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Optimizing Indoor Comfort and Energy Efficiency using Right-Angled Triangular Responsive Facades in Cairo, Egypt

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A B S T R A C T

Building energy consumption has been rapidly increasing in recent years due to several factors such as climate change and global population growth. Besides, the majority of buildings are not designed with the consideration of the alteration of the severe conditions of the external surrounding environment, which affects the indoor environment negatively. As a result, excessive HVAC systems are utilized in order to maintain the indoor environment and achieve the indoor human comfort. Thus, large amounts of energy are being consumed and the rates of the energy consumption are increasing rapidly. Responsive architecture is considered as one of the solutions that architects, and façade designers use in order to block the excessive solar radiation and direct natural light and thus enhance the indoor comfort zone. However, the majority of the façade's pattern designs are not following specific guidelines. This study contributes to the field by identifying an optimal right-angled triangular façade design that effectively enhances indoor thermal comfort, reduces solar radiation, and minimizes energy consumption, thereby providing a practical solution for improving building performance in response to climate change and urban growth challenges. This article will study four different façade pattern cases, which are common in the rotational movement, façade orientation and pattern dimensions; however, they differ in the orientation of the axes of movement. The four-façade pattern proposals will be investigated through simulating the solar radiation, consumed cooling energy and the indoor operative temperature during the maximum solar exposure day. A comparative analysis will be conducted between the results in order to highlight the most efficient right-angled triangular pattern that can be used on the south façade in Cairo, Egypt in order enhance the indoor thermal comfort, enhance the energy consumption rates, reduce the solar radiation and improve the building performance.

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1. Introduction

The rapid increase in building energy consumption, driven by climate change and global population growth, poses significant challenges to sustainable architecture and urban living. Many existing buildings fail to account for the severe external environmental conditions, leading to a reliance on excessive HVAC systems to maintain indoor comfort, which in turn exacerbates energy consumption issues. This study addresses these pressing problems by investigating the potential of responsive architecture, specifically through the design of façade systems that can adapt to environmental conditions.

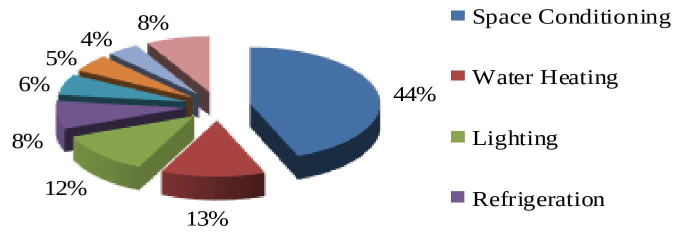


Figure 1. Building Energy Consumption by Type (Source: Thermal Comfort: Designing for People, 2022)

The significance of this study lies in its aim to identify an optimal right-angled triangular façade design that enhances indoor thermal comfort while minimizing solar radiation and energy consumption. This research is vital as it not only contributes to the development of more sustainable building practices but also offers practical solutions that can significantly reduce the environmental impact of buildings in urban settings, particularly in regions like Cairo, Egypt, where extreme solar exposure is prevalent.

To achieve the objectives of this study, several research questions will be explored: What are the most effective façade configurations for maximizing indoor comfort? How do different façade patterns influence energy consumption and solar radiation absorption? What design guidelines can be established for future façade designs based on the findings of this research?

The paper begins with a comprehensive literature review on responsive architecture, outlining the current state of knowledge and identifying gaps in façade design practices. Following this, the methodology employed in this study will be described, including the design tools and software used to simulate different façade patterns. A comparative analysis of four distinct façade configurations will be conducted to determine the most efficient design for maximizing indoor thermal comfort and minimizing energy use. Ultimately, the findings will provide insights into effective façade design strategies that can enhance building performance and address the urgent energy challenges facing the built environment today.

2. Research Background

Worldwide, the rates of energy consumption have been increasing rapidly due to the global population growth and their power consumption, manufacturing power demands, climate changes and other several aspects. According to the international energy agency in 2021, buildings consumed 35 % of the global energy consumption. Energy consumption in buildings increased from 115 EJ in 2010 to 135EJ in 2021. Moreover, the carbon emissions by buildings increased by 5% in 2021 more than the emission in 2020. Nevertheless, energy consumed due to space cooling has increased three times since 1990. The energy consumed due to cooling loads in 2021 records the highest annual growth compared to the previous years (International Renewable Energy Agency, 2023). Energy is consumed in order to maintain the indoor comfort and thus cool or heat the buildings. HVAC systems are consuming 44 % of the building energy, as shown in figure (1). Thus, there is huge demand of designing buildings, which consumes less energy, and improving the air conditioning systems (Ardente et al., 2020).

Many researchers defined the building skin as the boundary where the building interact with the surrounding mediums. It reacts with the air, light, sun, moisture, heat and sound. It has the ability to maintain and control the indoor comfort conditions. Moreover, building skin is defined as the layer where the exchange of the energy and materials occurs in (Tabasi & Banihashemi, 2020). A well-designed shading technique on the building skin can protect the building from the alteration of the surrounding environment such as, direct solar gain, direct sunlight, glare, the extreme temperature and humidity. By designing an efficient skin, the indoor comfortable parameters can be maintained and thus the energy consumed can be controlled (Wang, Zhang, Tang, & Li, 2018). The majority of the buildings is static and fixed entities. However, buildings need to be designed to adjust to the unpredictable changes of the surrounding environment. The changes in climate, behavior and user's demand require building's flexibility and adaptation capacity. In order to maintain a stable comfortable interior environment, buildings that adjust to the outdoor environment are demanded. Although buildings need stability in their structure and elements, they are required to be designed to seek equilibrium using elements that depend on frequent adjustment in order to maintain variable meteorology (Preiser, Hardy, & Wilhelm, 2017).

3. Literature Review

3.1. Responsive Architecture

Responsive architecture is defined as "Buildings or building components that can adapt to external influences, external conditions, and the overall external environment (Mohamed, Abd El-Rahman, & Sadek, 2023). The building and its elements use physical states and force effects (light, heat, humidity, noise) in the form of sun, wind, and rain. These effects are used to change building elements or the building as a whole and to sensitively adapt in creating appropriate (self-sustaining, self-healing) sustainable architecture, buildings, and environments" (Katunsky & Huang, 2019). As the computer has a significant impact on the built environment, automated building components have been integrated in façade systems as a solution for decreasing the energy consumption and maintaining the indoor comfortable level. As an example of the automated building components, automated shading devices are used to control the solar radiation entering the building (Preiser, Hardy, & Wilhelm, 2017). Responsiveness in Architecture can be divided into two categories; either reshaping the building's elements to adapt the user's interaction or adapting to the interior and exterior environment. The two typologies can be achieved by changing the façade's pattern or by changing the material's properties, as shown in figure (2). The changing in the façade's pattern is called active system; however, the changing in the material's properties is called passive system (Kızılörenli & Maden, 2021). The article will focus on changing the façade's pattern in order to adapt to the interior and exterior environment.

