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# Mapping Biomimicry Design Strategies to Achieving Thermal Regulation Efficiency in Egyptian Hot Environments

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**ABSTRACT:**

This paper focuses on the study of biomimicry. Biomimicry has been widely applied in architecture and environmental engineering as an approach that can integrate ecosystem strategies and technologies in architecture to generate a responsive and adaptive built environment.

Today, with the development of building technology, the design of the buildings no longer gives importance to the surrounding environmental conditions. So, the built environment contributes nearly 40% of total energy consumption to provide thermal comfort in the world and the third of $Co_2$ emissions. As a result of the urgent need to find solutions to these problems, architects have tended to take inspiration from ecological systems that can introduce sustainable and innovative solutions to solve human challenges. The main objective of this paper is to map biomimicry design strategies as a guideline matrix to achieving efficiency in thermal regulation in the Egyptian climatic regions. For achieving this objective, a research methodology has depended primarily on a deep understanding of ecological systems to make a framework for biomimicry design strategies and the thermal properties of Egyptian climatic regions. Then, it will be an analysis and comparison between several experimental techniques and architectural examples that depend on biomimicry for achieving thermal regulation efficiency in the levels of building design, building envelope, building components, building structure, and material technology.

The paper seeks through this study to extract a set of biomimetic strategies that constitute a guideline towards an approach to generate adaptive built environments and to achieve thermal regulation efficiency in Egyptian environments.

**KERWORDS:** Biomimicry, Thermal regulation, responsive architecture, Bio-inspired building envelope, Bio-structure, Material technology.

## 1. INTRODUCTION:

Recently, architects have begun to pay great attention to the biomimetic approach as a design approach that studies the mechanism of adaptation of organisms and ecosystems to the surrounding environmental changes (Kuru et al., 2019) (Badarnah, 2015). Architects can inspire by their thermoregulation strategies for developing new techniques in architecture to create a responsive built environment (Kuru et al., 2019).

This research aims to create an organized methodological framework as a guiding interface for some strategies and techniques based on biomimicry principles in achieving thermal regulation efficiency for applying in different climatic zones in Egypt. Therefore, the research methodology was based first: Studying the basic concepts, approaches, levels of biomimicry, and thermal regulation mechanisms. Second: Presenting and analyzing some techniques and architectural examples developed with the biomimicry principles and explaining their role in achieving thermal regulation efficiency in building with the surrounding environment.

## 2. MATERIALS AND METHODS:

### *2.1. Biomimicry overview:*

Biomimicry is a mixture of the Greek words bios (meaning life) and mimesis (meaning to imitate) (Aanuoluwapo & Ohis, 2017) (Elsamadisy et al., 2019). The biomimicry concept was first invented in 1960 by biologist Janine Benyus and popularized in her book *"Biomimicry-Innovation Inspired by Nature"* in 1997 (Zari & Storey, 2007).

The concept of biomimicry is a showing of a deep understanding of the physiological and morphological behaviors of living organisms for achieving adaptation to environmental

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conditions as nature provides many successful examples in this field (Garcia, 2015) (Margariti, 2020). These examples do not only depend on the individual behavioral characteristics of an ecosystem but also the overlap and integration of ecosystem characteristics together for creating a responsive built environment that merges with nature into a single entity (Aanuoluwapo & Ohis, 2017).

Biomimicry focuses on drawing inspiration from biological systems (active & passive) in creating technologically architectural solutions that are more adaptive and in harmony with the environment (Widera, 2016). Biomimicry has two main approaches:

- Design influenced from biology: Determining the design problem and trying to find solutions to it from nature.
- The biology that influenced design: this means developing innovative designs inspired by natural sciences (Sai Harsha & Sree Lakshmi, 2020) (Badarnah & Kadri, 2015).

