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# REDUCTION OF THERMAL LOADS BY BIOMIMETIC RESPONSIVE SKINS

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## ABSTRACT

Previous studies proved that building skins are mostly responsible for the energy consumed inside the buildings. Recently, new perspectives for building skins appeared; some of them were enhancing their responsiveness to the surrounding environment. Biomimicry is also one of the innovative approaches that the world starts to head for, to find ideas and solutions for humans' problems through mechanisms and materials found in nature. This paper is seeking to integrate biomimetic characteristics of plants into the design of a responsive skin as a way to reduce thermal loads in office buildings by adjusting the model and testing variables using Grasshopper as a simulation program to reach the best result.

The study took place in Giza, Egypt, for a medium-sized office building consisting of 3 levels of open spaces with an area of 1,665 $m^2$ for each floor. Results showed That the proposed skin could decrease the thermal loads, especially cooling loads with an 8% reduction.

**KEYWORDS:** Biomimicry, biomimetic architecture, Responsive skin, Thermal loads, Energy efficiency

**تقليل الأحمال الحرارية بواسطة المحاكاة البيولوجية في الأغلفة المتجاوبة**

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**الملخص**

أثبتت الدراسات السابقة أن الأغلفة الخارجية للمباني هي المسؤولة غالبا عن الطاقة المستهلكة داخلها. في الآونة الأخيرة، ظهرت رؤي جديدة لأغلفة المباني، بعض منها كان لتعزيز استجابتها للبيئة المحيطة. تعتبر محاكاه الطبيعة ايضا من أحد

الأساليب المبتكرة التي بدأ العالم في التوجه إليها، للعثور على أفكار وحلول لمشاكل البشر من خلال الآليات والمواد الموجودة في الطبيعة. تسعى هذه الورقة البحثية إلى دمج خصائص المحاكاة البيولوجية للنباتات في تصميم الغلاف المتجاوب كوسيلة لتقليل الأحمال الحرارية في المباني الإدارية، من خلال ضبط النموذج المُصمم واختبار المتغيرات باستخدام Grasshopper كبرنامج محاكاة للوصول إلى أفضل نتيجة.

تمت الدراسة في محافظة الجيزة بمصر، لمبنى إداري متوسط الحجم يتكون من ٣ مستويات من المساحات المفتوحة بمساحة ١،٦٦٥ م ٢ لكل طابق. أظهرت النتائج أن الغلاف المقترح يمكن أن يقلل من الأحمال الحرارية، خاصة أحمال التبريد بتخفيض قدرة ٨٪.

**الكلمات المفتاحية:** محاكاه الطبيعة، المحاكاة البيولوجية المعمارية، الغلاف المتجاوب، الأحمال الحرارية، كفاءة الطاقة.

## 1. INTRODUCTION

One of today's challenges is the world's energy crisis which rises every year. Statistics showed that buildings are responsible for 36% of the global total energy consumption. Space heating and cooling only accounted for around 50% of the total building energy consumption. Also, it remains heavily depend on fossil fuels and contributes nearly 40% of global energy-related CO2 emissions [1].

Over 50% of the world's population currently works in some form of office. The indoor environment influences the performance, productivity, and well-being of office workers. According to a study by Vimalanathan & Babu, room temperature has the most effect on employees' performance as it contributes (38.56%), while the effect of illumination is (19.91%) [2].

The building skin is the primary subsystem through which prevailing external conditions can be influenced and regulated to meet the comfort requirements of the user inside the building [3]. It is similar to natural skin in that it is composed of layers and filters that react to light, air, moisture, sound, and heat in the same way that natural skin does. Natural skin is known for its ability to maintain interior conditions while remaining responsive to its function [4].

## 2. RESEARCH PROBLEM

During the design process of office buildings, architects focus on the illumination and achieving visual comfort, also on the aesthetic aspects of the buildings. So, they were directed to use fully glazed facades, which leads to an increase in solar heat gain [5]. As a result, spaces became thermally uncomfortable, and to reach thermal comfort, the reliance on HVAC increases over time, leading to excessive thermal loads. The paper worked on a solution for this problem through nature.

## 3. RESEARCH METHODOLOGY

### A. Theoretical study

-Defining Biomimicry and responsive architecture.

-Illustrating thermal loads in buildings.

**B. Analytical study**

-Inspiration from a specific organism and extraction of its characteristics.

-Description of characteristics as design constraints.

**C. Simulation**

-Applying biomimetic principles to the design of responsive building skin.

-Analyzing simulation results.

Rhinoceros and Grasshopper plug-in were used to model the building and the responsive skin. After that, ladybug tools were used for the simulation process, using radiance, open studio, and energy plus files.

# 4. BIOMIMETIC AND RESPONSIVE ARCHITECTURE

Nature's innovative solutions have inspired the emergence of new fields of science, such as biomimetic (biomimicry), biomorphic and bionic approaches in architecture and engineering [6]. Awareness is raised about the environment because of the increased interdependence and reliance on computation in our daily lives. Continuously, the environment's data is stored, processed, shared, and transmitted to adapt and react to our actions and signals smoothly, and when it comes to climatic adaptation, responsiveness becomes a major topic in architecture.