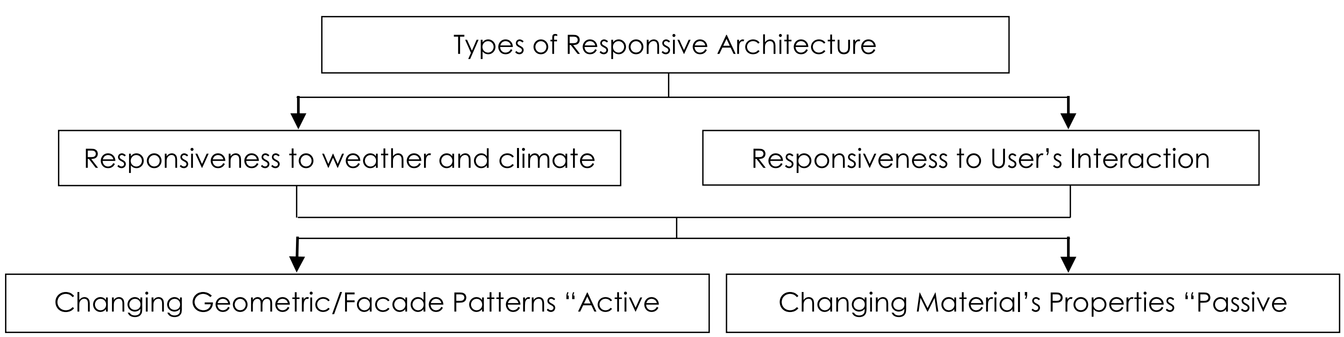


Figure 2. Types of Responsive Architecture (Source: Developed by Authors, 2024)

3.2. Climatic Conditions in Egypt

Climatic conditions of a region define its ecology, water availability, species distribution, land suitability for building and construction (Konapala, Mishra, Wada, & et al., 2020). Thus, classification of regions based on climate is crucial for development planning and building implementation. As a result, different climate variables such as temperature, humidity and rainfall, are being studied as the main contributor of the climate classification in order define and classify some geographical regions (Sa'adi, Shahid, & Shiru, 2021). In Cairo, the length of the day varies significantly over the year. As shown in figure (3), December 21 is considered the shortest day with 10 hours and 13 minutes of solar radiation, however, June 21 is considered the longest day of the year with 14 hours and 5 minutes of solar radiation (El-Shazly, 2021). As shown in figure (4), 4:35 am is the earliest sunrise on June 11, however the latest sunrise

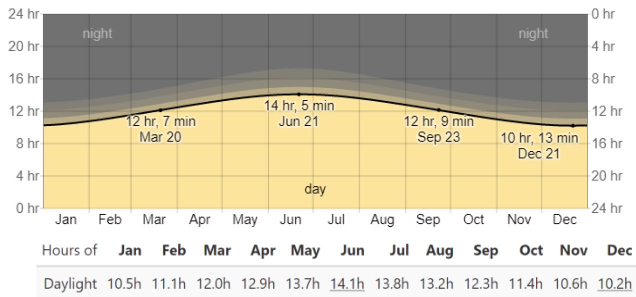


Figure 3. Hours of Daylight and Twilight in Cairo, Egypt (Source: Climate and Average Weather Year-round in Cairo, 2024)

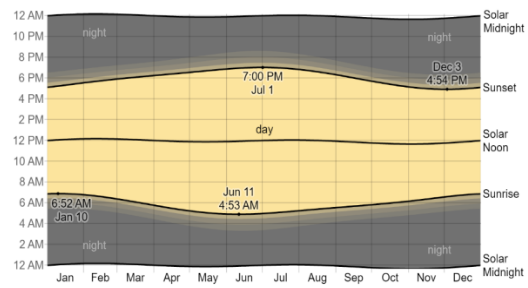


Figure 4. Hours of Daylight and Twilight in Cairo, Egypt (Source: Climate and Average Weather Year-round in Cairo, 2024)

is at 6:52 am on January 10. Moreover, 4:54 pm is the earliest sunset on December 3 and 7:00 pm is the latest sunset on July 1 (El-Shazly, 2021).

3.3. Selected Comfort Index

Human comfort is defined as the ways the space user perceives and feels towards the environment of a specific space. Space occupant perceives the indoor environment based on their health, productivity and wellbeing. The indoor human comfort is based on four aspects, thermal comfort, visual comfort, acoustic comfort and respiratory comfort (Song, Mao, & Liu, 2019). This study will focus on the thermal comfort aspect as it is considered as the most crucial aspect for the human comfort compared to visual, acoustic and respiratory comfort parameters. It was proved that thermal comfort has a greater influence on the space user's satisfaction (Solano, Caamaño-Martín, Olivieri, & Almeida-Galarraga, 2021).

Thermal comfort is defined as "a condition of mind that expresses satisfaction with the thermal environment in which it is located" based on ISO Standard 7730 (1994) and ASHARE Standard 5 (Chow, 2017). ASHRAE is a professional association, that defines guidelines and standards for thermal comfort. Moreover, thermal comfort is considered as the main factor of the operation of the HVAC systems in buildings [14]. HVAC systems consume 44 % of building energy (Ardente et al., 2020). By controlling thermal comfort inside buildings and thus reducing the HVAC systems, the energy consumed during the operational phase of the buildings can be reduced. As a result, the study will focus on the thermal comfort aspect in order to propose solutions for reducing the excessive energy consumed by buildings and thus enhance the building performance.

4. Research Methodology

4.1. Research Design

As shown in Figure (5), the research is composed of four sections, each aimed at investigating and analyzing the optimal right-angled triangular facade design that enhances indoor thermal comfort, reduces solar radiation, and improves energy consumption rates. The following sections outline the approach taken in this study:

Stage one: a comprehensive literature review on responsive architecture and climatic conditions in Egypt was conducted to establish a solid foundation for the research.

Stage two: the research selected a comfort index as well as identified the simulation model's spatial configuration where simulations were carried out to compare the selected comfort index with and without various proposed responsive facades.

