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TECHNICAL PAPER

Solar radiation analysis: computational performance analysis for the foldable axis of a responsive external skin on the south façade

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Abstract

There has been an interest in responsive façade technology as a new paradigm shift where external skin can change and alter in response to its surrounding environment to maximize building performance and increase the user's comfort zone. The application of responsive facades is an effective strategy toward further energy efficiency improvements in built environments. This can help control the interior environment within the building, and so minimize the energy consumption of building services systems. The study will detect geometric pattern alternatives for a kinetic facade that respond to the climatic performance aspects. It presents a methodology, which define a performance-based design, an approach to analyze the design and simulate responsiveness of kinetic facades during the early design phase. The simulation analyzes the direct solar radiation for an optimal layout for the proposed given shading system. The study demonstrates how the process of designing and developing responsive facades can be effectively tested and evaluated.

Keywords Responsive architecture · Façade design · Mechanism of movement · Rotating typology and solar radiation

Introduction

Operational energy use in buildings counts for 30% of global final energy consumption that jumps to 34% when including the embodied energy for the construction of buildings [1]. Energy consumption is rapidly increasing due to the population growth, urbanization, and industrialization. Therefore, low-energy utilization and increasing environmental awareness have become substantial for energy conservation in buildings.

As building envelope is the mediator between the interior and the exterior, thus greatly influences indoor climate energy saving. Recent studies on façade performance show an increasing interest in building envelope, its impact on building performance, and various strategies and approaches.

Architecture faces a paradigm shift where it is crucial to introduce a developed correlated system. Digital technology provides the evolution from static media into kinetic and responsive strategy. Facade systems have recently been transformed to an advanced and complex active system that are able to respond to the surrounding environment in terms of characteristics of its external skin design [2]. Subsequently, advanced parametric tools tends to fasten different parameters of complex geometric pattern in façade within the surrounding environment design that was hard to analyze [3]. Geometric parameterization provides generating alternative parametric design to fulfill the required performance criteria, through defining the overall shape of the facade and the pattern, the density and the configuration of its modular shading element.

Responsive architecture

Responsive architecture is a building design that can adjust its properties and control various aspects of the building envelope in response to the changes in the external climatic conditions. This allows the building to maintain a comfortable interior environment for the building's occupants [4]. Tristan d'Estree Strek defined responsive buildings as "a class of architecture or building with the objective of physically reconfiguring themselves to meet changing needs with variable mobility, location or geometry" [5]. According to Brian Cody, a professor at

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Graz University of Technology, this can be achieved through carefully considering several factors such as the materials and the building's design, as well as the façade design [6].

By using responsive design techniques, buildings can adjust its parameters to the changes in the surrounding weather and environment, resulting in enhancing the building performance and reducing the solar radiation. Two techniques are commonly used to achieve this aim, changing the geometric patterns of the building facade or altering the properties of the façade's materials used [7]. The paper focuses on investigating the façade's geometric patterns that reduce and control entering the solar radiation inside the building. Responsive facade that controls the entering of the solar radiation through the alteration of the façade's geometric patterns, usually incorporates advanced materials, sensors, actuators, and computerized systems that enable automated kinetic movements. These movements can be programmed to control various aspects of the building's environment, including light, air, sound, thermal transfer, and air quality. This can be achieved through several typologies of movement, such as rotating, folding, moving, and scaling [8]. Since the facade is directly exposed to the sun, it is important to design it in a way that maximizes energy efficiency and indoor comfort [9].

By using responsive design principles, architects and builders can create structures that are able to respond to changes in temperature, humidity, and other environmental factors in real-time, providing a comfortable and sustainable living or working environment for occupants. Overall, the goal of responsive envelopes is to create buildings that are not just passive structures, yet active and dynamic entities that can adapt and respond to their surroundings in order to optimize energy efficiency and occupant comfort [4].

Solar radiation in Cairo, Egypt

In Cairo, the duration of solar radiation and daylight changes throughout the year. The duration of the solar radiation is one of the contributors that affects the temperature throughout the year. As shown in Fig. 1, the temperature as well as the duration of solar radiation is at its maximum in June. The longest day of the year, which has 14 h and 5 min of sunlight, occurs on June 21 [10]. Moreover, as shown in Fig. 2, sunrise in June 21 is4:54 AM; however, the sunset is 6:59 PM [6].