## 4.1. Biomimicry In Architecture

Biomimicry has several definitions but the term itself (bios: life, mimesis: imitation) was first coined by Janine M. Benyus as “the conscious emulation of nature’s genius”. It’s an innovation method that searches for sustainable solutions by emulating nature's patterns and strategies, to create designs, products, and processes to solve human problems [7].

Biomimicry has two approaches to the design process:

**A. Biology influencing design (Solution-based)**
It's used when the design process is based on biologists' and scientists' scientific knowledge rather than human design issues.

**B. Design looking to biology (Problem-based)**
It’s about the designers' search for solutions to the identified problems, and then biologists have to match them to organisms that solved similar issues. This approach is effectively guided by designers that identify goals and parameters for the design [8].

For understanding the application of biomimicry, a framework is suggested that redefines these different levels while also attempting to explain biomimicry's potential as a tool for increasing the built environment's regenerative ability.

There are 3 levels of mimicry: organism, behaviour, and ecosystem. A further five possible dimensions to mimicry exist within each of these levels. The design may be biomimetic in terms of how it looks (form), what it's made of (material), how it's built (construction), how it works (process), or what it could do (function) [9].

### 4.2. Responsive Architecture

The term "responsive architecture” is defined as "a class of architecture or building to physically reconfigure themselves to meet changing needs with variable mobility, location, or geometry"[10]. Responsive architecture seeks to provide an Architectural solution that can learn to solve problems on its own by establishing a perfect symbiotic link between Technology, Structures, Nature, Humans, Building Materials, Building, and Environmental forces.

Buildings can respond to the weather and environment around them to improve their performance and lower the amount of solar radiation they receive, by changing geometric patterns or modifying the material properties of the façade.

**A. Changing geometric patterns**

This type of environment interface responsiveness is mostly depending on changing patterns and fragments on the facade. Building's skin is divided into patterns that change its location to decrease solar radiation entering the building.

**B. Changing material's properties**

This type of environment interface responsiveness is mostly depending on changing the materials properties of the façade. When a material is exposed to high levels of solar radiation, it changes its properties to reduce the amount of solar radiation that enters the building [11].

Learning from nature could be particularly helpful for biomimetic integration into responsive building skin design. Mimicking nature solves static facades problems allowing them to respond to changing conditions by playing multiple roles instead of one at a time, like permitting solar heat at certain times, not at others, and preventing glare while allowing daylighting and visual contact of occupants with the outside.

## 5. THERMAL LOADS IN BUILDINGS

Are the amount of heat energy that must be added to or removed from an area to keep the temperature within an acceptable range and achieve thermal comfort.

According to Pérez-Lombard et al. Heating, ventilation, and air conditioning (HVAC) account for (50%) of the energy consumed in office buildings, followed by lighting (15%), appliances (10%), and the remaining 25% by other activities [12].

Thermal loads are affected by six factors [13], [14]:

A. Orientation
B. External walls
C. Openings and windows
D. Air infiltration

E. Massing
F. Occupants, artificial lights, and equipment.

## 6. EXTRACTION OF MIMOSA PUDICA'S RELEVANT CHARACTERISTICS

The selection criteria of the inspired plant are summarized in three points:
-Energy-saving: An organism that can save energy.
-Responsiveness: An organism that responds rapidly to environmental conditions.
-Intelligence: An organism that can learn and memorize.

Mimosa pudica is one of the very few plants that can respond to the environment with a relatively large and vigorous movement in only a matter of seconds. It's also a good example of plants' learning and intelligence, as it learns not to close its leaves in response to thousands and thousands of caressing fingers. It has been learned that being touched repeatedly is a disturbance, with no life-threatening consequences, and therefore requires no reaction, to save more energy [15].

### A. Movement

It is known that the mimosa pudica leaf movements are correlated with the alternation of day and night, including the gradual opening, and closing of the leaves and the changes in the position of the petioles, while shock movements, consisting of the sudden closure of the leaves and the drop of the petioles, may be caused by mechanical, chemical, thermal or electrical stimulation [16].
Mimosa leaves close at night to save energy as there is no light and the temperature is relatively low. At night there is no photosynthesis, so leaving leaves unfolded is a waste of nutrients.