The previous two approaches consist of three levels of mimicking (Zari & Storey, 2007):

- Organism Level: this means mimicking a specific organism or any part of it.
- Behavior Level: this means mimicking the behavioral characteristics of a specified organism.
- Ecosystem Level: this means mimicking the level of the whole ecosystem.

Each of the three levels of mimic deals with five main dimensions (Form, Material, Construction, Process, and Function) (Atef, 2013) (Sai Harsha & Sree Lakshmi, 2020).

### *2.2. Egyptian climatic zones:*

Egypt extends between latitudes $22^0$ N to $31^0$ $37^/$ N, and longitudes $24^0$ $57^/$ E to $35^0$ $45^/$ E. In general, Egypt has a hot, dry climate most days of the year because most of Egypt's land surface is desert. The National Center for Housing and Construction Research divides Egypt into 8 different climatic zones for climatic design requirements that can be applied to reach the optimum thermal performance of the buildings (Mahmoud, 2011) (Saleem et al., 2016). They differ from one zone to another according to their thermal properties, as shown in fig. 1.

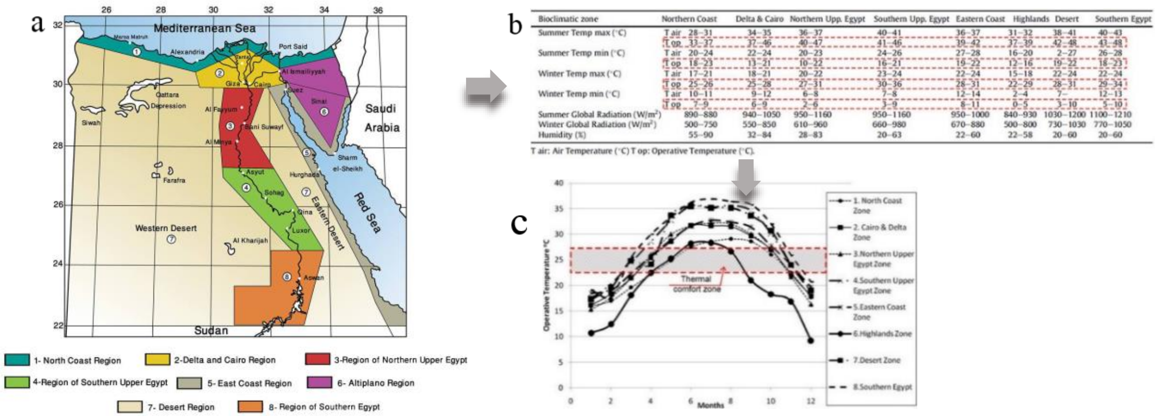


Fig. 1 - (a) Classification of climatic zones in Egypt according to HBRC; (b) Monthly range of operative temperature; (c) Average operative temperature profiles of climatic zones in Egypt.
Source: (Mahmoud, 2011) (Saleem et al., 2016).

### *2.3. Biomimetic thermoregulation strategies:*

Ecosystems have developed several adaptation mechanisms through 3.8 billion years of evolution to deal continuously with changing environmental conditions represented by the active exchange processes with the environment for achieving the efficiency of light regulation, air regulation, water regulation, and thermal regulation (study subject) (Widera, 2016). The thermoregulation strategies in living organisms depend on controlling their physiological and morphological behaviors (Badarnah, 2015) to complete the heat flow process between the

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system and the environment to reach the optimum thermal performance (Mercedes Garcia-Holguera et al., 2015).

As temperature is one of the most influencing environmental factors affecting organisms to reach the desired thermal comfort levels, the thermoregulation processes represent the adaptation mechanism of living organisms with temperature changes (Imani & Vale, 2020). The biomimetic approach aims to transfer thermal regulation strategies in organisms to buildings to create a responsive and adaptive built environment. The thermal regulation strategies in living organisms and buildings are divided into two main approaches (active thermal regulation strategies & passive thermal regulation strategies) (Imani & Vale, 2020). The difference between these approaches can be clarified as shown in table 1.