Stage three: a comparative analysis was performed to evaluate the results and determine the optimal right-angled triangular facade design for enhancing indoor comfort and reducing energy consumption.

Stage four: discussion and analysis of the results were conducted in order to highlight the most efficient façade proposal in terms of reducing the solar radiation, improving the indoor thermal comfort and enhancing the building performance. This methodology ensures a systematic and comprehensive analysis of responsive facade patterns in Cairo, Egypt.

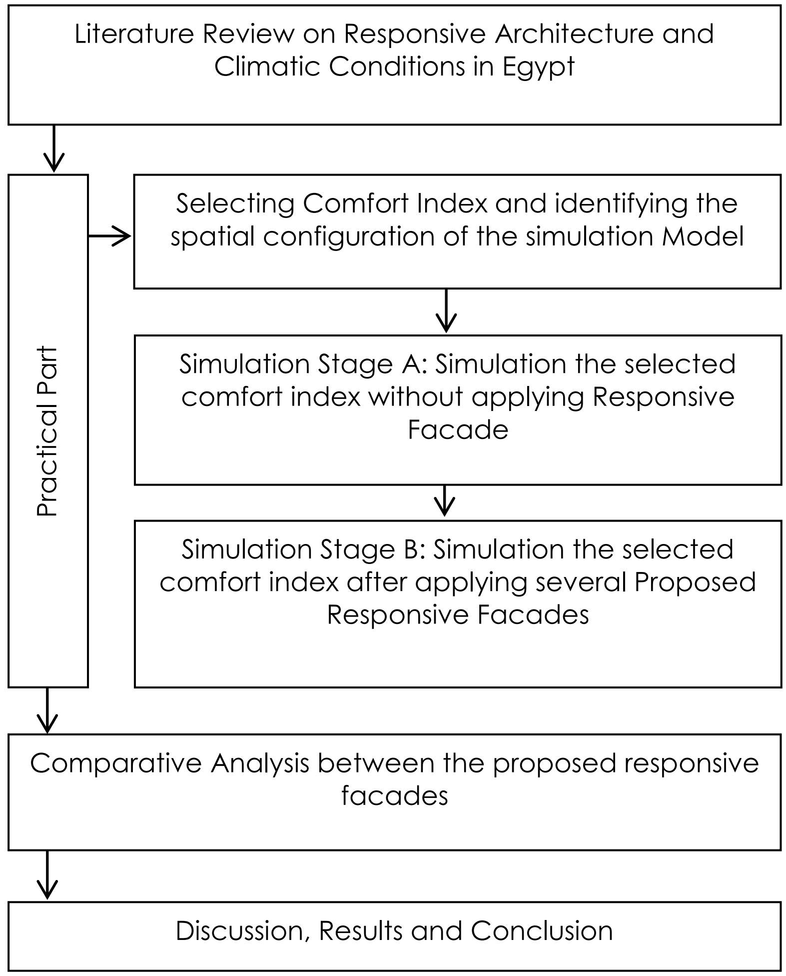


Figure 5. Research Methodology (Source: Developed by Authors, 2024)

4.2. Spatial Configurations of the simulation Model

The simulation model is located in New Cairo district, Cairo city in Egypt, as shown in figure (6). The simulation model

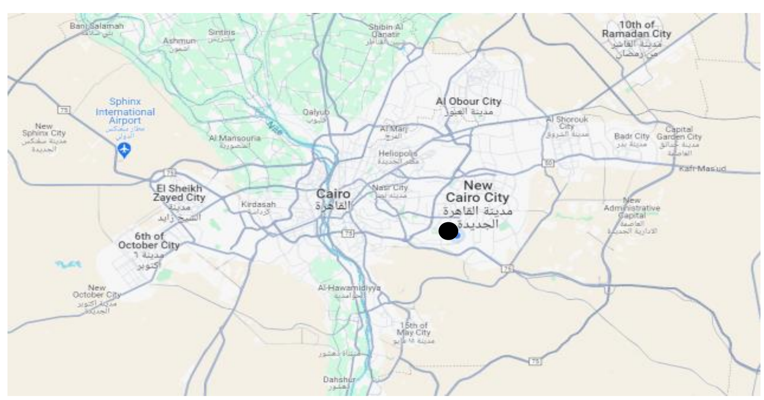


Figure 6. Empirical Case Study Location (Source: Developed by Authors, 2024)

is an office room with the below specifications, as shown in figure (7),

- <u>Room Clear Dimensions:</u> 4 meters * 5.5 meters
- <u>Room Clear Height:</u> 3 meters
- <u>Window Dimensions:</u> The window will be located on the south façade with a full coverage of the façade. The dimensions of the window 4m*3m
- <u>Room Accessibility:</u> Wooden Door with dimensions of 0.9m width and 2.2m height, located on the East Wall.
- <u>Room Occupancy:</u> Two users
- <u>Room Furniture:</u> Two chairs, two desks and one shelve
- Room Equipment: Two computers

The selected dimensions and specifications of the case study are derived from "Office space standards and guidelines" book, where it specified that the footprint for an office that occupies two users should be 22 square meters (Baker & Hutton, 2019).

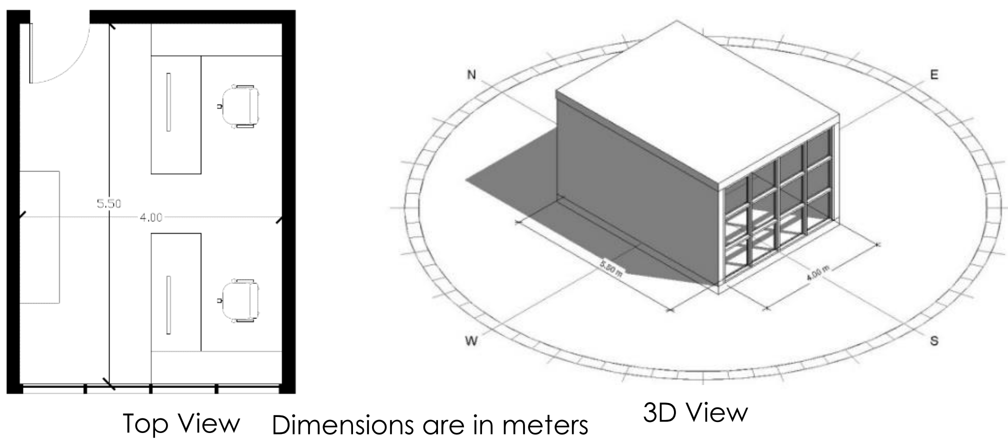


Figure 7. Empirical Case Study Specification (Source: Developed by Authors, 2024)

4.3. Methods and Simulation Tools

The empirical Study is carried out using Rhino 7, Grasshopper 11.2 Plugin, Ladybug 0.0.69 Plugin and Honeybee 0.0.69 Plugin. A shown in figure (8), the simulation process on Grasshopper plugin was divided into several stages. The first stage, each proposed responsive façade was created through an explicit script. Afterwards, the empirical room was created were the Honeybee zone, room program, room HVAC system and room construction material were defined. The room program and HVAC system were set according to ASHREA 90.1 2019. Then, the simulation process was implemented where the solar radiation, cooling energy as well as operative temperature were investigated.

