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Comparative Analysis between Different Proposed Responsive Façade Designs for Reducing the Solar Radiation on the West Façade in the Hot Arid Region

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***Abstract*—**Designing buildings which are sustainable and can control and reduce the solar radiation penetrated from the building facades is such an architectural turn. One of the most important methods of saving energy in a building is carefully designing its facade. Building's facade is one of the most significant contributors to the energy budget as well as the comfort parameters of a building. Responsive architecture adapts to the surrounding environment causing alteration in the envelope configuration to perform in a more effective way. One of the objectives of the responsive facades is to protect the building's users from the external environment and achieve a comfortable indoor environment. Solar radiation is one of the aspects that affect the comfortable indoor environment, as well as affects the energy consumption consumed by the HVAC systems for maintaining the indoor comfort conditions. The aim of the paper is to introduce and comparing between four different proposed responsive façade designs in terms of solar radiation reduction on the west façade of a building located in the hot arid region. In addition, the paper highlights the reducing amount of solar radiation for each proposed responsive facade on the west façade. At the end of the paper, a proposal is introduced which combines the four different axes of movements which reduces the solar radiation the most. Moreover, the paper highlights the definition and aim of the responsive architecture, as well as the focusing on the solar radiation aspect in the hot arid zones. Besides, the paper analyzes an international responsive façade building in Essen, Germany, focusing on the type of responsive facades, angle of rotation, mechanism of movement, and the effect of the responsive facades on the building's performance.

***Keywords*—**Kinetic facades, mechanism of movement, responsive architecture, solar radiation.

I. Introduction

THE building sector plays a great role in the non-renewable energy consumption resulting in polluting the environment, emitting greenhouse gasses and changing the climate. In order to achieve a sustainable society, the energy consumed by buildings needs to be reduced. The Intergovernmental Panel on Climate Change in 2007 stated that the building sector consumes energy more that the transport and the industrial sectors. It also stated that, it is one of the sectors that large amount of energy can be saved from [1]. Improvements in the materials and the mechanical systems installed have made it possible to increase the buildings efficiency and decrease the energy consumption. Building's main purpose is protecting the occupancies from the external surrounding environment and achieving comfortable indoor environment. It was designed to deal with the environmental alteration surrounding it [2].

Nowadays, large numbers of buildings are designed without taking into considerations the surrounding environmental conditions. The development of building technology results in designing buildings that depend on additional systems during large periods of the year. Intensive HVAC (Heating, ventilation and air conditioning) system is used to reduce the unwanted conditions and to maintain a comfortable indoor environment. This system requires advanced control systems and energy input to follow the changing conditions, while the building envelope is left static mostly as a surrounding barrier. The building envelope, which is the outer skin of the building, is the layer of maximum thermal exchange between the indoor and the outdoor environment. The building envelope is subjected to cyclic changes in the exterior climate through day and night and seasonal periods. Thus, the skin of the building should be designed taking into consideration saving the energy as well as the surrounding changes [3].

Designing elements which has the ability to alter in response to the surrounding changes has been taken into consideration through decades. Due to the technological development and enhancement, the building elements can now easily move and alter their position in response to the variation of the external environmental situations. The possibilities of responsive building envelopes can play a great role in the reduction of the solar radiation and energy consumption consumed by HVAC systems for heating and cooling spaces [2].

II. Responsive Architecture

Kinetic movement has been defined as a tool for self-adaptation and responsiveness through Contemporary. Tristan d'Estree Sterk defined responsive architecture as *"a class of architecture or building with the objective of physically reconfiguring themselves to meet changing needs with variable mobility, location or geometry"* [4].

Responsive architecture is the architecture that has the ability to change its properties and flexibly control the different parameters of a building envelope, in order to adapt to the alteration of the external climatic environment to maintain the interior comfort. The changes can be introduced by several

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ways, such as the use of moving elements in the façade or the chemical change in the properties of the façade material [2].

Brian Cody, professor at Graz University of Technology, stated that the entire idea behind responsive envelopes is the building design, materials and shape that uses the alteration of the surrounding environment in order to create comfortable interior spaces [5].