Table 1- The difference between thermal regulation in organism & building, Source: researcher.

| Thermal regulation | Adaptation in Organism | Adaptation in Building |
|---|---|---|
| Active strategies | -The adaptive mechanism relies on the opposite heat exchange processes.<br>-Some physiological changes in the structure occur in it according to the thermal changes (Imani & Vale, 2020). | -The adaptive mechanism in buildings relies on intelligent thermoregulation strategies that regulate the internal temperature by heat exchange with the environment (Imani & Vale, 2020). |
| Passive strategies | -The adaptation mechanism relies on causing some behavioral changes (expansion, contraction). It does not cause any changes in the structure and functions (Imani & Vale, 2020). | -An adaptation mechanism relies on the regulation of thermal gain and loss through Glazing & Skylights (Imani & Vale, 2020). |

The thermoregulation mechanisms are divided into four main functions (Heat gain, Heat retention, Heat dissipation, Heat prevention). Each of these functions contains a group of processes to complete the thermal regulation process between the building and the environment (Badarnah, 2015) (Badarnah Kadri & Technische Universiteit Delft, 2012).

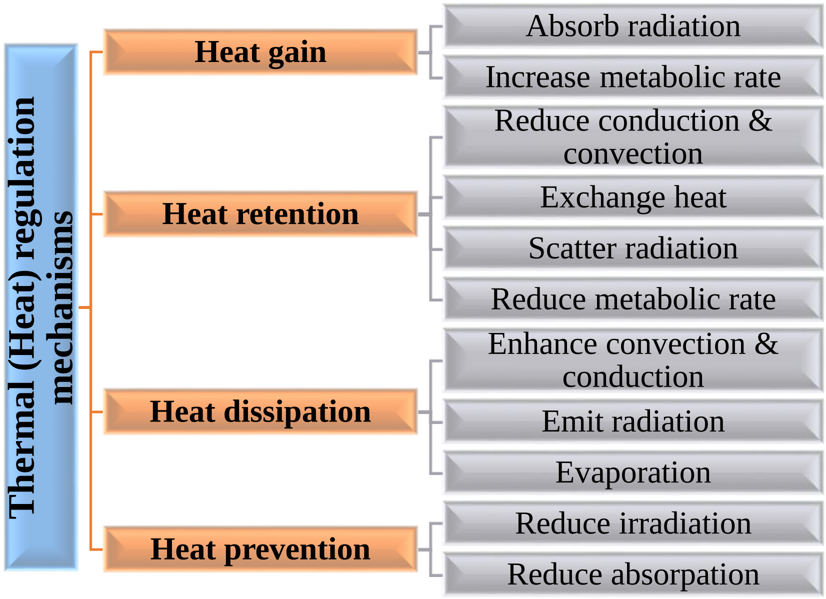


Fig. 2 – Thermal regulation mechanisms (functions & processes).
Source: researcher

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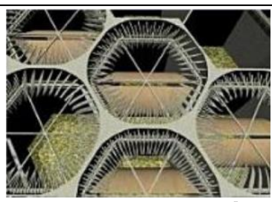
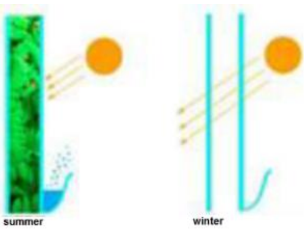
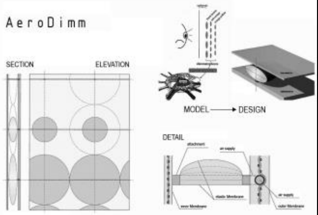
### *2.4. Biomimetic experimental techniques:*

Some laboratories specialized in biomimicry have developed architectural techniques at the design level of the building envelope, structure, building components, and material performance for enhancing adaptation with changing environmental conditions and thermal regulation efficiency. In this part of the research, we have presented and analyzed some of these techniques that improve thermal regulation efficiency.