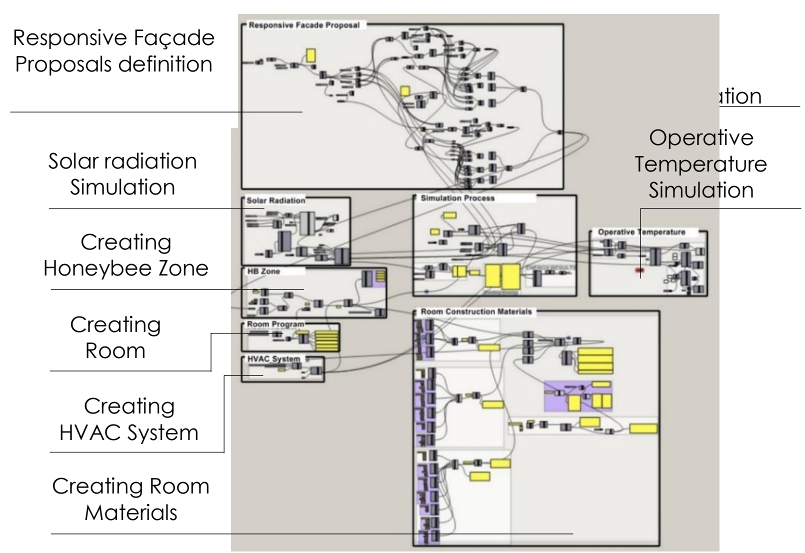


Figure 8. Empirical Study Simulation Grasshopper Definition (Source: Developed by Authors, 2024)

5. Research Analysis

The thermal comfort simulation is divided into two stages. In stage A, the solar radiation, room operative temperature and the cooling energy required for maintaining the indoor thermal comfort is examined without applying responsive façade on the south window façade. However, in stage B the same parameters after applying several responsive proposed facades on the south glazed façade will be examined. The two stages will be carried out in order to investigate the effect of the proposed responsive facades on the window façade as well as identifying the most efficient proposal in enhancing the thermal comfort, reducing the solar radiation, minimizing the cooling energy and improving the building performance.

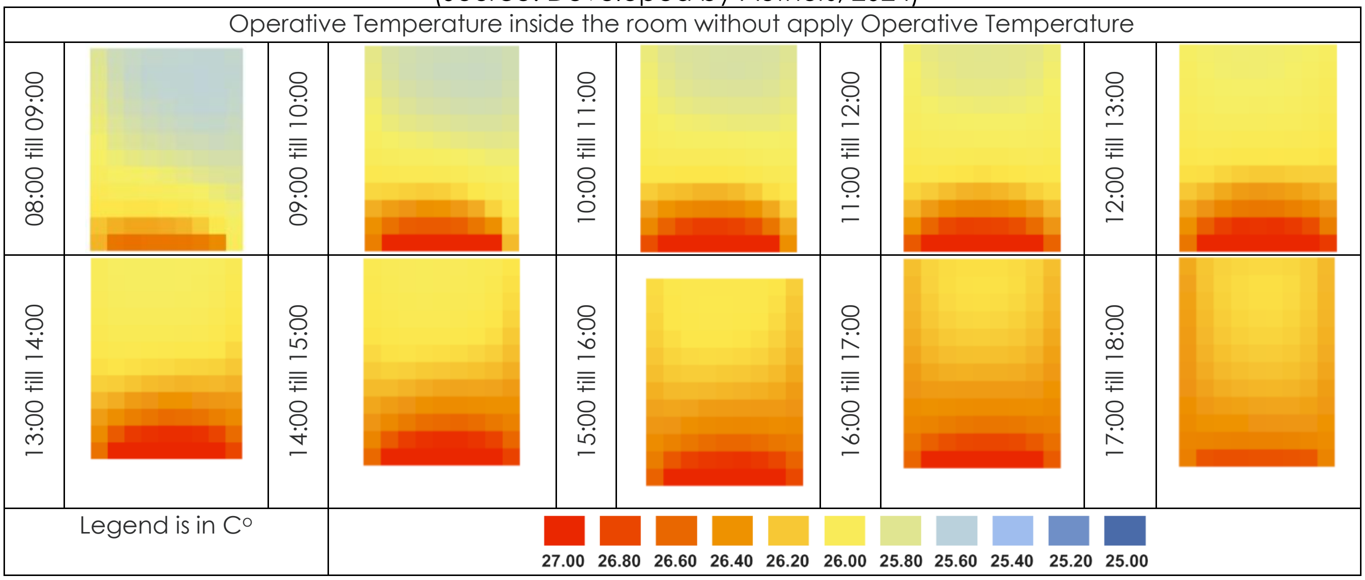
5.1. Thermal Comfort Without Applying Responsive Façade

Solar radiation on the south glazed façade as well as the cooling energy is simulated on June 21 without applying any proposed responsive façade, starting from 08.00 am till 06.00 pm with an hour interval time, as shown in table (1). Besides, the operative temperature consuming the cooling energy to maintain thermal comfort inside the room is simulated, as shown in table (2).