The building performance is affected by many forces such as, climate, energies, information and human agents. These forces are not static and fixed, but rather mutable and dynamic. These forces have serious effect on the building envelope which must be designed to act as a barrier separating the inside from the outside. Responsive building façade is designed as a complex system of materials that adapt to the surrounding climate. The façade is equipped with new performative materials, sensors, actuators and computerized systems that support automated kinetic movements. The façade movements can be designed to regulate the building's light, air and sound transmission, thermal transfer and interior air quality. As the building façade is directly exposed to the sun, it should be designed effectively to save energy and improve the indoor environment [6].

The building can alter its outer skin according to the variation of the outer environmental condition so as to enhance the performance and control the solar radiation entered inside the building. This can be achieved through two techniques, either changing the geometric patterns or changing the properties of the materials used [7]. The paper focuses on investigating the geometric patterns that reduce the solar radiation rather than the changing the properties of the materials.

III. Hot Arid Region Climate

Egypt is affected by high solar radiation intensity all over its territory. The solar radiation intensity ranges from 1.9Wh/m2/year to 2.6Wh/m2/year. The solar radiation intensity reaches 2.4Wh/m2/year when moving from sea to desert [8].

The solar radiation intensity is affected by the length of the day which varies over the year. In 2021, the shortest day is December 21, with 10 hours, 13 minutes of daylight; the longest day is June 21, with 14 hours, 5 minutes of daylight, as shown in Fig. 1. At 4:53 am on June 10 is the earliest sunrise; while at 6:52 am on January 9 is the latest sunrise. At 4:54 pm on December 2 is the earliest sunset; while at 7:00 pm on June 30 is the latest sunset [9].

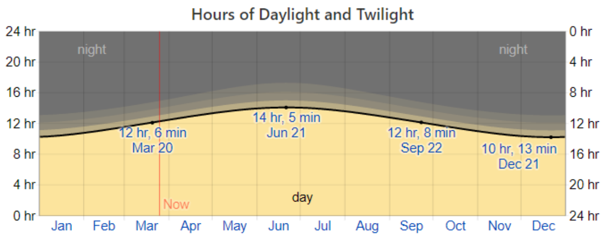


Fig. 1 Daily Hours of Daylight and Twilight in Egypt (Hour) in 2021

The black line, shown in Fig. 1, represents the number of hours during which the Sun is visible, however the color bands, which are most yellow to most gray represents various degrees of daylight, twilight, and night [9].

IV. International Responsive Façade Building

A. Q1 Building, Essen, Germany

Fig. 2 Q1 Building, Essen, Germany

The Q1 Building, shown in Fig. 2, is a part of the new Thyssen Krupp Quarter in Essen, Germany. It was completed in 2010 and designed by Frener and Reifer. Their goals were to design a building which creates a comfortable working environment for the employees, while designing a beautiful creative façade for the building's owner [10].

They designed a metal façade not only as a design element, but also as a sophisticated responsive façade. This responsive façade adapts to the surrounding environment in order to reduce the company's spending countless dollars on climate control [11].

Q1 Building uses the responsiveness to weather and Environment type of responsive architecture in the form of rotating movement. The façade's responsive units rotate around their axes, as shown in Fig. 3 to respond to the sun's path and the surrounding environment in order to regulate the indoor working environment, reducing solar gain and the solar glare [11].

Fig. 3 Rotating Axis

The responsive façade is composed of approximately 400,000 horizontal metal "feathers" which are fixed to a 3,150 vertical stainless steel stalks. The vertical stalks have the ability to move and rotate around their axes due to the motion of 1,600 motors. They are closed when the solar rays reach the facade in order to create a solid façade and prevent the solar rays from entering the façade, while they are opened when the solar rays aren't reaching the façade in order to allow maximum view and daylight. The horizontal feathers are fixed in the vertical stalks. Their forms vary from trapezoids to triangles and rectangles. They are designed to be shifted from each other in order to fill the gaps and prevent as much solar gain as possible from entering the building, as shown in Fig. 4 [11].

The four facades of Q1 building contain responsive units, however only the units applied to only three facades (west, east and south facades) have the ability to rotate. The units applied on the north façade are not kinetic as they are not exposed to solar rays. The building contains a data station located at the roof which can detect the climate weather and can measure the angle of the solar rays on each façade. The control unit receives the data from the data station and correspondingly rotates the responsive units. They can rotate between 0° (total blocking for the solar rays: parallel to the faced) to 90° (maximum daylight exposure: perpendicular to the façade). The degrees of rotation of the responsive units are divided into 5 types, as shown in Table I. Besides, the control unit is very sensitive, when there are cloudy days, the responsive units will be opened for maximum daylight exposure [10].