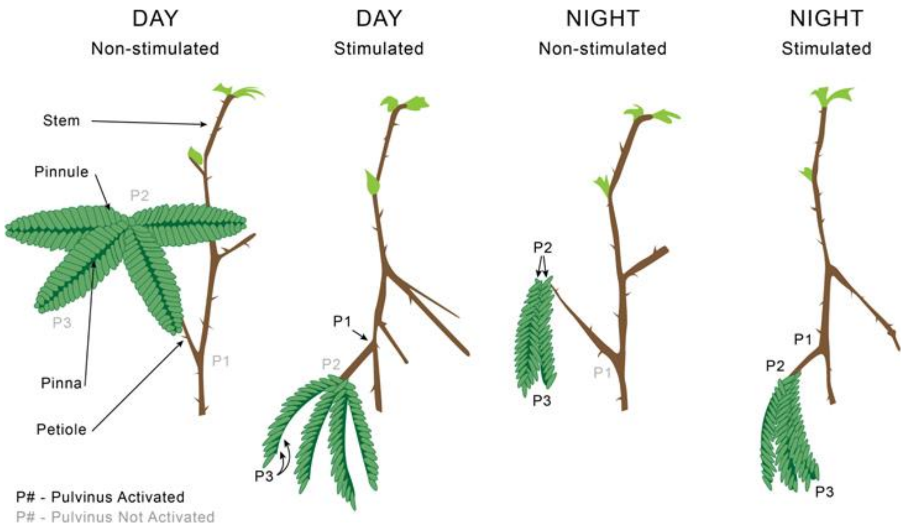



**Figure 1: Mimosa pudica response to stimulation during day and at night for the three pulvinus levels [17].**

### B. Cell shape

If the structure in the leaves of mimosa is examined, it can be seen that bending moments are caused by differences in turgor pressure, which causes the volume and shape of the cells to change greatly. These turgor pressure differentials cause the leaf structures to open and/or close. It appears how the cell took the hexagonal shape, which could be used in the design later [18].

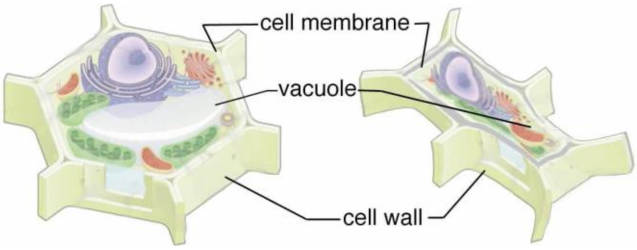



**Figure 2: Cellular Configurations of Plant Cells during opening** and **closing [18]**

## 7. DEFINITION OF CHARACTERISTICS AS DESIGN CONSTRAINTS

### A. Movement

Mimosa leaves folding and rotating forward from day to night appeared in the louvres' rotation on one axis by $90^0$, affected by the sun's path. As well as when it was stimulated thermally by being exposed to much cold in the daytime; when the interior temperature was below the comfort level, building skin louvres would also open during the day to let the radiation in for space's heating. During strong wind, skin louvres would close to protect themselves from being taken off.

### B. Shape

The hexagon shape was found a lot in the natural world. It was selected as there is no waste area between the cells' outlines. It also can be divided into triangles which consider the strongest shape that provides stability. Comparing how other shapes stand up to pressure proves the triangle's resilience. No matter the amount of pressure applied to a triangle, it would absorb the pressure and remain rigid.

## 8. APPLYING BIOMIMICRY

### 8.1. Modelling

Using the Problem-based approach, the skin design was inspired by the mimosa plant's cell. The hexagon shape was divided into 6 equal responsive louvres, and then the hexagon was repeated in a network form on the building's elevation.

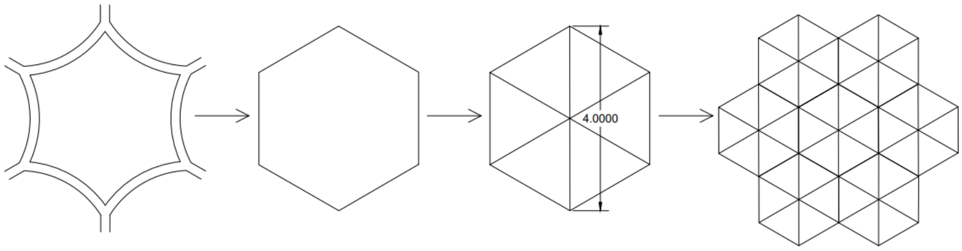



**Figure 3: Skin design from mimosa's cell**
**Source: Authors**

Louvres' movement was inspired by the mimosa leaflets' opening and closing technique.

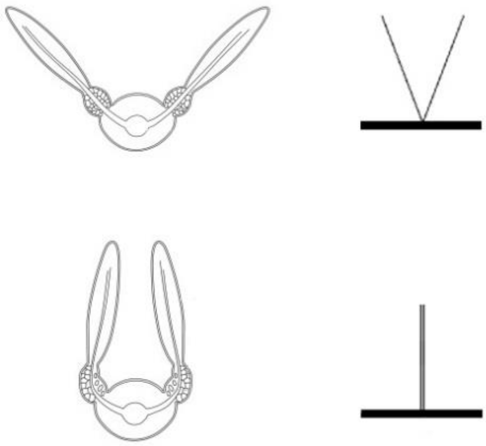


**Figure 4: Mimosa leaflets and louvres movement**
**Source: Authors**

The skin would depend on light sensors and temperature sensors in tracking the sun's path, and on motor-based actuators in its louvres' movement. At $90^0$, louvres were fully opened and perpendicular to the curtain wall. While at $0^0$, louvres were fully closed and parallel to the curtain wall.