Table 1. Solar Radiation and Cooling Energy Analysis without applying Responsive Façade (Source: Developed by Authors, 2024)

Time During the Day	Solar Radiation on the Window Façade (KWh)	Cooling Energy (KWh)
08:00 till 09:00	2.254	0.557
09:00 till 10:00	3.187	0.595
10:00 till 11:00	4.202	0.688
11:00 till 12:00	4.362	0.783
12:00 till 13:00	4.071	0.814
13:00 till 14:00	4.018	0.905
14:00 till 15:00	3.507	0.974
15:00 till 16:00	2.523	1.008
16:00 till 17:00	1.819	1.024
17:00 till 18:00	1.493	0.955
Total during the day	31.436	8.303

Table 2. Operative Temperature inside the Room without applying Responsive Façade
(Source: Developed by Authors, 2024)



As shown in table (1), the solar radiation intensity differs during the day starting from 08:00 am till 06:00 pm, where the solar radiation is at its highest from 10.00 am till 14.00 pm, however the solar radiation is at its lowest from 5.00 pm till 06.00 pm. The responsive facades designs proposed by the research rotates around their axis of movement in order to block the entrance of the solar radiation and thus reduce the cooling energy and enhance the indoor operative temperature. According to the solar radiation and the cooling energy results, a grasshopper remapping process was done in order to create the moving angles of the proposed responsive facades, as shown in table (3). The results of the remap process were transformed to the nearest 15 degrees. The same proposed angles of movement will be used for the responsive façade proposals.

Table 3. Proposed angles of movement for the responsive façade proposals
(Source: Developed by Authors, 2024)

Axis of Movement of the Proposed Responsive Facades										
Time during the Day	08:00 till 09:00	09:00 till 10:00	10:00 till 11:00	11:00 till 12:00	12:00 till 13:00	13:00 till 14:00	14:00 till 15:00	15:00 till 16:00	16:00 till 17:00	17:00 till 18:00
Grasshopper Remapping Angles	66.1 °	36.9 °	5 °	0 °	9.1 °	10.8 °	26.8 °	57.7 °	79.7 °	90 °
Approximate Angles to the Nearest 15 °	60 °	30 °	0 °	0 °	15 °	15 °	30 °	60 °	75 °	90 °

5.2. Thermal Comfort with Applying Proposed Responsive Façade

All the proposed responsive façade designs have the right-angled triangle properties. The research focused on investigating the right-angled triangle shape to applied in a responsive façade pattern. As the right-angled triangle is well-known for its simplicity in calculation. It allows for straightforward calculations using the Pythagorean theorem, which states that in a right triangle, the square of the length of the hypotenuse is equal to the sum of the squares of the other two sides. This relationship simplifies many mathematical problems, especially in design and construction. Besides, in a right triangle, two squares can be inscribed such that they share a vertex at the right angle. This unique property allows for an efficient pattern design in terms of area and materials when designing structures that incorporate square patterns. Moreover, the right-angled triangle can be easily designed and embedded in both square and rectangular design patterns. This versatility makes them a popular choice in architectural designs and engineering applications (Khan & Ali, 2020).

After studying the properties of the right-angled triangle, it was concluded that the right-angled triangle can be applied in the pattern with two opposite diagonals, as shown in figure (9). Thus, the right-angled triangle with the rotational movement will be investigated using those two opposite diagonals. Besides, the two opposite diagonals will be studied on two different axes of movement, the vertical and the horizontal axes of movement, as shown in figure (9). The proposed pattern is designed within a 1m*1m rectangle. As the dimensions of the window on the south façade are 4m*3m, 12 motifs are created to cover the whole south glazed façade. Table (4) shows the movement of each proposed case according to the rotational movement. Moreover, table (6) shows that results of the solar radiation and the cooling energy required to maintain the thermal comfort zone after applying the proposed pattern of case 1. Moreover, table (7) shows the results of the operative temperature inside the room. Nevertheless, table (8) shows the operative temperature inside the room after applying the proposed responsive facades.