Responsive façade case study in Cairo

In this section, the paper will analyze the effect of reducing the solar radiation of three proposed façade designs on the south façade of a selected case study in Cairo, Egypt. The three proposed façade design are similar in shape, size,

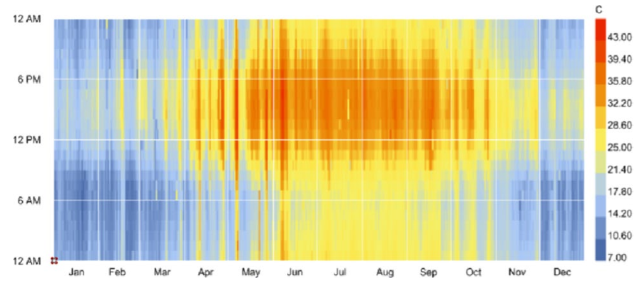


Fig. 1 Dry bulb temperature (°C), Cairo, Egypt

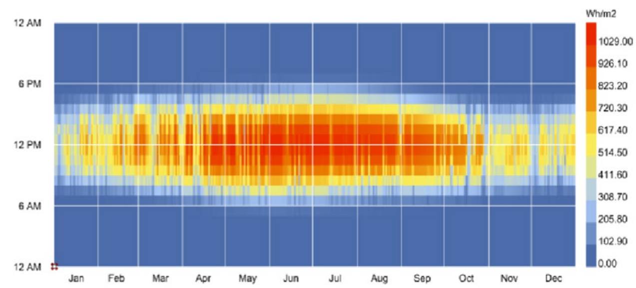


Fig. 2 Solar radiation (Wh/m^2), Cairo, Egypt

and mechanism of movement; however, they differ in the direction of foldable axes. The aim of the study is to highlight the most efficient façade design out of the three proposed designs in minimizing the solar radiation on the south façade, and thus enhance the building performance.

Selected case study description

The selected building, shown in Fig. 3, is an educational building, located in the German university in Cairo campus. It is composed of five floors and used by the architecture and urban design department, applied and arts department, civil engineering department and law studies department. The building skin of the four upper floors are glass curtain wall material. The building is composed of four different south façades. Figure 4 shows the selected façade on which the solar radiation will be examined. The four upper floors on selected south façade are occupied mainly by architecture and urban design studios.

Solar radiation on the south facade

The paper conducts a solar radiation simulation on the south façade of the selected buildings on June 21, the longest solar radiation day over the year. The solar radiation will be measured every two hours, starting from 5:00 AM to 7:00 PM. The simulation will be conducted via Grasshopper and Ladybug plugins in Rhino software, and it will involve two stages. The first stage will calculate the

Fig. 3 D-building in the German university in Cairo

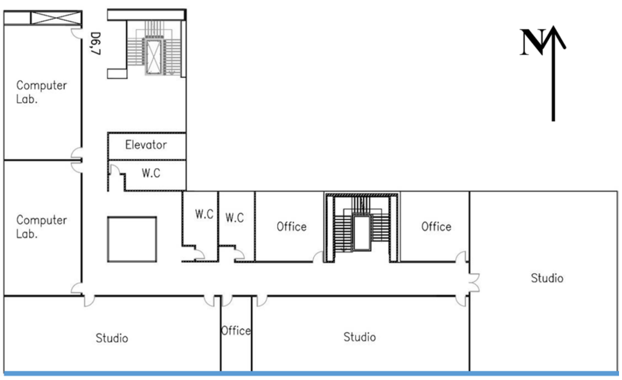


Fig. 4 Typical floor plan of the architectural department of the D-building

amount of solar radiation hitting the south-facing side of the building without applying any responsive façade. The second stage will calculate the solar radiation on the south façade after applying the three responsive façade designs proposals. The three designs will have the same dimensions and geometrical shape, but they will differ in their foldable axis. Afterward, a comparative analysis will be conducted to determine which design is the most efficient at reducing solar radiation, in comparison to the initial state of the façade.

Three proposed responsive facades

The methodological approach of this study integrates modeling, simulation, and optimization. The study proposes an external foldable façade system to assess the optimal foldable axis in optimizing the direct solar radiation on a south façade. A quadrilateral geometric pattern of footprint of 2 m × 1 m form a module to compose the whole façade. The configurations of the folding pattern consider the foldable axes along y-axis and the two diagonal axes.

The considered design parameter is the different foldable axes for a quadrilateral geometric pattern. As shown in Tables 1 and 2, the three proposals will fold around their axis in seven different angles, starting from 90 till it reaches 0. The analysis will show the reconfiguration of the geometric pattern along different foldable axes to simulate the different alternatives impact on controlling the direct solar radiation during different hours of the day.

Solar radiation simulation before and after applying responsive facade

As shown in Table 3, the intensity of the solar radiation is simulated on the 21st of June on the south facades without applying responsive facades starting from 05:00 AM till 07:00 PM over an interval of two hours. The solar radiation intensity is simulated through calculating the solar radiation on each test points in kWh/m2 multiplied by the façade area.