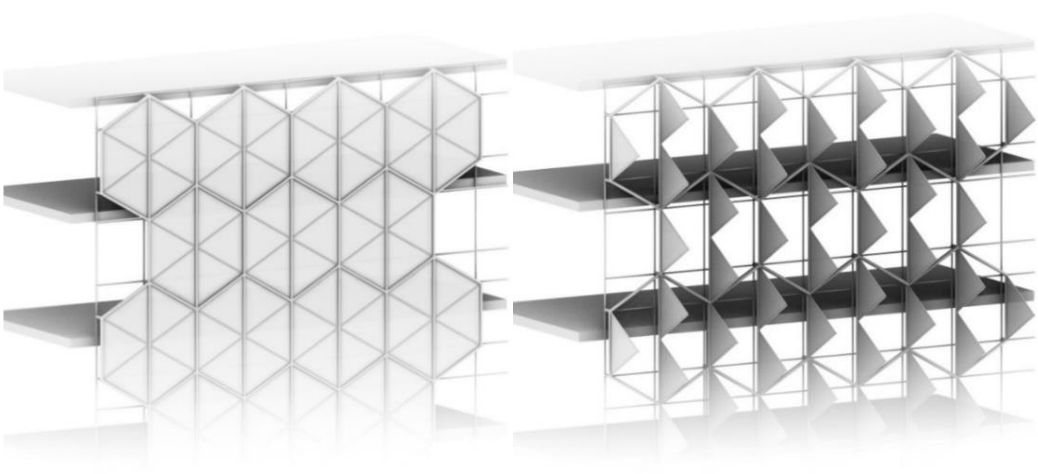


**Figure 5: The final appearance of the skin on the building**
**fully closed (on the left side) - fully opened (on the right side)**
**Source: Authors**

### 8.2. Simulation

### A. Simulation constraints

-Location: Smart Village in City of 6th of October- Giza, Egypt.
-Base case parameters: The base case of a medium office building from ASHRAE Standard 90.1 was used, but with a 100% window-to-wall ratio instead of 33%. The building consists of 3 floors with dimensions of 50m in length, 33.3m in width, and 12 m in height.

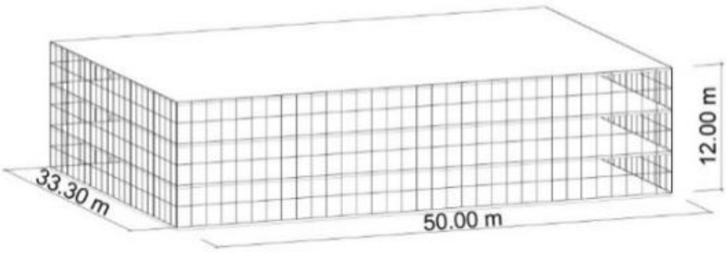



**Figure 6: The base case**
**Source: Authors**

-Direction: The designed skin was located on the east and the west sides because they have the largest solar intensities [19].
-Time: The study was performed on the 21st of June when the solar angle is at its maximum (summer). Through 9 hours, from 9 am to 5 pm, which is the most occupied hours.

### B. Simulation phases

The simulation process went through three phases:
-Phase one: Measuring louvres' angles.
-Phase two: Measuring operative temperature.
-Phase three: Measuring thermal loads.

## 9. RESULTS ANALYSIS

### 9.1. Phase One: Louvers' Angles

In this phase louvres' angles according to the sun path were measured, considering that the simulation time step is 1 hour.

### A. East

During the 9 hours of simulation, the east side of the building was exposed to direct sun radiation for 3 hours from 9:00 am to 11:00 am. At 9:00 am, louvres on the left side were about to close with $1^0$ while the right side was already closed. At 10:00 am louvres on the right side opened with $7^0$ and kept opening gradually till $24^0$ at 11:00 pm, while the left side kept closed until the sun radiation moved to the west at noon, then both sides opened to $90^0$.