Fig. 4 Vertical stalks and Horizontal feathers

The applied responsive façade affects the building's performance by 30% reduction of the solar gain, 30 % reduction in the energy consumption, 27 % reduction in carbon emission and better natural lighted spaces due to reflecting the light inside the space by using glossy material in the responsive units [12].

TABLE I
ROTATION ANGLES OF THE RESPONSIVE UNITS IN Q1 BUILDING

Time	Optimum Angle of Rotation	Angle of Rotation on each facade			
		North Facade	South Facade	East Facade	West Facade
From 06:00 to 08:00	90°	90°	80°	20°	90°
From 08:00 to 10:00	80°	90°	20°	80°	90°
From 10:00 to 12:00	20°	90°	0°	90°	90°
From 12:00 to 13:00	0°	90°	0°	90°	90°
From 13:00 to 14:00	20°	90°	0°	90°	90°
From 14:00 to 16:00	80°	90°	20°	90°	80°
From 16:00 to 20:00	90°	90°	80°	90°	20°

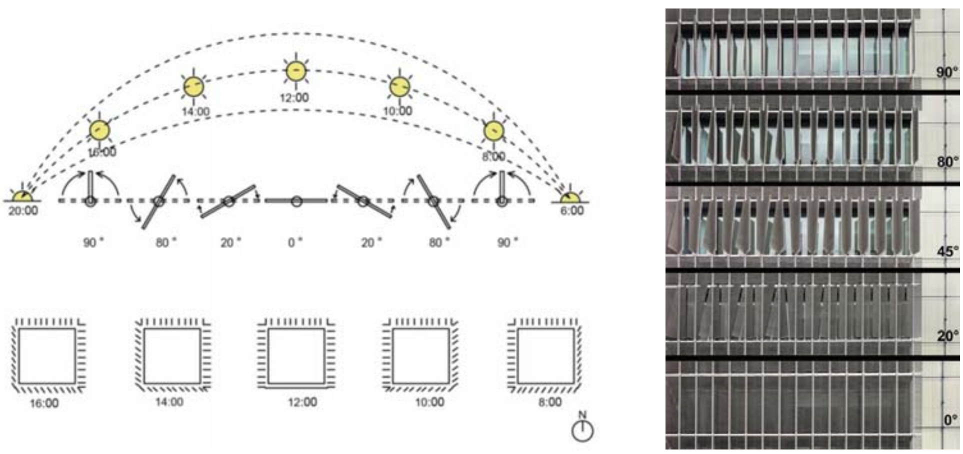


Fig. 5 Time and Rotation Angles of the Responsive Units in Q1 Building

V. Responsive Case Study in Cairo, Egypt

In this section, a comparative analysis between four different responsive façade designs will be investigated on a selected educational building located in Cairo, Egypt. The aim of the comparative analysis study is to determine the most efficient façade design in terms of reducing the solar radiation on the west façade.

A. Description of the Selected Building

The chosen building, shown in Figs. 6 and 7, is an educational building located called D-Building located in the German University Campus in Cairo, Egypt. The D-Building is a five-floors building used by 4 departments which are architecture and urban design department, civil engineering department, applied arts department and law studies department.

Fig. 6 D-Building in the German University in Cairo

Fig. 7 Typical Floor Plan of the Architectural Department of the D-Building

B. Solar Radiation Simulation

The solar radiation simulation will be applied on the west façade of the building on two chosen days in the year. As the intensity of the solar radiation is affected by the length of the day, the chosen days are the longest and the shortest days of the solar radiation in Cairo, Egypt. December 21st is the shortest day in Cairo with 10:13 hours of daylight, while June 21st is the longest day with 14:05 hours of daylight [9].

The solar radiation simulation will be carried using grasshopper and ladybug plugin, rhino software. It will be on two stages. The first stage is calculating the solar radiation on the west façade without applying any responsive façade on the two specified dates from 05:00 till 20:00. The second stage is calculating the solar radiation on the west façade after applying four different responsive façade. The four proposals of the responsive façade are designed to have the same dimension and geometrical shape; however they differ in axis of rotation. At the end of the simulation, a comparative analysis between the four proposals and the initial state of the façade is investigated in order to highlight the most efficient design in terms of reducing the solar radiation.