According to the intensity of the solar radiation, the angles of foldability of the proposed facades were determined. As the maximum solar radiation is from 09:00 am till 11:00 am, the angle of foldability is determined to be 0° where the façade will be totally closed. On the other side, as the minimum solar radiation is from 05:00 am till 07:00 am, the angle of foldability is determined to be 90° where the façade will be totally opened. The angles of foldability during the rest of the day were determined according to a ratio related to the maximum and minimum values.

Table 1 Three proposed responsive facades

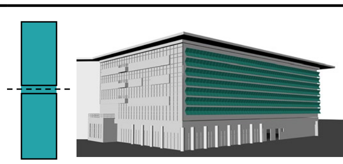
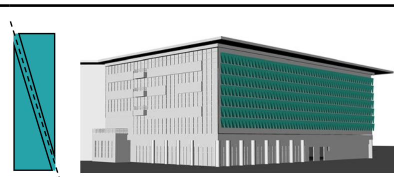
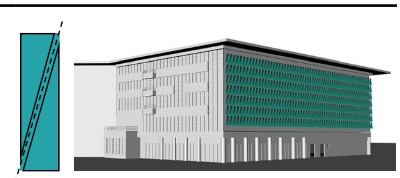
Angle of rotation	Three proposed responsive facades		
	Proposal A	Proposal B	Proposal C
3D view—axis of foldability			

Table 2 Angles of the three proposed responsive facades

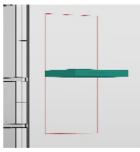
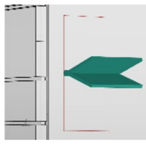
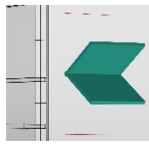
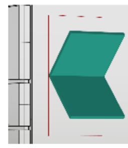
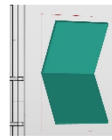
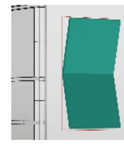
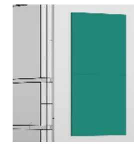
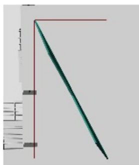
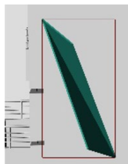
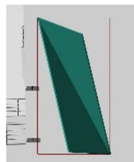
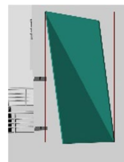
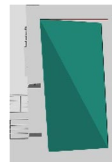
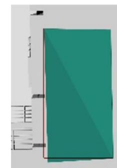
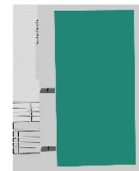
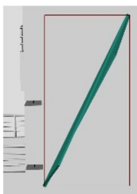
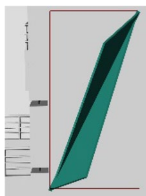
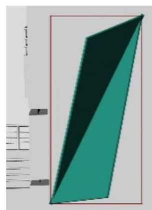
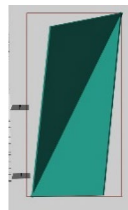
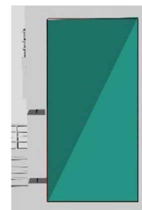
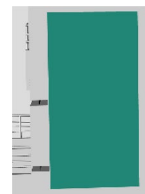
	Angles of foldability						
	90°	75°	60°	45°	30°	15°	0°
Proposal A							
Proposal B							
Proposal C							

Table 3 Total solar radiation before and after applying the responsive facade

Time during the day	Solar radiation before applying responsive façade (kWh/m^2) on 21st of June	Angle of foldability	Total solar radiation after applying responsive façade (kWh/m^2) on 21st of June		
			Proposal A	Proposal B	Proposal C
05:00 till 07:00	41.473	90°	29.543	24.402	24.995
07:00 till 09:00	185.21	60°	88.41	78.148	88.067
09:00 till 11:00	321.694	0°	32.905	42.545	35.697
11:00 till 13:00	261.738	15°	33.828	53.79	50.454
13:00 till 15:00	217.743	30°	49.657	56.47	57.69
15:00 till 17:00	195.071	45°	69.407	71.002	68.695
17:00 till 19:00	101.358	75°	61.29	53.827	51.742
Total solar radiation (KW)	1324.287		365.04	380.184	377.34

The underline indicates the lowest solar radiation accomplished by the proposed design facade

Discussion and conclusion

In this paper, through simulation, the external skin performance on the south façade is analyzed. Specifically, the impact of foldable axes direction for the quadrilateral pattern. The results, based on a comparative evaluation of the different alternatives, allowed for indicating the appropriate geometrical configurations for the external skin able to reduce the direct solar radiation.