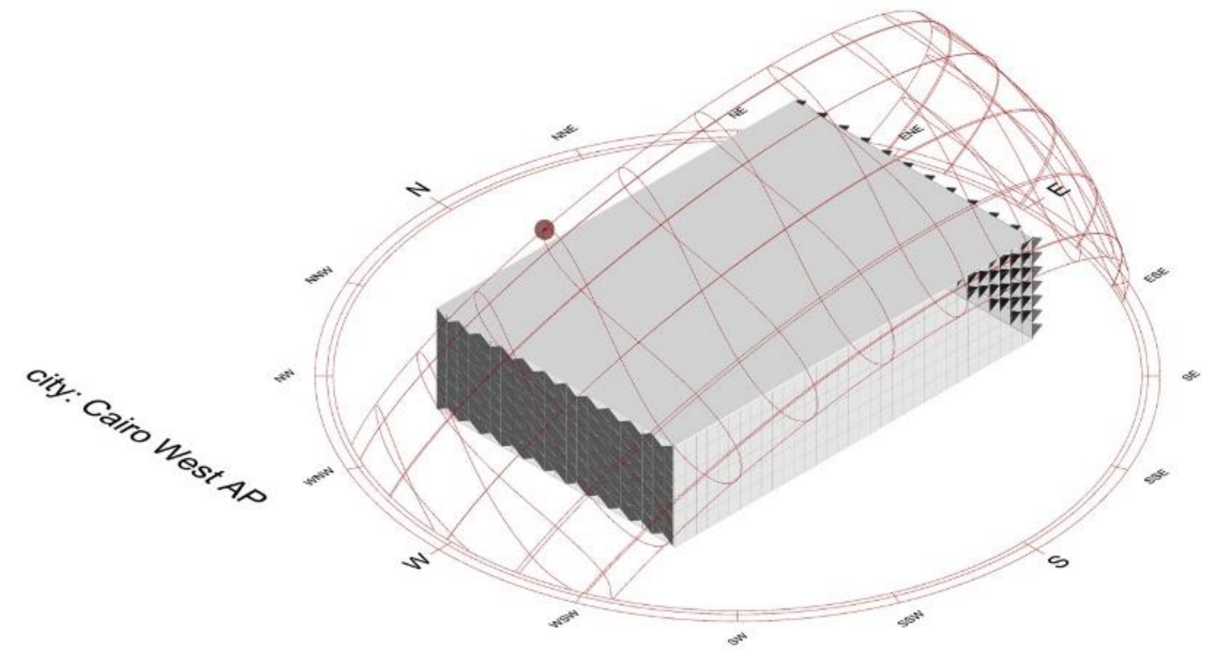
### B. West

During the 9 hours of simulation, the west side of the building was exposed to direct sun radiation for 6 hours from 12:00 pm to 5:00 pm. The louvres were kept open with $90^0$ until it exposed to direct sun radiation at noon. The right side was completely closed while the left was starting to close gradually with 860 till it was completely closed at 4:00 pm, and then the right side was opening again gradually with $8^0$ till the sunset where both sides completely opened.

The figure in the table below is showing louvres angles at 3 pm.

**Table 1: Louvers' angles on 21 June**

| Date | Hours | East | | West | |
|---|---|---|---|---|---|
| 21 June | | Right | Left | Right | Left |
| | 9 Am | $0^0$ | $1^0$ | $90^0$ | $90^0$ |
| | 10 Am | $7^0$ | $0^0$ | $90^0$ | $90^0$ |
| | 11 Am | $24^0$ | $0^0$ | $90^0$ | $90^0$ |
| | 12 Pm | $90^0$ | $90^0$ | $0^0$ | $86^0$ |
| | 1 Pm | $90^0$ | $90^0$ | $0^0$ | $22^0$ |
| | 2 Pm | $90^0$ | $90^0$ | $0^0$ | $6^0$ |
| | 3 Pm | $90^0$ | $90^0$ | $0^0$ | $2^0$ |
| | 4 Pm | $90^0$ | $90^0$ | $8^0$ | $0^0$ |
| | 5 Pm | $90^0$ | $90^0$ | $14^0$ | $0^0$ |




Source: Authors

## 9.2. Phase Two: Operative Temperature

The measured temperatures in the table below were considered to be the worst case, as temperatures at 3 pm were recorded to be the hottest during the working hours.

### A. Ground floor

At 3 pm, the sun radiation was concentrated on the west side**. Before** the skin installation, the operative temperature was 30.7$^{o}$C for about 5 meters away from the western curtain wall, and about 28.1$^{o}$C further than that, with an average operative temperature for the whole space of 28.4$^{o}$C. **After** the installation, the operative temperature decreased to 27.7$^{o}$C on the west side, while the average operative temperature for the whole space was 27.8$^{o}$C.

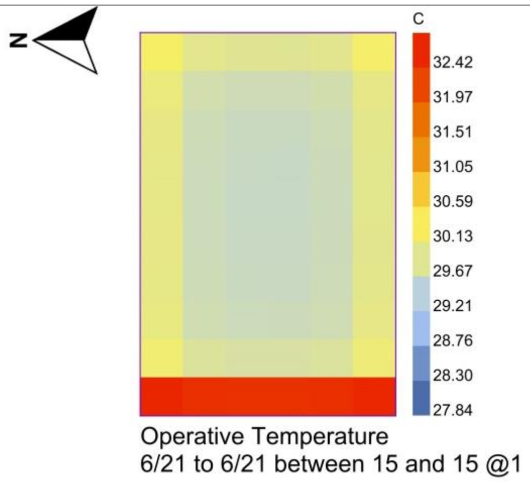
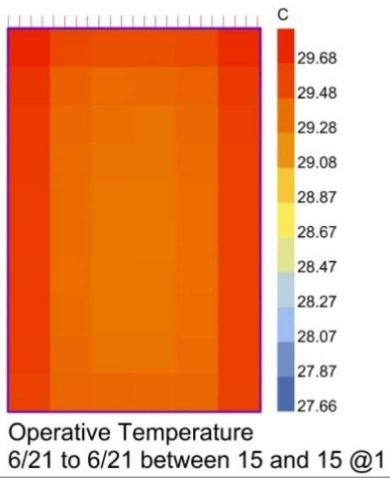
### B. First floor