C. Initial State of the West Facade

A solar radiation simulation has been carried out in two different days. The two days are 21st of June (maximum solar radiation during the day) and 21st of December (minimum solar radiation during the day). The solar radiation is simulated starting from 05:00 till 20:00 in the two days.

Sun path simulation was carried out on the west façade on both days which shows that in 21st of June the sun is directly facing the façade starting from 13:00 till 19:00; however the sun is facing the roof façade starting from 06:00 till 13:00, as shown in Fig. 8. In 21st of December, the sun is directly facing the façade starting from 12:00 till 19:00; however the sun is facing the roof façade starting from 06:00 till 13:00, as shown in Fig. 8. As a result, the solar radiation is increasing rapidly starting from 13:00 till 19:00, as shown in Table II.

TABLE II
Initial Solar Radiation on West Façade

Time during the day	Total Solar radiation (kWh) on the west facade	
	21st of June	21st of December
05:00 till 06:00	0	0
06:00 till 07:00	13.04	0
07:00 till 08:00	34.13	1.63
08:00 till 09:00	49.23	13.15
09:00 till 10:00	59.66	30.99
10:00 till 11:00	59.37	45.99
11:00 till 12:00	55.39	47.69
12:00 till 13:00	60.22	75.32
13:00 till 14:00	153.13	181.64
14:00 till 15:00	314.09	238.94
15:00 till 16:00	453.85	284.23
16:00 till 17:00	493.86	172.78
17:00 till 18:00	446.33	0
18:00 till 19:00	200.81	0
19:00 till 20:00	0	0