Table 2 - Some biomimetic architectural experimental techniques, Source: researcher.

| Levels | Techniques | Details | Sketch | Challenges | | | |
|---|---|---|---|---|---|---|---|
| | | | | **Heat gain** | **Heat retention** | **Heat dissipation** | **Heat prevention** |
| **Envelope** | **Stoma Brick (SB)** | - A system was developed for building envelope by (The Facade Research Group). Its idea mimics the behavior and principles of some ecosystems (human skin & plant stomata). It depends on the evaporative cooling system to achieve the thermal regulation between the building and the environment. (Yeler & Yeler, 2017): |  Fig. 3 - Stoma Brick Source: (Yeler & Yeler, 2017) | | | | |
| | **Foliage Facade** | - A building envelope system was developed by the Ulrich Knaack Group, based on the incorporation of seasonal foliage between a double envelope structure consisting of two layers of glass. The system works to block the sun's rays from penetrating the building in the summer to reduce heat absorption, while the leaves of the plants fall in the winter to allow the sun's rays to penetrate the envelope (Yeler & Yeler, 2017). |   Fig. 4 - Foliage Facade Source: (Yeler & Yeler, 2017) | In winter | | | In summer |
| | **Aero Dimm** | - A building envelope was developed by Stefan Pfaffstaller. Its idea was inspired by the coloration of the cephalopod mollusks skin (Loonen, 2015).<br>- It depends on the change in the size of an air chamber with the air pressure change inside it between the two layers of the building's double envelope (flexible membranes) according to the temperature changes, which leads to a change in its color and thus the radiative heat exchange rate changes (Loonen, 2015). |   Fig. 5 - Aero Dimm Source: (Gruber & Gosztonyi, 2010) | | | | |

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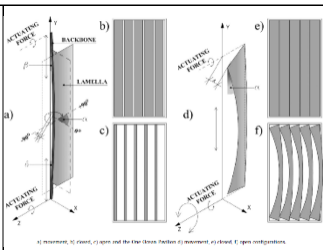
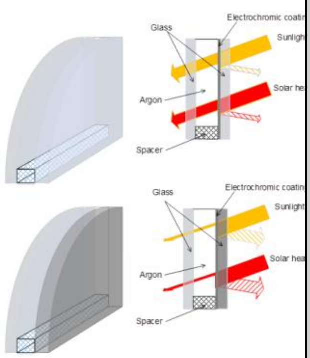
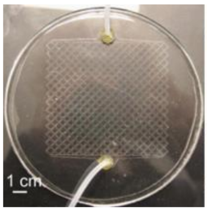
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Envelope** | **Flectofin ™** | - An innovative building envelope system, its idea was inspired by the change in the behavior of the Strelitzia reginae plant and its adaptation to any external change. The plant moves in a bending motion when exposed to an external force (a bird landing), which leads to the landing of two petals (Kuru et al., 2019). |  Fig. 6- Flectofin™ System Source: (Kuru et al., 2019) | In winter | | | In summer |
| **Envelope & Material** | **Hygroskin** | - An innovative research pavilion was developed at the Institute for Computational Design (ICD) at the University of Stuttgart (Öztoprak, 2018).<br>- Its idea was inspired by a change in the hygroscopic behavior of wood that changes according to relative humidity changes as a negative design approach to the building envelope. It aims to study the ability of materials to respond and adapt to the environment (Öztoprak, 2018) (López et al., 2017). |  Fig. 7- Hygroskin pavilion Source: (Öztoprak, 2018.) | | | | |
| **Component** | **EC Window** | - It is an adaptive window system inspired by the adaptive behavior of chameleon and the advanced evolution of EC glass. The system consists of two layers of glass, between which is a layer filled with argon.<br><br>-The thermal regulation system's mechanism depends on coating the inner surface of the outer layer with EC paint, as this layer can change its color to a dark color to control the amount of heat gain and the transparency of the system (inspiration of the behavior of chameleon skin's adaptation) (Bui, 2020). |   Fig. 8- EC window in clear and dark states. Source: (Bui, 2020) | In winter | | | In summer |
| **Component** | **Artificial Vascular window** | - It is an innovative active adaptive window system developed at the Weiss Institute of Biologically Inspired Engineering, Harvard University. Its idea was inspired by the vascular network of most thermally homogeneous organisms (Loonen, 2015).<br>- The thermal control mechanism in the window depends on the presence of the array of ultra-thin transparent tubes provided with water (a microfluidic layer) to act as a mediator for the heat exchange process (Loonen, 2015). |   Fig. 9- Artificial Vascular window system Source: (Loonen, 2015) | | | | |