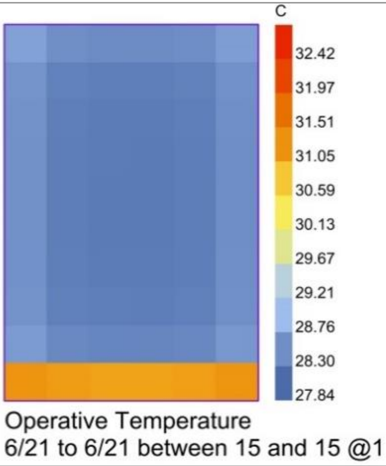
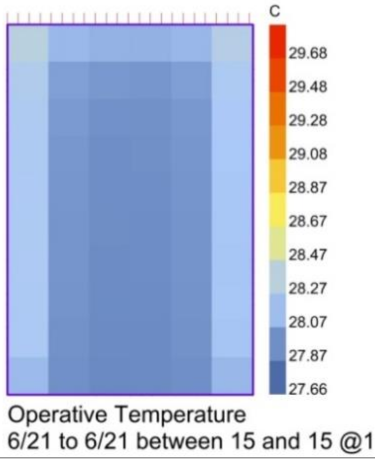
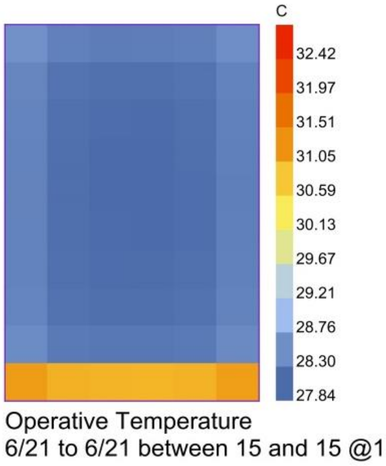
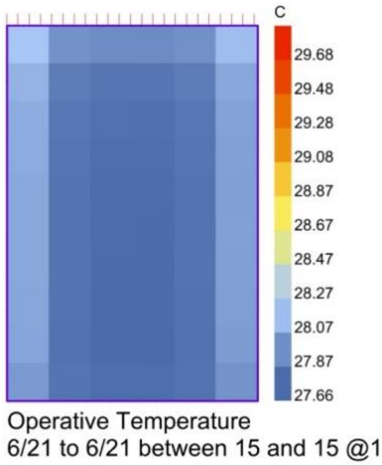
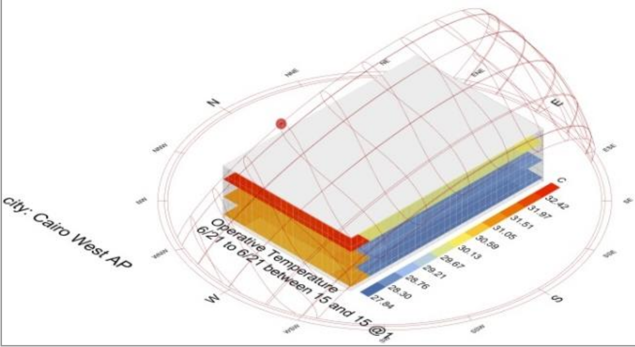
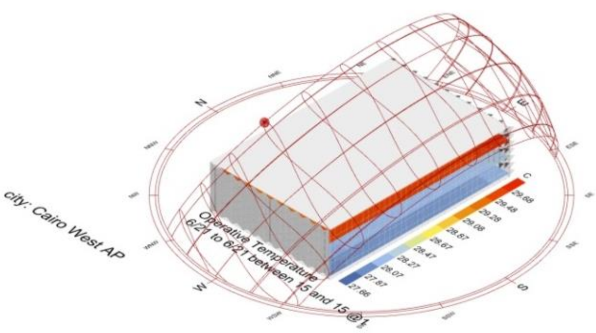
**Before** the skin installation, the operative temperature was 30.9$^{o}$C for about 5 meters away from the western curtain wall, and about 28.1$^{o}$C further than that, with an average operative temperature for the whole space of 28.5$^{o}$C. **After** the installation, the operative temperature on the west side, and the average operative temperature for the whole space decreased to 27.9$^{o}$C.

### C. Second floor

The second floor has the highest temperature because it was affected by the roof heat. **Before** the skin installation, the operative temperature was 32$^{o}$C and reached 32.4$^{o}$C in corners for about 5 meters away from the western curtain wall, and about 29.5$^{o}$C further than that, with an average operative temperature for the whole space of 29.7$^{o}$C. **After** the installation, the operative temperature decreases to 29.3$^{o}$C on the west side, while the average operative temperature for the whole space was 29.2$^{o}$C.