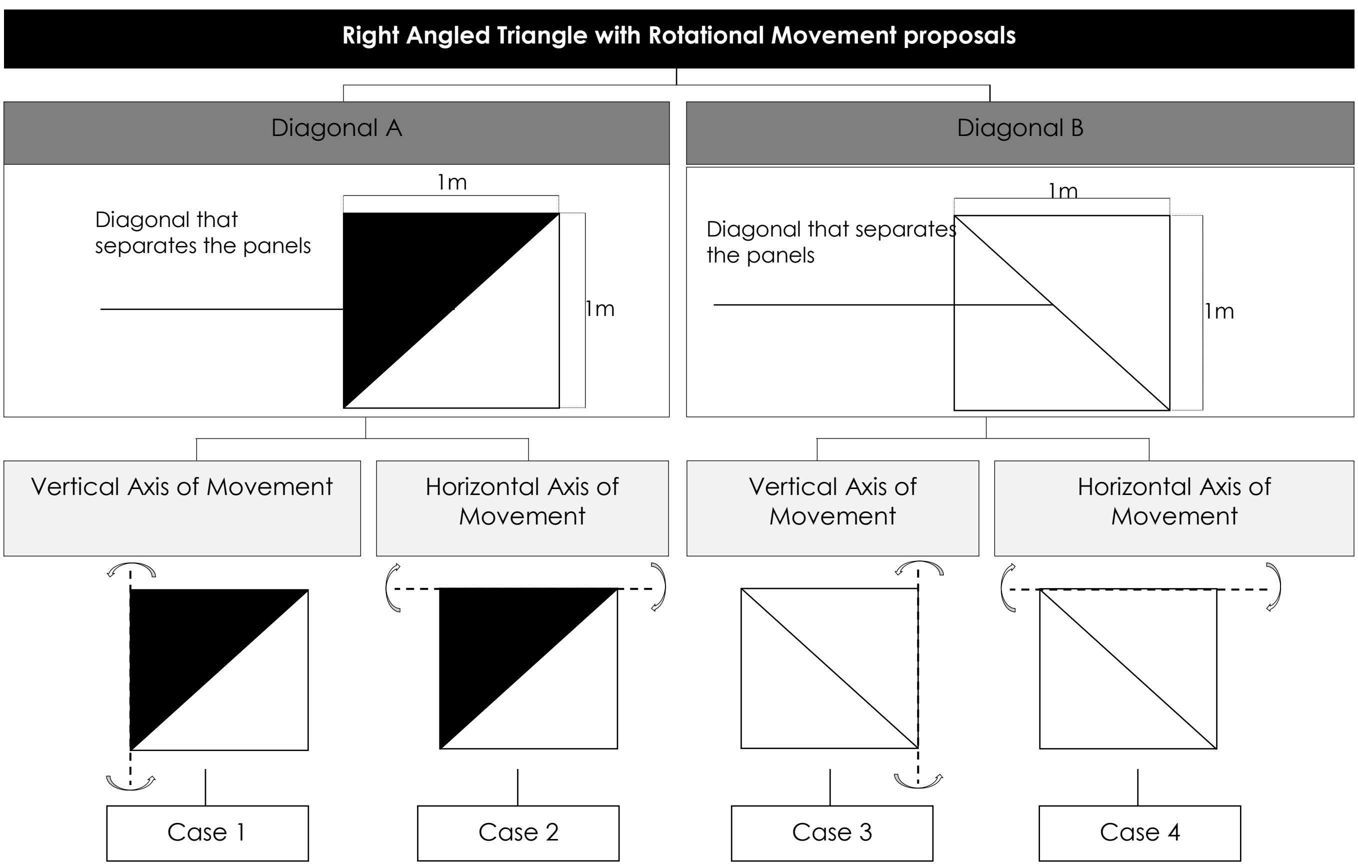
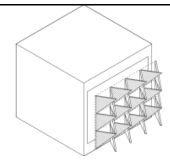
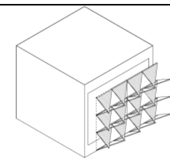
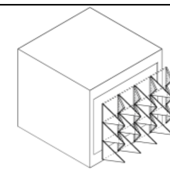
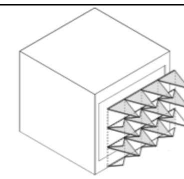
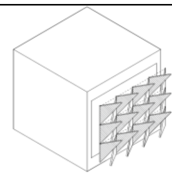
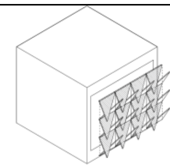
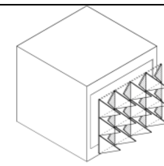
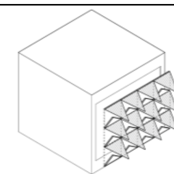
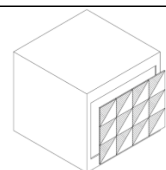
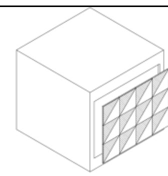
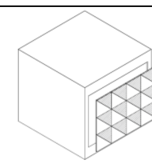
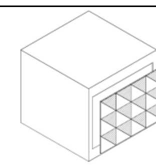
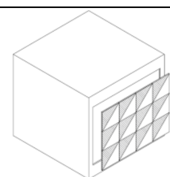
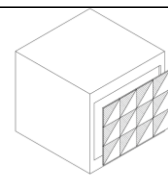
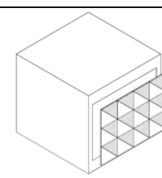
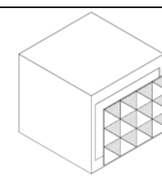
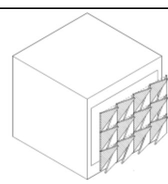
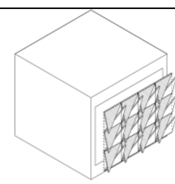
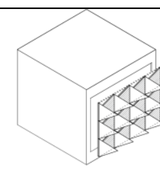
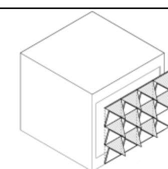
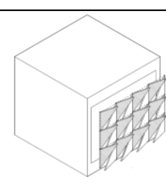
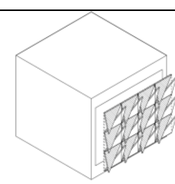
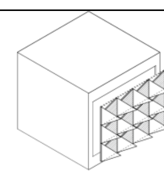
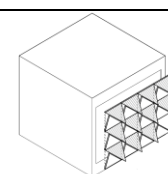
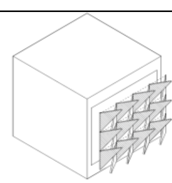
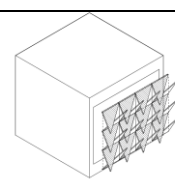
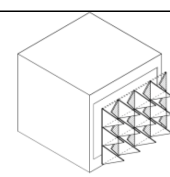
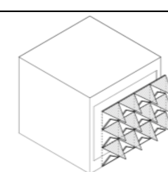


Figure 9. Right Angled Triangle with Rotational Movement Proposals (Source: Developed by Authors, 2024)

Table 4. Rotational Movements Configurations of the proposed Responsive Façade

Rotational Movements Configurations					
Time During the Day	Angle of Movement	Case 1	Case 2	Case 3	Case 4
08:00 till 09:00	60 °				
09:00 till 10:00	30 °				
10:00 till 11:00	0 °				
11:00 till 12:00	0 °				
12:00 till 13:00	15 °				
13:00 till 14:00	15 °				
14:00 till 15:00	30 °				

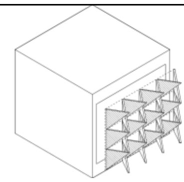
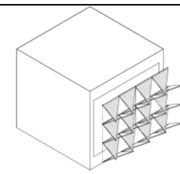
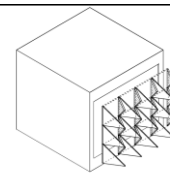
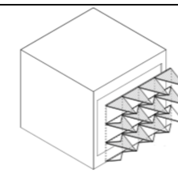
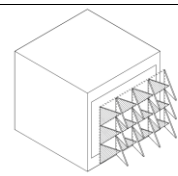
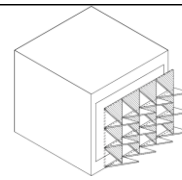
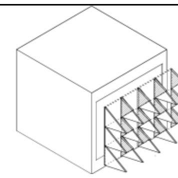
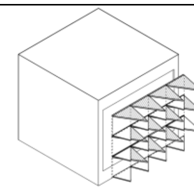
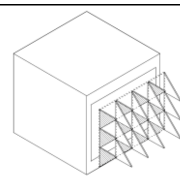
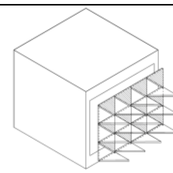
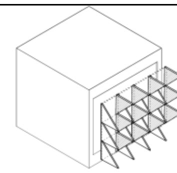
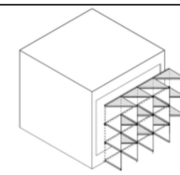
15:00 till 16:00	60 ᵒ				
16:00 till 17:00	75 ᵒ				
17:00 till 18:00	90 ᵒ				

Table 5 shows a comparative analysis between the four proposed responsive façade designs where the four proposals rotate around their axis of movement starting from 08:00 till 18:00 with the same angle of rotation each one-hour interval of time. Besides, table 6 shows the results of the cooling energy after applying the four responsive facades proposals. Moreover, table 7 shows the operative temperature inside the room after applying the four proposed responsive façade designs.

