al Bahr Towers structure concept.

Kinetic façade description

The façade of the Al Bahar tower in Abu Dhabi is a very complex kinetic folding façade. It is made of 1000 individual shading devices which present an alternative to the traditional wood screen "mashrabiya". Each shading device is a triangle shape screen coated with micro fiberglass supported in a structure of hexagons which create a folding and unfolding movement when responding to the changing environmental conditions. This façade has three kinetic states: totally closed, mid-open and fully open which are programmed to respond to the movement of the sun as a way to reduce glare and solar heat. The mashrabiya elements are organized and grouped in sectors and actuated by sun tracking software that controls the folding and unfolding movement of the elements according to the sun position. The shading systems also allow the manual control of the opening or closing the individual mashrabiya screen.

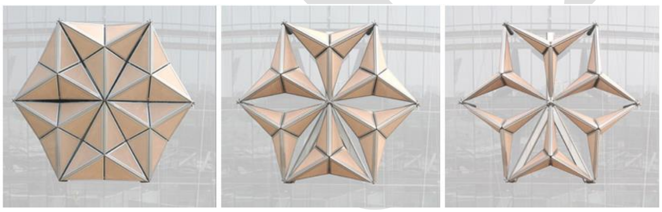


Figure 10: The three states of the folding movement: closed, mid opened and opened

Kinetic design key elements

1) Structural engineering

Kinetic structure type: this kinetic system falls under the embedded kinetic structure type as the system is specifically designed for this building and it is responsible for adapting the whole building to the changing environment conditions and user needs.

Ways of kinetic motion: Al Bahr towers have folding kinetic façades as their mashrabiya screens fold and unfold like umbrellas depending on the sun path.

Means of kinetic motion: this kinetic system uses electrical actuation as the mechanism of the mashrabiya screens are based on liner electrical actuator that receives commands from the control system to set the screens in motion.

2) Embedded computation

Similar to the previous projects, Al Bahr towers have responsive in-direct movement control system. The control system is connected to solar radiation sensors that track the movement of the sun and an anemometer. It gives orders to the liner actuators to progressively open and close in response to a pre-programmed sequence that is calculated to prevent direct sunlight and solar gain to rise more than 400 watts per meter. The data collected from the various sensors is used to command the screens to open in case of prolonged overcast conditions, or close in case the wind speed is greater than the maximum set threshold. [11]

3) Adaptive architecture

The main purpose of this project is to protect the interior space from direct sunlight and unwanted heat gains, thus, the façade of the towers can be classified as a solar and heat adaptable kinetic facades. Through the use of this innovative kinetic system, it was found that heat gains and glare occurrence were reduced by 50% whereas the daylight penetration was improved leading to less dependence on artificial lighting which resulted in CO_2 emissions reduction by 1,750 tonnes per year.

4) *Q1 ThyssenKrupp Headquarters*

Figure 8: ThyssenKrupp Headquarters

General information

Location: Essen, Germany
Architect: JSWD Architekten, Chaix & Morel et Associés
Year of construction: 2010
Main usage: Office building
Total floor area: 29,800 m²
Stories: 14
Building cost: 115,960,000$

Building description

ThyssenKrupp is a German company specialized in steel production and other industrial service products such as machines, car parts, high speed trains and submarines. The company decided to construct a new corporate quarter that accommodates around 2000 of its employees. The quarter contains a total of 13 building each dedicated to a specific usage. The Q1 building is the most important object in the quarter as it is the company's headquarters and the centre piece of the campus. It mainly contains office spaces except for the ground floor which is designed as a reception area. The building features a transparent central atrium that rises over 10 story height and is divided with numerous footbridges and mezzanines. However, what distinguishes this building is its adaptive sun shading system that is installed on the facades surrounding the office spaces.

Location and climate description

The new company quarter is located near the centre of Essen, Germany. The location was not chosen randomly as the company decided to return to its corporate roots where the first steel factory Fried. Krupp was built in 1811. The Q1 building is positioned in the northern part of the campus, about 300 meters from the main road.

Essen has a generally temperate climate with mild winters and cool summers. The warmest months are July and August with an average high temperature of 22.3°C while the coldest months are January and February with average low temperature of 2°C. Essen have an average of 1454 hours of sunshine per year.

Building concept

The aim of the design was to create a company headquarters that is open to employees and citizens and reflect the company policy of transparency, innovation and versatility. Another important objective of the design was to achieve energy efficiency and sustainable use of resources.