**Table 2: Operative temperature on 21 June before and after the skin's installation.**

| Before | After |
|---|---|
|  |  |
| Second floor | Second floor |

| Before | After |
|---|---|
|  |  |
| First floor | First floor |
|  |  |
| Ground floor | Ground floor |
|  |  |

Source: Authors

### 9.3. Phase Three: Thermal Loads

Figures (7) and (8) show the annual heating and cooling loads in the building before and after the skin installation. **Before** the installation of the skin, the cooling loads were 190.5 kWh/m$^2$ per year. **After** the installation, the cooling loads reduced by 8% to be 175 kWh/m$^2$ per year.

Heating loads almost remain the same in the two cases with only 5 kWh/m$^2$ per year.

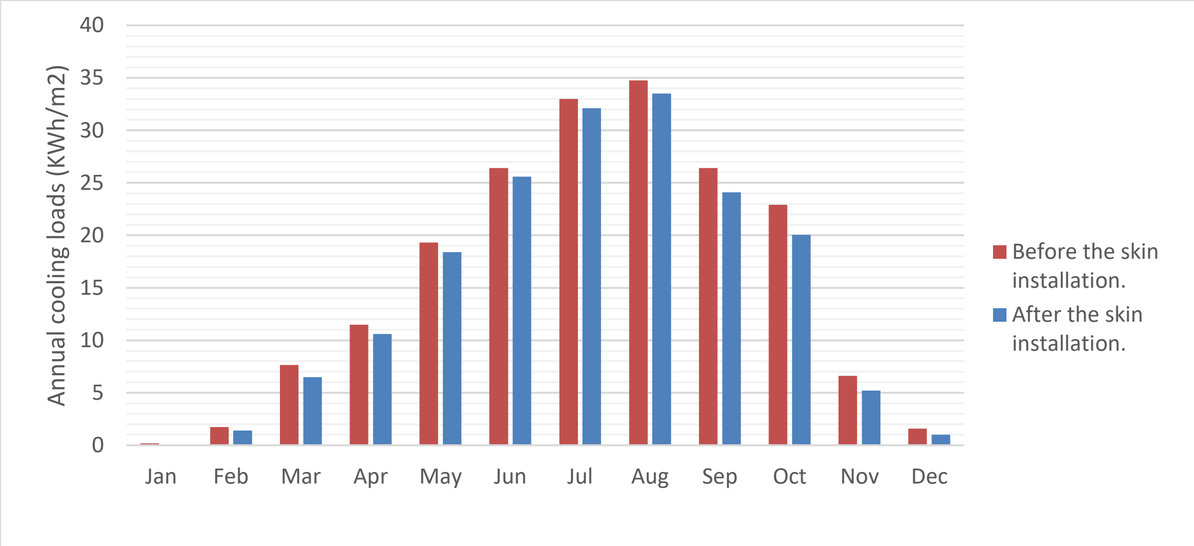



**Figure 7: Annual cooling loads before and after the skin installation.**
**Source: Authors**

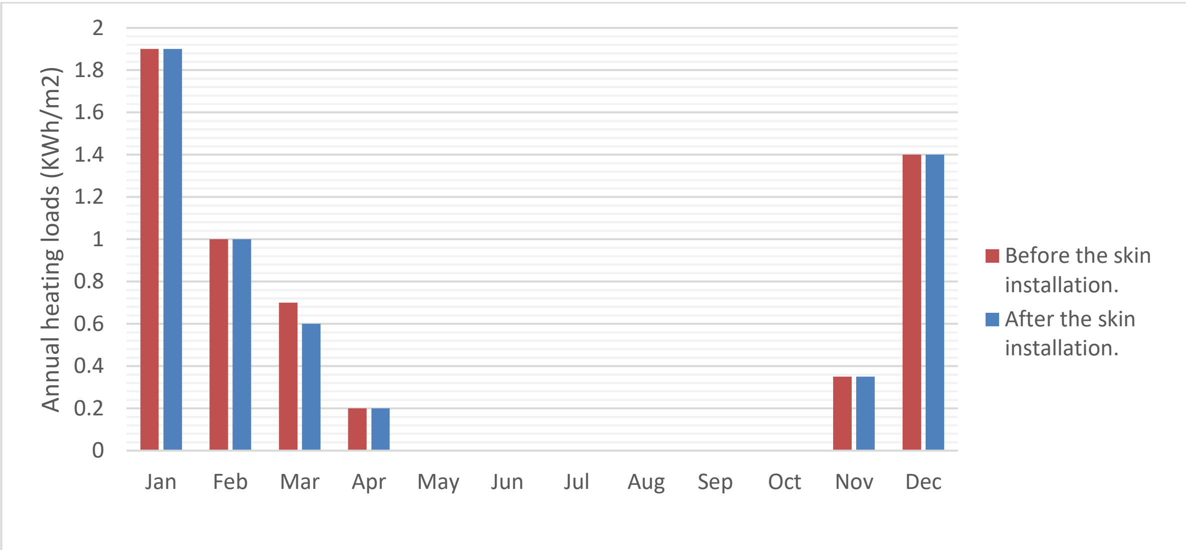



**Figure 8: Annual heating loads before and after the skin installation.**
**Source: Authors**

## 10. CONCLUSION AND RECOMMENDATION:

Plants are flexible structures and sensitive to environmental conditions, as they have evolved many techniques and features to help them overcome these challenges. This paper discussed the usage of the biomimicry approach in designing a responsive skin inspired by the mimosa's movement and cell shape to treat the external walls of the building. Simulation results showed how skin's louvres track the sun's path during working hours. On 21st June at 3 pm, the operative temperatures' reduction ranged from 2.8ºC to 3ºC in the exposed areas to sun radiation and from 0.5ºC to 0.6ºC in the whole space. The proposed skin proved its efficiency in solar gain reduction while keeping on the daylight penetration instead of reliance on artificial lighting, where visual comfort is essential in office spaces, and static skin wouldn't achieve that. Throughout the whole year, it’s noticed how thermal loads reduced, as cooling loads decreased by 8 % while heating loads almost remained the same.

The research recommends the installation of the biomimetic responsive skin on the south façade as well, as it would increase the thermal loads' reduction in the building.

## REFERENCES


[1] Renewables 2019 global status report. 2019. Available at: https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf. Last accessed at 25/11/2020

[2] Vimalanathan K, Babu R. (2014). The effect of indoor office environment on the work performance, health and well-being of office workers. Journal of Environmental Health Science and Engineering. p. 12:113.

[3] Schittich, C. (2012). Building Skins: in detail. Walter de Gruyter. P.29.