Table 5. Solar Radiation Analysis Results after applying the investigated Responsive Façade (Source: Developed by Authors, 2024)

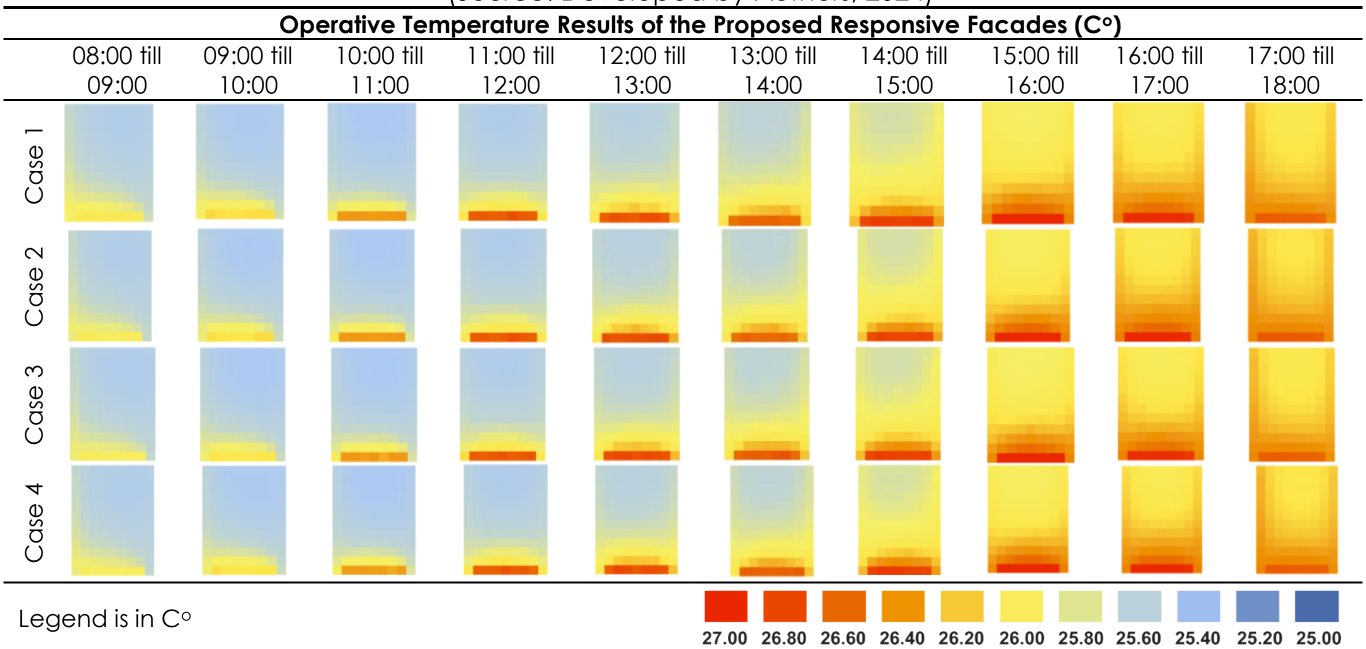
Solar Radiation Simulation Results of the Proposed Responsive Facades (KWh)					
Time During the Day	Angle of Movement	Case 1	Case 2	Case 3	Case 4
08:00 till 09:00	60 ᵒ	1.204	1.138	1.178	1.108
09:00 till 10:00	30 ᵒ	1.269	1.260	1.179	1.216
10:00 till 11:00	0 ᵒ	1.191	1.191	1.191	1.191
11:00 till 12:00	0 ᵒ	1.711	1.711	1.711	1.711
12:00 till 13:00	15 ᵒ	2.338	2.349	2.334	2.354
13:00 till 14:00	15 ᵒ	2.216	2.303	2.213	2.256
14:00 till 15:00	30 ᵒ	1.913	1.979	1.971	1.903
15:00 till 16:00	60 ᵒ	1.546	1.477	1.542	1.483
16:00 till 17:00	75 ᵒ	1.066	1.130	1.037	1.087
17:00 till 18:00	90 ᵒ	0.826	1.004	0.914	1.026
Total during the day		15.28	15.542	15.27	15.335

Table 6. Cooling Energy Analysis Results after applying the investigated Responsive Façade (Source: Developed by Authors, 2024)

Cooling Energy Simulation Results of the Proposed Responsive Facades (KWh)					
Time During the Day	Angle of Movement	Case 1	Case 2	Case 3	Case 4
08:00 till 09:00	60 ᵒ	0.537	0.536	0.534	0.536
09:00 till 10:00	30 ᵒ	0.552	0.550	0.549	0.551
10:00 till 11:00	0 ᵒ	0.616	0.616	0.616	0.616
11:00 till 12:00	0 ᵒ	0.713	0.713	0.712	0.712
12:00 till 13:00	15 ᵒ	0.742	0.744	0.745	0.746
13:00 till 14:00	15 ᵒ	0.826	0.828	0.830	0.830

14:00 till 15:00	30 °	0.905	0.904	0.902	0.907
15:00 till 16:00	60 °	0.967	0.969	0.963	0.966
16:00 till 17:00	75 °	0.991	1.002	0.982	0.999
17:00 till 18:00	90 °	0.932	0.943	0.930	0.940
Total during the day		7.781	7.805	7.763	7.803

Table 7. Operative Temperature Results after applying the investigated Responsive Façade (Source: Developed by Authors, 2024)



6. Discussion and Results

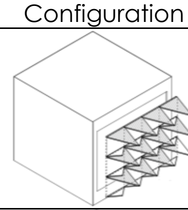
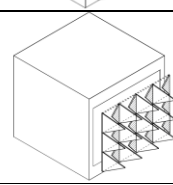
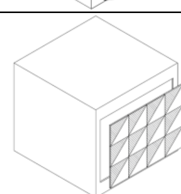
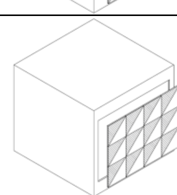
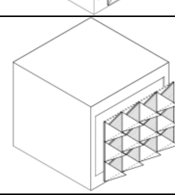
Energy consumption worldwide is rising rapidly due to factors like population growth, increased manufacturing demands, and climate change, with buildings alone accounting for 35% of global energy use in 2021 (International Renewable Energy Agency, 2023). Notably, energy for space cooling has tripled since 1990, and HVAC systems are responsible for 44% of building energy consumption (Ardente et al., 2020). This has led to a pressing need for energy-efficient building designs and improved air conditioning systems. The research focused on a right-angled triangular façade for a south-glazed building in Cairo, aiming to enhance indoor thermal comfort while minimizing solar radiation and energy consumption.