The Company exploited this project to demonstrate its innovation capabilities by using its own products and materials for the building construction. For instance, the sunshade elements of the shading system covering the façade is manufactured by the company. Additionally, more than half of the materials used in the construction were also fabricated by the company. The design of the shading device can be considered traditional but with innovative technological twist. It uses numerous small metal blinds positioned horizontally that can move around their vertical axis.

Kinetic façade description

The façade shading system is made of stainless sunscreen elements that consists of 3150 vertical twisting fins and approximately 400,000 horizontal overhangs bolted into them. All of these elements are centrally controlled by engines depending on the position of the sun. Each of the twisting fins that are connected to a central stud from both sides can twist independently and reach the position between 0° (widely open i.e. blocking direct sunlight) and 90° (perpendicular to the façade allowing maximum daylight penetration). Behind the shading system there is grids located between two floors that act as a catwalk which enables the opening of the windows and the façade maintenance process. There are a total of 1,600 liner motors that are responsible of the fins movement located in the grid.

Kinetic design key elements

1) Structural engineering

Kinetic structure type: this kinetic system falls under the embedded kinetic structure type as the system is specifically designed for this building and it is responsible for adapting the whole building to the changing environment conditions.

Ways of kinetic motion: Q1 Building has a rotating façade as the numerous metal shades rotate around their vertical axis.

Means of kinetic motion: The actuation in this kinetic façade is also electric as the movement of the blinds is actuated by liner motors installed in the grid. Each liner motor is responsible for the movement of two axels resulting in the rotating of both pair of blinds on each axle.

Figure 13: The rotating movement of the shading device in accordance to the sun's position

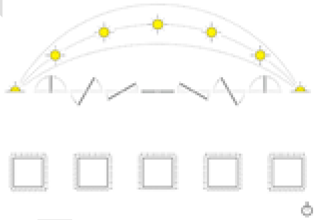


Figure 12: demonstration of the transition movements from the closed to the opened state of the facade

Figure 14: Detail of the stud with the twisting fins connected to it

2) Embedded computation

The Q1 kinetic façade also a have responsive in-direct movement control system. The building is installed with sensors that track the sun's position and radiance in addition it's seasonal movement and other weather conditions. The data collected from the sensors are sent to the control system to be analysed and then translated into orders. Orders are then sent to 1,600 electric motors to perform on of the three actions: close the blinds i.e. parallel to the façade, move the blinds in accordance to the sun movement, open the blinds i.e. horizontal to the façade.

3) Adaptive architecture

Tracking the sun position in addition to real-time measurements of weather conditions is basis of the shading system adaptiveness, thus the façade can be considered as a solar and heat adaptive kinetic façade. As the shading system move in accordance with sun movement, it prevents direct sunlight to get inside and consequently reduces heat gains while the slat surfaces of the blinds direct the incoming light deep inside the offices making them brighter even if the sun shading is closed. The sustainable strategies adopted in the building design including the kinetic façade prove that the energy consumption of the building is 58% lower than in similar building. Also, the building's ecological footprint is described by 27% less CO2 emissions than similar office buildings. [4]

*5) **Media-ICT***

Figure 15: Media-ICT

General information

Location: Barcelona, Spain
Architect: Enric Ruiz-Geli from Cloud 9
Year of construction: 2009
Main usage: mixed usage
Total floor area: 3,572 m²
Stories:10
Building cost: 24,500,000€

Building description

The MEDIA-TIC was designed as a part of the 22@Barcelona district with the aim to create a symbolic centre of the digital world that brings various parties of the world of information technology and media into one place. The building has a cubic shape with dimensions 40*40*40 meters. The lower floors are designed as large public spaces that will be used for exhibitions, workshops and large auditorium with capacity of 300 people as well as restaurant and coffee spaces. The higher floors are dedicated to office spaces, galleries, communication centres, installation supports and so on.

Location and climate description

The MEDIA-TIC building is located in Barcelona, Spain, within in the 22@Barcelona district at the intersection of Carrer Roc Boronat and Carrer Sancho de Avila. The district is a project established by the city hall, with the aim to transform the industrial area into innovative district with flexible and unique spaces, dedicated to knowledge and technology.

Barcelona has a humid subtropical climate with hot summers and mild winters. The average temperature in the hottest months is 22°C whereas the average temperature in the coldest months range between 0 and 18°C. Barcelona has an average of 2437 hours of sunshine per year. It is also familiar with its strong solar radiation that causes heat gain problems in buildings, thus making the use of shading devices, a must.