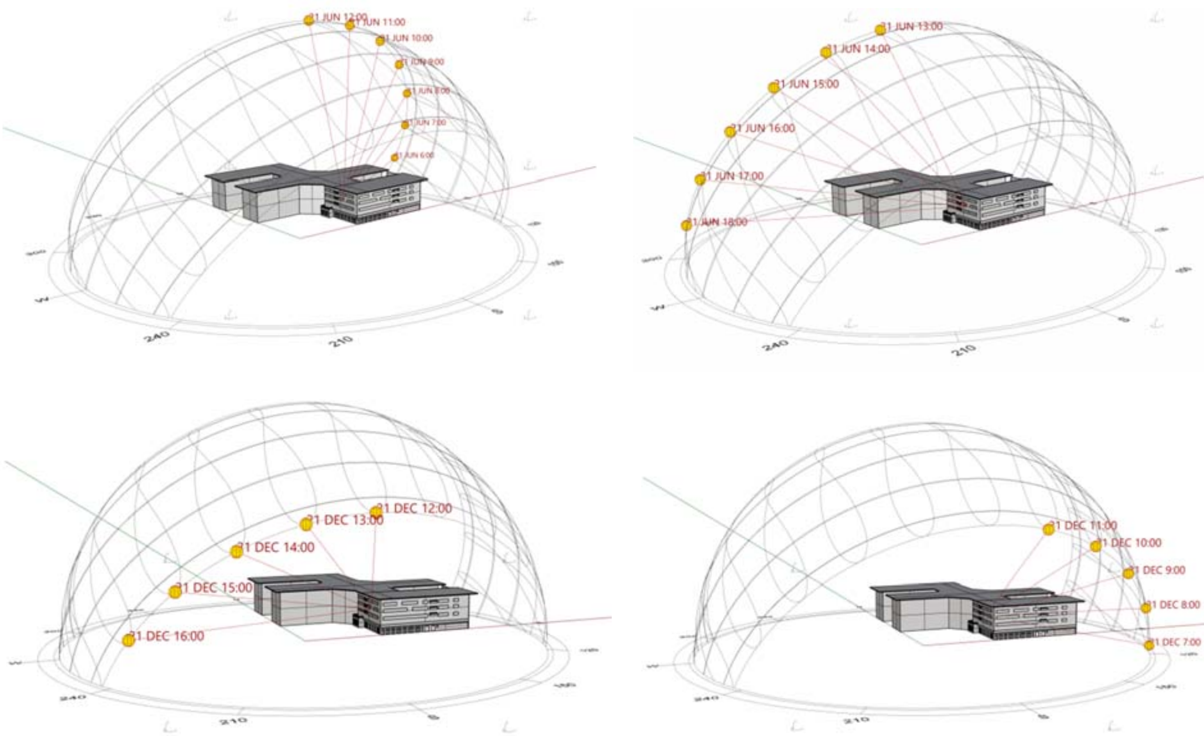


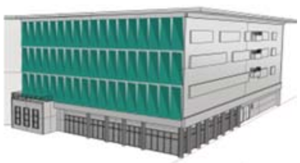
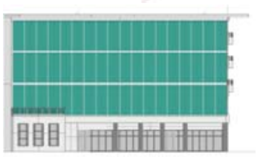
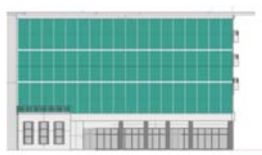
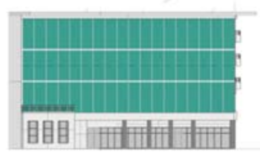
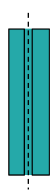
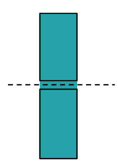
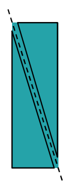
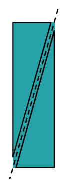
Fig. 8 Sun path simulation on west façade for 21st of June and 21st of December