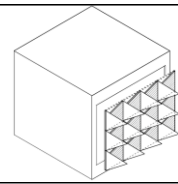
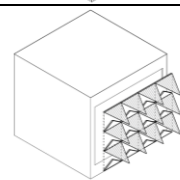
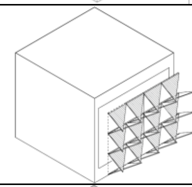
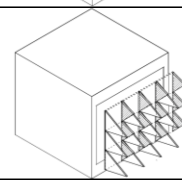
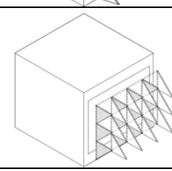
The study successfully achieved its initial hypotheses by demonstrating that implementing responsive façades can significantly reduce both cooling energies needs and solar radiation exposure. This is evidenced by the comparative analysis conducted between buildings equipped with the proposed responsive façades and those without. The study's hypotheses regarding the positive impact of the façade designs on energy efficiency and thermal comfort were supported by substantial findings.

The study proposed four different responsive façade designs that rotate around their axis of movement from 08:00 AM to 06:00 PM. The rotational angles were designed to change at hourly intervals based on solar radiation results obtained in Stage A. A remap process using Grasshopper allowed the four proposals to rotate from 0° to 90°, with a 15° increment at each hour. During peak solar radiation hours (10:00 AM to 12:00 PM), the façades were fully closed, while they opened completely during lower solar radiation periods (5:00 PM to 6:00 PM). The comparative analysis of the study concluded the following:

- Solar Radiation Reduction: Applying a responsive façade on the south-glazed façade in Cairo can reduce solar radiation by 50.62% to 51.43%. Although the differences among the four designs are minimal, Case 3 emerged as the most effective, achieving a reduction of 51.43%.
- Cooling Energy Reduction: The reduction in cooling energy among the proposals also showed slight variation, with Case 3 again leading with a 6.5% reduction. The other cases achieved reductions ranging from 5.99% to 6.29%.
- Indoor Operative Temperature: All four responsive proposals enhanced the indoor operative temperature within the investigated room, further supporting the study's hypothesis regarding improved indoor comfort.
- As the four responsive proposals shared similar properties, dimensions, and rotational movement, as a combined design can be proposed where the axis of movement can differ in each one-hour interval of time as shown in table (9). The combined proposal is created according to selecting the proposed façade with the lowest solar radiation result in each one-hour time interval. The combined proposal reduces the solar radiation with 52.35% and minimizes the cooling energy with 6.323%.

Table 8. Combined Responsive Façade Proposal (Source: Developed by Authors, 2024)

Combined Responsive Facade Proposal					
Time During the Day	Angle of Movement	Case Number	Rotational Configuration	Solar Radiation (KWh)	Cooling Energy (Kwh)
08:00 till 09:00	60 °	Case 4		1.108	0.536
09:00 till 10:00	30 °	Case 3		1.179	0.549
10:00 till 11:00	0 °	Any one of the cases		1.191	0.616
11:00 till 12:00	0 °	Any one of the cases		1.711	0.712
12:00 till 13:00	15 °	Case 3		2.334	0.745

13:00 till 14:00	15°	Case 3		2.213	0.830
14:00 till 15:00	30°	Case 4		1.903	0.907
15:00 till 16:00	60°	Case 2		1.477	0.969
16:00 till 17:00	75°	Case 3		1.037	0.982
17:00 till 18:00	90°	Case 1		0.826	0.932
Total Result on June 21				14.979	7.778

In summary, the findings affirm that the proposed right-angled triangular façade designs effectively meet the initial objectives of the study, validating the hypothesis that responsive façades can enhance indoor thermal comfort while significantly reducing both solar radiation exposure and energy consumption. This highlights the importance of integrating such innovative architectural solutions in response to the growing challenges posed by climate change and energy demands in urban environments.

7. Conclusion

In conclusion, this research aims to identify the optimal design proposal for a right-angled triangular façade applied to a south glazed façade in Cairo, Egypt. The study focused on prioritizing indoor thermal comfort, minimizing solar radiation, reducing energy consumption, and improving overall building performance. By conducting a comparative analysis of four different responsive façade proposals, it was observed that applying a responsive façade on the south glazed façade significantly reduced solar radiation, minimized cooling energy requirements, and enhanced indoor operative temperature. The analysis revealed that among the four proposals, Case 3 was identified as the most efficient in reducing solar radiation on the south glazed façade. However, the difference in solar radiation reduction among the proposals was not substantial. Furthermore, the study found that applying a responsive façade on the south glazed façade in Cairo, Egypt, on June 21 resulted in a range of 5.99% to 6.5% reduction in cooling energy requirements for maintaining indoor thermal comfort. Case 3 is the most efficient proposal in reducing the cooling energy among the four proposals. Additionally, all four responsive proposals improved the indoor operative temperature inside the investigated room. As a future recommendation, a combined design proposal could be considered, where the axis of movement is adjusted in each one-hour interval based on the proposed façade with the lowest solar radiation result. This combined proposal achieved a reduction of 52.35% in solar radiation and a decrease of 6.323% in cooling energy consumption. Overall, this research highlights the benefits of implementing responsive façade designs to optimize energy efficiency, minimize solar radiation, and enhance indoor thermal comfort in buildings with south glazed façades.

Research Limitation

The research is limited to a room located in Cairo, Egypt, featuring a wide opening that faces the southern façade. The results were gathered on June 21st, a day chosen for its peak solar radiation, providing a focused analysis of the room's performance and its energy consumption.

Future Research

The research results can be examined in the future with the below aspects,

- The effect of applying the proposed responsive facades on the visual comfort parameter
- The effect of applying the proposed responsive facades on the heating load
- Optimization between the solar radiation and the daylighting
- Investigating effect of applying the proposed responsive facades on the user’s psychological factor
- Investigating the proposed responsive facades on the west, east facades
- Investigating the proposed responsive facades on during the whole year

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statements

Studies involving animal subjects: No animal studies are presented in this manuscript.
Studies involving human subjects: No human studies are presented in this manuscript.
Inclusion of identifiable human data: No potentially identifiable human images or data is presented in this study.

Conflict of Interests

The author declares no conflict of interest.

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