Building concept

The main purpose of the MEDIA-TIC building is to exhibit a combination of creative spaces, environmental awareness and a display of new technologies, that should be obtainable by all citizens. In the eyes of the Cloud 9, architecture should be a technological stage in which innovative materials, nanotechnology, connectivity, bits are one of the most important elements of design. This concept is evidential in the design of MEDIA-TIC as it is a digital design constructed using CAD-CAM digital processes.[19]

For instance, its construction can be called anything but an industrial typical one. It is a digital structure with construction of information, that allowed the design of an innovative complex façades, using a new material called ETFE.

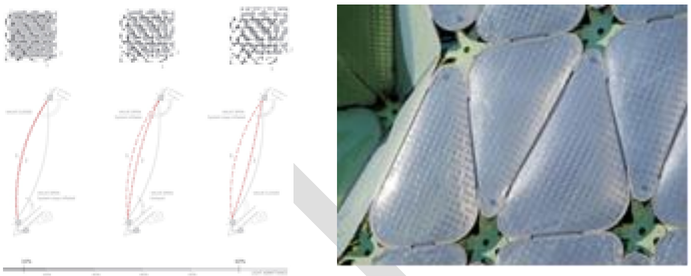


Figure 16: The different states of the Southeast façade depending on the air flow.

Kinetic façade description

The kinetic features can be found on the Southeast and the Southwest facades, which are mostly exposed to direct sunlight and probable heat gains.
The Southeast façade is covered with a membrane of lightweight ETFE air pillows that are responsive to heat temperature and incident sunlight angle. The pillows consist of three layers of plastic and two air chambers between them. The outer layer is transparent, the middle layer is printed with a ceramic frit pattern, while the inner layer is printed with a reverse frit pattern. When the ETFE pillows are filled with air, the patterns of the both layers are joint together to create blurred surface that blocks solar gains. When the air cavity is deflated, the two layers are separated allowing solar light to get in. The ETF air pillows of the Southwest façade are filled with nitrogen during the period of the day when the sun is at its peak, thus changes the transparent façade into translucent surface that blocks around 90% of the sun's radiation. [5]

Figure 17: The opaque state when filled with nitrogen (left) and the transparent state (right) of the Southwest façade.

Kinetic design key elements

1) Structural engineering

Kinetic structure type: this kinetic system falls under the embedded kinetic structure type as the system is specifically designed for this building and it is responsible for adapting the whole building to the changing environment conditions.

Ways of kinetic motion: MEDIA-TIC Building has a layered façade as the ETFE air pillows are composed of three layers, two of them are printed with different patterns.

Means of kinetic motion: the actuation here is also electric as the two kinetic facades are installed with a grid of small electrical motors that activate the pneumatic mechanisms to inflate or deflate air inside the air chambers depending on the command received from the main control system.

2) Embedded computation

The MEDIA-TIC façade has a responsive in-direct movement control system. The building is installed with more than 500 sensors with different specifications that collect environmental data. There are temperature, motion, luminance, humidity, fire and other sensors. A building management system is what controls all the building facilities. It communicates with each facility and collects information from its installed sensors, then it analysis the data and sends actuation commands depending on the analysis. [6]

3) Adaptive architecture

As mention in the previous section, this is an example of a solar heat adaptable kinetic façade. Each ETFE air pillow is installed with sensor that measures the incident solar heat and then sends it to the control system. Depending on these measurements, the control system gives order to either inflate or deflate air inside the pillow chambers. The building is predicted to be nearly a Net Zero Building with total of 95% CO_2 reduction of each 55% comes from the installation pf the ETFE sun pillows and other 10% related to smart sensors installation. [6]

1) RMIT Design Hub

Figure 8: ***RMIT Design Hub***

General information
Location: Melbourne, Australia
Architect: Sean Godsell
Year of construction: 2012
Main usage: Education and accommodation
Total floor area: 13.000 m²
Stories: 10
Building cost: 80,000,000€

Building description

The main purpose of the building is to provide a creative environment for exchanging ideas and expertise among a range of design fields such as fashion, industrial design, architecture, fine art textile and other. It provides research facilities and accommodation for postgraduate students of these fields. The Hub is composed of two buildings with central forecourt in between. It offers various spaces dedicated for researching, exhibiting, archiving and discussing designs. It also provides research warehouse spaces, seminar rooms, café in addition to a 180-seat lecture theatre and 200-seat multi-purpose space.