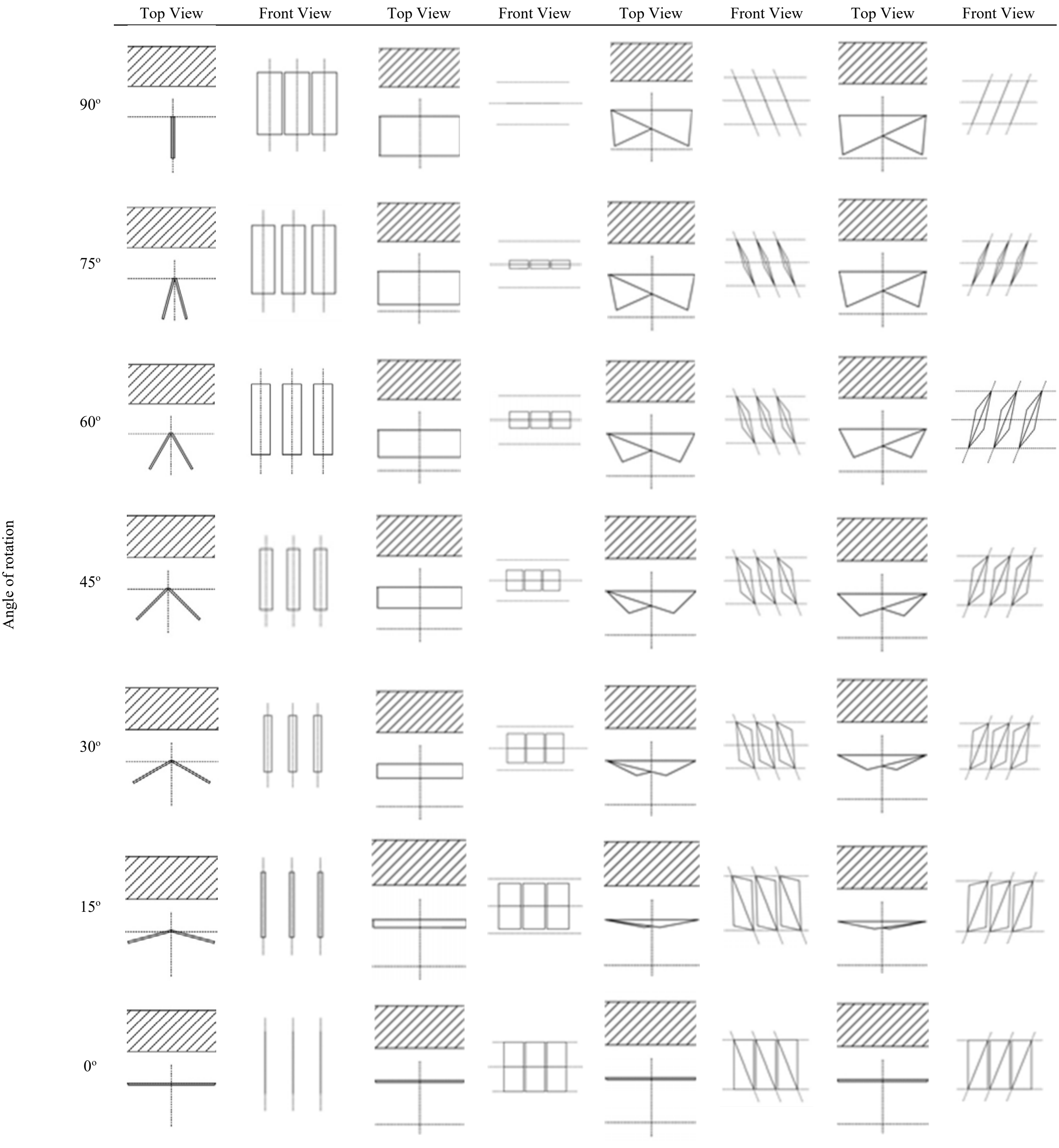
D.Proposed Responsive Facades

The four proposed responsive façade have the same geometrical form, dimensions and angle of rotation; however they differ in the axis of rotation, as shown in Table III. The four responsive façades are divided into 3 horizontal panels and 18 vertical panels. Each panel is divided into two parts.

The dimension of the panel is 2m width and 5m height. The type of movement for the four proposed facades is the same, which is the rotational movements; however they differ in the axis of rotation. The angle of rotation ranges from 90˚ till 0˚, as shown in Table III.

TABLE III
FOUR PROPOSED RESPONSIVE FACADES

	Proposed Responsive Façade Design			
	Proposal A	Proposal B	Proposal C	Proposal D
3D View				
				
Axis of Rotation				



The result of the solar radiation on the west façade in 21st of June showed that the intensity of the solar radiation ranges from 0 to 1.28 kWh/m^2, however the intensity of the solar radiation in 21st of December ranges from 0 to .71 kWh/m^2. As a result, the responsive façade rotates automatically according to the intensity of the solar radiation on the west façade from 90˚ till 0˚, as shown in Table IV.

E. Solar Radiation After Applying the Four Proposals in 21st of June

Table V shows the total intensity of the solar radiation in the 21st of June on the west façade after applying the four responsive facades proposals from 05:00 till 20:00.

TABLE IV
SOLAR RADIATION (KWH/M^2) ON WEST FAÇADE

21st of June		21st of December	
Maximum Solar radiation on Façade (kWh/m^2)	Angle of Rotation	Maximum Solar radiation on Façade (kWh/m^2)	Angle of Rotation
0	90 °	0	90 °
0.12	75 °	0.21	75 °
0.24	60 °	0.43	60 °
0.36	45 °	0.64	45 °
0.48	30 °	0.85	30 °
0.59	15 °	1.07	15 °
0.71	0 °	1.28	0 °

TABLE V
SOLAR RADIATION IN 21ST OF JUNE ON WEST FAÇADE AFTER APPLYING THE FOUR PROPOSED RESPONSIVE FACADES

Time during the day	Initial Solar Radiation	Angle of Rotation	Total Intensity of the solar Radiation (kWh) in 21st of June			
			Proposal A	Proposal B	Proposal C	Proposal D
05:00 till 06:00	0	90 °	0	0	0	0
06:00 till 07:00	13.04	90 °	8.37	9.16	7.83	4.17
07:00 till 08:00	34.13	90 °	21.86	23.33	20.36	16.82
08:00 till 09:00	49.23	90 °	31.41	32.53	29.09	28.09
09:00 till 10:00	59.66	90˚	37.86	38.24	34.88	29.29
10:00 till 11:00	59.37	90 °	37.57	37.95	34.53	37.12
11:00 till 12:00	55.39	90 °	35.08	35.62	32.10	44.70
12:00 till 13:00	60.22	90 °	38.49	37.249	34.50	41.23
13:00 till 14:00	153.13	90˚ for first row – 60˚ for the other two rows	84.27	36.14	66.80	78.36
14:00 till 15:00	314.09	60˚ for first row – 15˚ for the other two rows	34.09	24.55	28.71	31.60
15:00 till 16:00	453.85	45˚ for first row - 0 ˚ for the other two rows	23.31	17.027	28.80	17.05
16:00 till 17:00	493.86	0 °	34.05	36.07	36.39	12.42
17:00 till 18:00	446.33	15 °	29.80	26.86	28.15	23.57
18:00 till 19:00	200.81	60 °	104.25	102.96	101.75	80.18
19:00 till 20:00	0	90 °	0	0	0	0
Total Solar Radiation (KW)	**2393.11**		520.41	457.68	483.89	**444.60**

F. Solar Radiation after Applying the Four Proposals in 21st of December

Table VI shows the total intensity of the solar radiation in the 21st of December on the west façade after applying the four responsive facades proposals from 05:00 till 20:00.