[4] Gruber, p, Gosztonyi, S. (2010) “Skin in architecture: towards bioinspired facades”. WIT Transactions on Ecology and the Environment, Vol 138.

[5] Elkhayat, Y. O., Ibrahim, M. G., Tokimatsu, K., & Ali, A. A. M. (2020). Multi-criteria selection of high-performance glazing systems: A case study of an office building in New Cairo, Egypt. Journal of Building Engineering, 32, 101466.

[6] Lee, P. (2016). “The Importance of Golden Ratio in Contemporary Architecture”. Widewalls. Available at: https://www.widewalls.ch/golden-ratio-in-contemporary-architecture. Last accessed at 22/08/2021

[7] Benyus, J. (2002). Biomimicry: Innovation Inspired by Nature. HarperAudio.

[8] El Ahmar, S. (2011). Biomimicry as a tool for sustainable architectural design, towards morphogenetic architecture. Faculty of Engineering, Alexandria University

[9] Zari, M., (2007). Biomimetic Approaches to Architectural Design for Increased Sustainability. Sustainable Building Conference.

[10] Sterk, T. D. E. (2005). Building upon Negroponte: a hybridized model of control suitable for responsive architecture. Automation in construction, 14(2), 225-232.

[11] Fouad, M, Ibrahim, V, Radwan, A. (2019). The impact of responsive systems on energy consumption and thermal performance of buildings. journal of Al Azhar University Engineering Sector Vol. 14, No. 52.

[12] Pérez -Lombard, L, Ortiz, J, Pout, C. (2008). A review on buildings energy consumption information. Volume 40, Issue 3, Energy and Buildings.

[13] Al-homoud, M. (1997). Optimum thermal design of office buildings. VOL. 21, 941—957, International journal of energy research.

[14] Najjar, M, Rosa, A, Hammad, A, Vazquez, E, vangelista, A, Tam, V, Haddad, A. (2021). A regression-based framework to examine thermal loads of buildings. Volume 292, Journal of Cleaner Production.

[15] Gagliano, M, Marder, M. (2019). What a plant learns. The curious case of Mimosa pudica. Botany One. Available at: https://www.botany.one/2019/08/what-a-plant-learns-the-curious-case-of-mimosa-pudica/. Last accessed at 3/08/2021

[16] Burkholder. P. R., Pratt. R. 1936. Leaf-movements of mimosa pudica in relation to light. American journal of botany Vol.23.

[17] Charpentier V., Hannequart P, Adriaenssens S, Baverel O., Viglino E., Eisenman S., 2017. Kinematic amplication strategies in plants and engineering. Smart Materials and Structures 26

[18] Barrett, R.M. and Barrett, R.P. (2016, September). Thermally adaptive building coverings inspired by botanical thermotropism. In Smart Materials, Adaptive Structures and Intelligent Systems (Vol. 50497, p. V002T06A008). American Society of Mechanical Engineers.

[19] Visser, F. and Yeretzian, A. (2013). Energy Efficient Building: Guidelines for MENA Region. MED-ENEC Project Office.