Location and climate description

The Design Hub is located in Melbourne, Australia at the north-west corner of Victoria and Swanston streets. The climate in Melbourne is temperate with hot summer, mild springs and autumns, and cool winter winters. Average summer temperatures are between 14 – 25.3°C whereas winter temperatures are 6.5 – 14.2°C. The average annual hours of sunshine are 2,200 hours.

Building concept

The main concept of the Design Hub was to provide flexibility and adaptability. For this reason, it was supplied by numerous environmentally sustainable design features such as rain water harvesting, internal waste management system in addition to the innovative kinetic façade. The Hub's interior was designed with large open spaces to encourage research groups to meet and discuss their ideas with each other.

Kinetic façade description

The Design Hub's façade is probably one of the most complex and expensive kinetic façades. The interesting thing about the façade is not only its unusual design, but also its capability of collecting solar energy through photovoltaic cells that are installed on the shading system. Its numerous sells were designed to be easily replaced in case new cells were improved. In addition to the incorporated cells, the shading system also includes evaporative cooling and fresh air intakes that enhance the indoor air quality and reduce the energy costs. The complex façade is made of two skins: double glazed inner skin and an operable outer skin shading system that is set out about 700mm from the building's certain wall. The shading system consists of 774 panels with a size of 1.8 by 4.8 meters which contain 21 glass disks within steel cylinders supported on a secondary galvanized steel frame. Each panel contains 12 movable glass disks and 9 static ones fixed to either a horizontal or vertical aluminium axis which is hooked to the outer face of the cylinder. Automated through a management system, the movable panels rotate according to the sun direction. For instance, these panels are programmed to close when direct sunlight hits the façade, preventing it to reach the main certain wall. [12] [13]

Figure 19: The Rotating movement of the disks.

Kinetic design key elements

1) Structural engineering

Kinetic structure type: this kinetic system falls under the embedded kinetic structure type as the complex kinetic is specifically designed for the RMIT design hub.

Ways of kinetic motion: The Hub's façade is a rotating kinetic façade as it has numerous glass disk that rotate in accordance with movement of the sun.

Means of kinetic motion: The façade uses electrical actuation as there are various separated electrical actuators that are controlled by the management system of the building.

2) Embedded computation

The RMIT design hub facade has also a responsive in-direct movement control system. The building has a sophisticated building information system that allows the disks to track the movement of the sun. Data collected from sensors is send to the central control rooms located on each floor of the building. The control system sends order to the electrical actuators that enable the motion of the disks.

3) Adaptive architecture

The RMIT design hub has also a solar and heat adaptive kinetic façade. The circular glass panels track the sun and shatter the direct solar light fallen on the glass thus preventing any solar heat gain and glare occurrence. The RMIT recently announced that the current glass panels will be replaced with new panels containing photovoltaic technology to generate electricity from the solar energy. The kinetic façade was specifically designed with the ability to change and replace panels to incorporate new advances in solar technology that will be discovered in the future. [14]

2) *Stony Brook University Simons Centre*

Figure 21: The Stony Brook University Simons Centre

General information

Location: New York, USA

Architect: Perkins Eastman

Year of construction: 2010

Main usage: Geometry and Physics Science center

Total floor area: 3,200 m²

Stories: 6

Building description

The centre is composed of two building masses: a brick mass with a strip shape located on the northside connected to the neighbouring existing buildings; a curved glass structure on the south side that forms the main façade of the centre. The two masses are connected together by a large atrium. The atrium is a three-story high and has a south facing clerestory and a reflective curved ceiling at the last floor providing sufficient natural daylight to the interior spaces. [15]

Location and climate description

The Simon centre is a part of the large campus of Stony Brook University located in New York, USA. New York is familiar with its unsteady climate throughout the year. Summers can be very hot and humid with temperatures range between 25°C and 30 °C. Winters tend to be cold and accompanied by snow falls. The average winter temperature is -5°C, however it can decrease dramatically to around -25°C. The average annual sunshine in New York is 2677hours. [16]

Building concept

The design of the building concentrates mainly on enhancing the quality of life while achieving sustainability. The centre is incorporated with various sustainable aiming strategies such as; rainwater collecting system that harvests the rain water which is then used in sanitary facilities and irrigation; sun shading systems that reduces the cooling needs; innovative mechanical systems for cooling that aims to reduce the overall energy demand and others. [15]