TABLE VI
SOLAR RADIATION IN 21ST OF DECEMBER ON WEST FAÇADE AFTER APPLYING THE FOUR PROPOSED RESPONSIVE FACADES

Time during the day	Initial Solar Radiation	Angle of Rotation	Total Intensity of the solar Radiation (kWh) in 21st of December			
			Proposal A	Proposal B	Proposal C	Proposal D
05:00 till 06:00	0	90˚	0	0	0	0
06:00 till 07:00	0	90˚	0	0	0	0
07:00 till 08:00	1.63	90˚	1.03	0.97	0.94	0.96
08:00 till 09:00	13.15	90˚	8.19	9.17	7.68	7.82
09:00 till 10:00	30.99	90˚	18.92	21.44	17.64	18.21
10:00 till 11:00	45.99	75˚	23.88	25.11	22.69	24.45
11:00 till 12:00	47.69	75˚	23.96	26.16	22.69	24.94
12:00 till 13:00	75.32	60˚	21.49	25.89	20.12	24.54
13:00 till 14:00	181.64	30˚	23.16	30.92	26.08	54.27
14:00 till 15:00	238.94	15˚	28.09	24.03	30.34	45.55
15:00 till 16:00	284.23	0˚	8.19	8.16	9.54	8.19
16:00 till 17:00	172.78	45 ˚	79.83	53.65	60.32	81.68
17:00 till 18:00	0	90˚	0	0	0	0
18:00 till 19:00	0	90˚	0	0	0	0
19:00 till 20:00	0	90˚	0	0	0	0
Total Solar Radiation (KW)	**1092.36**		236.74	225.5	**218.04**	290.61

Table V shows that the total intensity of the solar radiation from 06:00 till 20:00 on the west façade in the 21st of June without applying any proposed responsive façade design is 2393.11 KW. However after applying the proposed responsive facades design, the total intensity of the solar radiation reduced where proposal D (diagonal axis movement) is the most efficient proposal, compared to the other three proposals. Moreover, Proposal A (vertical axis movement) is the least effective proposal, compared to the other three proposals.

Table VI shows that the total intensity of the solar radiation from 06:00 till 20:00 on the west façade in the 21st of December without applying any proposed responsive façade design is 1092.36 KW. However after applying the proposed responsive facades design, the total intensity of the solar radiation reduced where proposal C (diagonal axis movement) is the most efficient proposal, compared to the other three proposals. Moreover, Proposal D (diagonal axis movement) is the least effective proposal, compared to the other three proposals.

VI. Discussion and Conclusion

After simulating the solar radiation on the west façade for the 21st of June and 21st of December, the following points were concluded,

- The four proposed responsive facades reduced the solar radiation exposed on the west façade in both days (21st of June and 21st of December).
- In 21st of December simulation,
  - Proposal C is the most effective design; however proposal D is the least effective one. This is due to the direction of the sun rays which are blocked most by proposal C.
  - The reduction of the solar radiation is by 80% (Proposal C) till 73.39 % (Proposal D)
  - The difference between the percentage of reduction of the four proposals ranges between 6.6%.
- In 21st of June simulation,
  - Proposal D is the most effective design; however proposal A is the least effective one. This is due to the direction of the sun rays which are blocked most by proposal D.
  - the reduction of the solar radiation is by 81.4% (Proposal D) till 78.25 % (Proposal A)
  - The difference between the percentage of reduction of the four proposals ranges between 3.15%.

After analyzing the solar radiation on the west façade on both dates, it was concluded that the most effective responsive façade is not the same for all hours of the two days, as shown in Table VII.