As shown in Table 3, the intensity of the solar radiation simulated on June 21 on the south facades without applying responsive facades starting from 05:00 AM until 07:00 PM over an interval of two hours. In addition, results deduced when applying the three alternatives configuration for the pattern over the same interval of time.

Integration between the different proposals in term of the optimal configuration for controlling the solar radiation at different intervals of the day is analyzed in Table 4. The results shows that:

- Proposal B is the most effective from 05:00 to 9:00 as solar radiation ranges from 24.402 to 78.148 kWh
- Proposal A is the most effective from 09:00 to 15:00, solar radiation ranges from 32.905 to 49.657 kWh

Table 4 Combined responsive façade proposal

Time during the day	Solar radiation before applying responsive façade (kWh) on 21st of June	Combined proposal of responsive façades		
		Angle of foldability	Proposal	Total solar radiation(kWh) on 21st of June
05:00 till 07:00	41.473	90°	Proposal B	24.402
07:00 till 09:00	185.21	60°	Proposal B	78.148
09:00 till 11:00	321.694	0°	Proposal A	32.905
11:00 till 13:00	261.738	15°	Proposal A	33.828
13:00 till 15:00	217.743	30°	Proposal A	49.657
15:00 till 17:00	195.071	45°	Proposal C	68.695
17:00 till 19:00	101.358	75°	Proposal C	51.742
Total solar radiation (KW)	1324.287			339.377

- Proposal C is the most effective from 15:00 to 19:00, solar radiation ranges from 68.695 to 51.742 kWh

Specifically, from 09:00 to 15:00 the most effective shading was Proposal A. At applying the external skin, a significant impact in reduction the intensity impinge the façade achieved. Although it represented the highest solar radiation intensity (without the external skin), Proposal A achieves to reduce the values dramatically when compared with different proposals during various different time of the day.

From 5:00 until 9:00, with low sun angle, Proposal B is the most effective configuration. On contrary, the opposite diagonal alternative, Proposal C, represents the optimal scenario for the duration between 15:00 until 19:00. The foldable axes direction needs to be conversed to follow the altitude angle of the sun.

According to the analysis, the pattern needs to be adaptable based on the variable solar radiation through the whole day. To achieve the optimal scenario, integration of the three alternatives at three intervals of the day should be applied to reach the maximum efficiency. Transformative geometric pattern is a powerful tool for improving the façade performance. Advanced technology introduced parametric tools tends to fasten complex geometric patterns in the façade design that were hard to analyze in the past.

Limitation and future research

The research didn't focus on the below points,

- The effect of the three responsive facades proposals on the heating and cooling loads
- The effect of the three responsive facades proposals on the Daylighting
- Optimization between the solar radiation and the daylighting
- The solar radiation on other days of the year was not studied.

Decelerations

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The authors declare no conflict of interest. The contributions of all authors were of equal significance in the conception, design, and execution of the study. The manuscript is not under consideration for publication in any other journal.

Declarations

Conflict of interest The authors declare that they do not have any conflict of interest.

Ethical approval The article does not include any research involving human or animal subjects conducted by the authors, thus formal consent is unnecessary for this particular study.

Informed consent For this type of study, formal consent is not required.

References

1. Fürbringer JM, Roulet CA, Borchiellini R (1999) An overview of the evaluation activities of IEA ECBCS Annex 23. Energy Build 30(1):19–33
2. Shi X, Abel T, Wang L (2020) Influence of two motion types on solar transmittance and daylight performance of dynamic façades. Sol Energy 201:561–580
3. Moloney J (2011) Designing kinetics for architectural facades: state change. Taylor & Francis

4. Modin, H., 2014, “Adaptive building envelopes”, MSc. Thesis, Department of Civil and Environmental Engineering, Division of Building Technology, Chalmers University of Technology, Sweden.
5. Sterk, T., 2005, “Building upon Negroponte: a hybridized model of control suitable for responsive architecture. Automation in construction, El Sevier United States of America.
6. Cody B., 2012, “Form follows energy”, xia-international-online Website, October 2015, http://www.xia-online.de/zeitschrift/aktuelle-ausgabe/.
7. Meagher, M., 2015, “Designing for change: The poetic potential of responsive architecture”, Frontiers of Architectural Research, ol.4, United Kingdom, P.159–165.
8. Shi X, Abel T, Wang L (2020) Influence of two motion types on solar transmittance and daylight performance of dynamic façades. Sol Energy 1(201):561–580
9. elikov, K., Geoffrey, T., (2015) Building envelopes: renewable energies and integrated practice. Routledge, France
10. *Climate and Average Weather Year Round in Cairo*. (2023, July). Retrieved from Weather Spark: https://weatherspark.com/y/96939/Average-Weather-in-Cairo-Egypt-Year-Round