Kinetic façade description

One of the most interesting sustainable features of the centre is its kinetic adaptive façade called Tessellate panels. It is a floor to ceiling shading system and it is made of multiple overlapping layers of perforated metal panels, each panel spins around the other on a defined track. As the panels move, the visual effect of the screen is changed from hexagons to circles, squares and triangles. For maximum open daylight space, all the perforated patterns are aligned allowing natural light to penetrate whereas for realizing a shaded space, the pattern becomes an opaque mesh. The kinetic surface spans 38 square meters providing solar shading and attractive appearance. [18]

Figure 22: The changing patterns of the façade

Figure 23: Interior view of the kinetic facade

Kinetic design key elements

1)Structural engineering

Kinetic structure type: this kinetic system falls under the embedded kinetic structure type as the Tessellate system is specifically designed for the Simons centre.

Ways of kinetic motion: The Tessellate system serves as a layered kinetic façade for the Simons centre as it is composed multiple layers of panels.

Means of kinetic motion: the system uses electrical actuation as it uses a single electrical motor to move the various panels.

2) Embedded computation

The Tessellate kinetic facade has also a responsive in-direct movement control system. A one computer processor is responsible for the module's movements. It collects data from installed sensors and accordingly specifies the speed and acceleration of the layers' motion. A single small electrical motor receives the orders from the computer system and actuates the panels. The system allows personal control as it can be programmed for various purposes. [17]

3) Adaptive architecture

The Simon centre's façade is a solar and heat adaptive kinetic façade. The façade responses depending on the intensity of the light fallen on the façade. The centre was granted with Gold LEED certification as it was able to achieve 34% of energy use reduction and 79% reduction of water use in addition to other accomplished reductions.

IV. Analyzation and Evaluation of the Case Studies

A. *Descriptive Analysis of the case studies*

After demonstrating some of the most famous kinetic facades used in the world today, it is important to make an evaluation and a comparison of these cases in order to reveal which case has the most efficient performance. Although the main concern of the paper is the daylight availability performance of a façade, several other factors should be considered during the evaluation process such as sustainability, cost, construction complexity and others.

1) Case study analysis

Location

Four of the case studies are located in Europe (France, Austria, Germany, Spain). One is located in USA, other in UAE, and another in Australia.

Location	Europe	USA	UAE	Australia
Number of projects	3	1	1	1

Table 4: The location of the selected case studies

Climate

Four projects are located in countries with temperate climate and generally warm to hot summers (France, Germany, Austria, Australia). One project is located in humid subtropical climate with hot summers (Spain). Another project is located hot desert climate (UAE) while yet another one is located in Unsteady climate with hot summers. UAE has the most annual sunshine hours of 3609 hours followed by USA, Spain and Australia with annual sunshine hours of 2677,2437, 2200. Austria has 1820 hours whereas France has 1779 hours of sunshine per year. Germany comes with the least hours of sunshine compared to the case study's locations of 1454hours per year. It can be concluded that all of these case studies have warm to hot summers long hours of solar radiation, as a result these projects adopted kinetic façade as a means to block direct solar radiation.

Case study	Location	Climate	Annual sunshine hours
Arab World Institute	France	Temperate with warm summers	1779h
Kiefer Technic Showroom	Austria	Temperate with warm summers	1820h
Al Bahr Towers	UAE	Hot dessert climate	3609h
Q1 ThyssenKrupp	Germany	Temperate with warm summers	1454h
Media-ICT	Spain	Temperate with hot summers	2437h
Simons Center	USA	Unsteady with hot summers	2677h
RMIT Design Hub	Australia	Temperate with warm summers	2200h

Table 5: The Climate and the annual sunshine hours of the analysed case studies

2) Kinetic façade concept and elements

The case studies have various concepts behind the design of their kinetic facades. However, three of the case studies were inspired by the traditional shading element called "mashrabiya" in the design of their kinetic devices. Al Bahr towers façade uses triangle shape screens with folding movement to create the mashrabiya like kinetic façade. Whereas the Arab world institute uses photosensitive mechanical diaphragms to create the same mashrabiya look façade. In the Simon centre building, through the movement of several layers with different patterns, the facade also imitates the mashrabiya concept. Media-IC building used also various layers, however the concept behind the façade's design was to display the innovative technologies such as the TEFE materials with which the kinetic façade was constructed. The concept behind the Kiefer showroom was to create dancing façade by using folding shutters that as a result draw the viewers' attention to the company capabilities.