- In the 21st of June, proposal D (diagonal Axis II) is the most effective design starting from 06:00 till 10:00 and from 16:00 till 19:00. Proposal C (diagonal Axis I) is the most effective design starting from 10:00 till 13:00. Proposal B (Horizontal Axis) is the most effective design starting from 13:00 till 16:00.
- In 21st of December, proposal C (diagonal Axis I) is the most effective design starting from 07:00 till 13:00. Proposal A (Vertical Axis) is the most effective design starting from 13:00 till 14:00. Proposal B (horizontal Axis) is the most effective design starting from 14:00 till 15:00 and from 16:00 till 17:00. Proposal D (diagonal Axis I) is the most effective design starting from 15:00 till 16:00.
- As a conclusion, a proposal for the responsive façade using the four responsive design techniques will be the following, as shown in Table VIII.

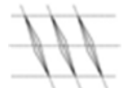
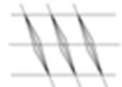
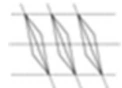
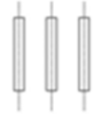
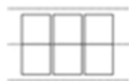
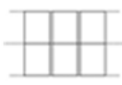
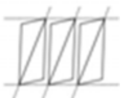
TABLE VII
MOST EFFECTIVE PROPOSAL PER HOUR ON THE WEST FAÇADE

Time during the day	Most effective proposal per hour	
	21st of June	21st of December
05:00 till 06:00	0	0
06:00 till 07:00	Proposal D	0
07:00 till 08:00	Proposal D	Proposal C
08:00 till 09:00	Proposal D	Proposal C
09:00 till 10:00	Proposal D	Proposal C
10:00 till 11:00	Proposal C	Proposal C
11:00 till 12:00	Proposal C	Proposal C
12:00 till 13:00	Proposal C	Proposal C
13:00 till 14:00	Proposal B	Proposal A
14:00 till 15:00	Proposal B	Proposal B
15:00 till 16:00	Proposal B	Proposal D
16:00 till 17:00	Proposal D	Proposal B
17:00 till 18:00	Proposal D	0
18:00 till 19:00	Proposal D	0
19:00 till 20:00	0	0

As a result, by applying the four responsive façade designs in the above stated period of time in the two days, the solar radiation will be reduced from 2393.11 KW to 373.39 KW which is 84.4% in the 21st of June and the solar radiation will be reduced from 1092.36 KW to 200.79 KW which is 81.6 % in the 21st of December.

TABLE VIII
MOST EFFECTIVE PROPOSAL PER HOUR ON THE WEST FAÇADE

Time during the day	21st of June				21st of December			
	Most effective façade design		Angle of Rotation	Total Solar radiation	Most effective façade design		Angle of Rotation	Total Solar radiation
05:00 till 06:00	0		90 º	0	0		90 º	0

06:00 till 07:00	Proposal D		90 º	4.17	0		90 º	0
07:00 till 08:00	Proposal D		90 º	16.82	Proposal C		90	0.94
08:00 till 09:00	Proposal D		90 º	28.097	Proposal C		90 º	7.68
09:00 till 10:00	Proposal D		90 º	29.29	Proposal C		90 º	17.64
10:00 till 11:00	Proposal C		90 º	34.53	Proposal C		75 º	22.69
11:00 till 12:00	Proposal C		90 º	32.10	Proposal C		75 º	22.69
12:00 till 13:00	Proposal C		90 º	34.50	Proposal C		60 º	20.12
13:00 till 14:00	Proposal B		90˚for first row – 60˚for the other two rows	36.14	Proposal A		30 º	23.16
14:00 till 15:00	Proposal B		60˚for first row – 15˚for the other two rows	24.55	Proposal B		15 º	24.03
15:00 till 16:00	Proposal B		45˚for first row - 0 ˚for the other two rows	17.03	Proposal D		0 º	8.19
16:00 till 17:00	Proposal D		0 º	12.42	Proposal B		45 º	53.65
17:00 till 18:00	Proposal D		15 º	23.57	0		90 º	0
18:00 till 19:00	Proposal D		60 º	80.18	0		90 º	0
19:00 till 20:00	0		90 º	0	0		90 º	0
	Total Solar Radiation (KW)			373.39	Total Solar Radiation (KW)			200.79

VII. Limitation and Future Research

The following is further researches needed to examine,

- The effect of the four proposed responsive facades on the heating and cooling energies consumed by the building.
- The effect of the four proposed responsive facades on the day-lighting aspects.
- Optimization between the solar radiation and the performance of the day-lighting for the four proposed responsive facades.

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