The Q1 thyssenKrupp façade is inspired by the traditional reflective shading blinds installed with technological capabilities that allow them to track sun's movement. The concept behind the RMIT hub was to create façade that promotes innovative and environmentally sustainable design which was achieved by using numerous rotating glass disks that can track the position of the sun.

Case study	Kinetic façade concept	Kinetic façade elements
Arab World Institute	Mashrabiya concept	photosensitive mechanical diaphragms
Kiefer Technic Showroom	Dancing facade	folding shutters
Al Bahr Towers	Mashrabiya concept	triangle shape screens
Q1 ThyssenKrupp	Classical blinds with technological twist	Twisting fins with horizontal reflective blinds
Media-IC	Display of new technologies	ETFE air pillows
Simons Center	Mashrabiya concept	multiple layers of metal panels
RMIT Design Hub	Display of innovative and sustainable design	rotating glass disks

Table 6: The concept and elements of the studied project's kinetic facades

Kinetic design key elements

1) Structural engineering

Kinetic structure type: All of the case studies fall under the embedded kinetic structure type as each one of the analysed kinetic systems are designed for the specific building, location and function it is installed upon.

Ways of kinetic motion: two of the case studies have folding kinetic facades, whereas another two have layered, and other two have rotating kinetic facades. There is only one case study with scaling kinetic facade

Means of kinetic motion: All of the case studies use electrical actuation to actuate their kinetic facades.

2) Embedded computation

All of the case studies have responsive in-direct movement control system as the kinetic facades are installed with numerous sensors and actuators that act together as whole network.

3) Adaptive architecture

All of the case studies are solar and heat adaptive facades except for the Media-Tic case study which has a solar heat adaptable façade as it maximizes the solar heat admission during winter and decreases solar gains during summer. Whereas the solar and heat adaptive facades regulates the quantity and quality of the light entering the building.

3) Daylight performance evaluation criteria

The adopted evaluation criteria are as following:

Solar shading

The solar shading performance of the facades will be evaluated i.e., analysing the amount of shading each case study provides to the space.

✓✓ The façade provides excellent solar shading.
✓ The façade provides sufficient amount of solar shading.
✓ The facade does not provide enough solar shading.
× The façade does not provide any solar shading.

Glare control

This aspect evaluates the performance of each case study in terms of preventing the occurrence of glare. It explores weather the kinetic system was able to prevent glare or it was only capable of providing certain amount of shading.

✓✓ The façade prevents any glare occurrence.
✓ The façade prevents partly glare occurrence.
✓ The facade does not adequately prevent glare occurrence.
× The façade does not provide any glare protection.

Daylight Redirecting

This criterion investigates the ability of the case studies to redirect daylight i.e., the system ability to provide daylight while blocking direct solar light to enter the space.

✓✓ The façade can redirect excellent amount of daylight
✓ The façade can direct good amount of daylight
✓ The facade can redirect only small amount of daylight.
× The façade does not allow any solar redirection.

Outside view

The case studies will be compared in term of their ability to provide external view while shading the space from unwanted solar radiation.

✓✓ The façade allows efficient outside view
✓ The façade allows partial outside view
✓ The facade does not allow enough outside view.
× The façade does not allow any outside view.

Energy efficiency

The creation will compare the amount of energy used and saved by the kinetic façade adopted in the case study i.e. Did the kinetic façade realized any energy savings and thus did it enhance the sustainability of the building?

✓✓ The façade achieves excellent efficiency.
✓ The façade archives good energy efficiency.
✓ The facade does not give enough energy savings.
× The façade is not energy efficient at all.

Complexity

This aspect evaluates and compare the level of the construction complexity of each kinetic system i.e. Did it have numerous, large or heavy parts or was it just simple system composed of several simple parts?

The façade is composed of simple parts
The façade is relatively simple
The façade is relatively complexed
The façade is extremely complexed

Cost

The cost of each case study will be compared. The cost creation includes constriction cost and maintenance needs of the kinetic facade costs.

- ▮ The façade can be considered low costed.
- ▮▮ The façade is relatively not that expensive.
- ▮▮▮ The façade is relatively high costed.
- ▮▮▮▮ The façade is extremely expensive.

4) *Case studies daylight performance evaluation*

The Kiefer Technic Showroom kinetic façade provides excellent solar shading and appropriate glare control however it does not have the ability to redirect daylight which can cause dimmed spaces when the shading device is closed. The outside view is also limited especially when the kinetic façade is half closed or closed. The façade is not complex compared to other however it has relatively high costed and do not achieve sufficient energy saving. Al Bahr Towers kinetic façade provides excellent solar shading and glare control however its extremely expensive and have a very complex structure. Similarly, to The Kiefer façade, this shading system does not redirect light and provides limited outside view. However, it achieves good energy savings.

The kinetic facade of the Simons Centre gives good solar shading, glare control and outside view. However, it does not redirect daylight and gives minimum energy efficiency. Although it is structure is not complex, its construction and maintain costs are relatively high. Media-ICT kinetic façade similarly to the Al Bahr Towers provides excellent solar shading and glare control and is not complex or expensive as much as Al Bahr façade is. It also achieves good energy savings but the outside view is very limited when it is in the opaque façade and it does not redirect light.

Q1 ThyssenKrupp provides excellent solar shading, glare control, energy savings. Unlike the other case studies, this façade provides good outside view and redirects daylight. However, the façade is considered relatively complex and high costed. RMIT Design Hub kinetic façade gives excellent solar shading, glare control, and energy savings. Nevertheless, it allows only limited outside view and does not have the possibility of daylight redirecting. The facade is extremely complexed as it contains numerous parts, consequently its construction and maintains costs are high. Kiefer Technic Showroom provides excellent glare control however it is not considered a good shading device. Also, the façade does not redirect daylight and provides only limited outside view. It is a very complex façade and its construction and maintains costs are very high, additionally it does not give enough energy savings. The comparison table shows that the rotating façade of the ThyssenKrupp Quarter Essen Ql building is probably the most efficient kinetic façade between the demonstrated precedents as it solves all the evaluation requirements that include solar shading, glare control, daylight redirecting, outside view availability and energy efficiency. Although it is considered to be relatively complex than other kinetic façades, the construction and the maintains costs are considerably more economical.

Type	Case studies	Solar shading	Glare control	Daylight Redirect-ing	Outside view	Energy savings	Comple-xity	Cost
Folding		✓✓	✓	✗	✓	✓ (yellow)	▮▮	▮▮▮
Folding		✓✓	✓✓	✗	✓ (yellow)	✓	▮▮▮▮	▮▮▮▮
Layered		✓	✓	✗	✓✓	✓ (yellow)	▮▮▮	▮▮
Layered		✓✓	✓✓	✗	✓ (yellow)	✓	▮▮▮	▮▮
Rotating		✓✓	✓✓	✓✓	✓	✓✓	▮▮▮	▮▮▮
Rotating		✓✓	✓✓	✗	✓ (yellow)	✓✓	▮▮▮▮	▮▮▮
Scaling		✓ (yellow)	✓✓	✗	✓ (yellow)	✓ (yellow)	▮▮▮▮	▮▮▮

Table 7: Comparison between the different kinetic façade types

V. CONCLUSIONS

From the case studies' analysis and evaluation, it can be concluded that:

1. Kinetic facades can be used in different environments, but are mostly used in hot desert and temperate with warm to hot summer climates as a mean to reduce heat gain and visual discomfort.
2. When designing a kinetic façade, three key elements need to be taken into account: Structural engineering which include kinetic structure types ways and means for kinetic motion, embedded computation and adaptive architecture.
3. There are three types of kinetic structures, however most of the kinetic façades used nowadays fall under the embedded kinetic structure type and use electrical actuation to operate their kinetic parts.
4. Folding, Rotating, and layered kinetic facades are the most used way of kinetic motion type. Whereas sliding and scaling facades are the most unfavorable.

5. Most of the kinetic facades use responsive in-direct movement control system and fall under the solar and heat adaptive architecture.
6. Although kinetic facades will increase construction and maintains costs, they can dramatically achieve energy efficiency by reducing heat gains during summer, maximizing solar gains during the cold months, providing adequate daylight by getting the most of natural resources such as solar light.
7. ThyssenKrupp Quarter Ql kinetic façade provides the best daylight performance comparing to the other examined case studies. The horizontal blinds fixed to the twisting suds do not only block unwanted solar light, but they also redirect light into the space, thus compensating the blocked direct solar light with indirect natural light. Additionally, this kinetic system allows sufficient outside view which can be hard to achieve in many kinetic facades.

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