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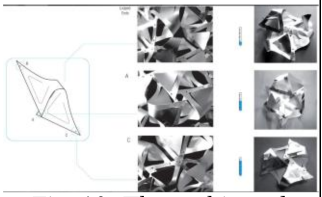
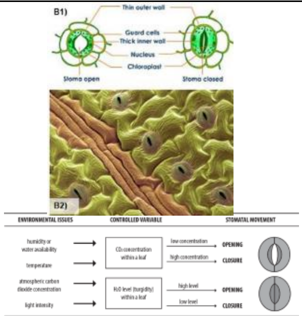
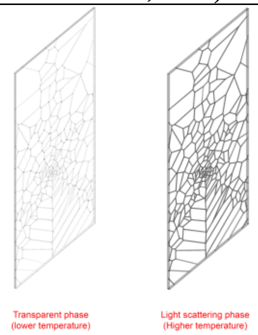
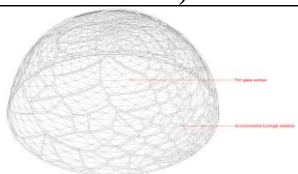
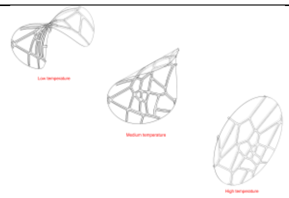
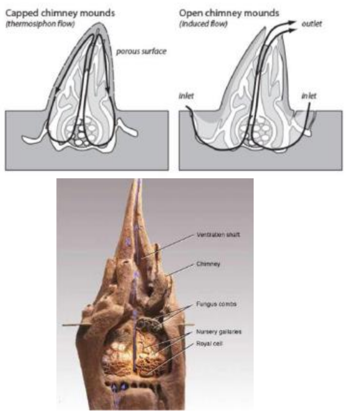
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Material | Heat-Sensitive BiMetal | - Thermobimetals is a technique developed for building materials. Its idea mimics the skin function in forming a defense body layer. It consists of at least two components, often in the form of strips made of minerals with different thermal expansion coefficients (one low (negative) and the other high (active)) and permanently linked to each other (Nessim, 2016). |  Fig. 10- Thermobimetal (TB) behavior with heat Source: (Nessim, 2016) | | | | |
| Material & Envelope | Active Material (Stomata) | - It is a technique developed for building materials to achieve a building envelope that adapts to the surrounding environmental conditions. Its idea was inspired by the stomata of plants and their sensing of environmental changes. It can change its structure by closing or opening to achieve environmental adaptation by reducing water evaporation, controlling temperature, the rate of solar radiation absorption, and achieving thermal regulation efficiency (N. Charkas, 2019). |  Fig. 11- Stomata mechanism. Source: (N. Charkas, 2019) | In winter | | | In summer |
| Structure | Hydrogel Structure | 1-Reciprocal intervention:<br>- It is a shading system for façade components from materials with variable physical and thermal properties and is heat directed to enhance response to changing environmental conditions. It has a composite structure of viscous hydrogel and conventional glass. The thermal effect of the system depends on the change in opacity of the hydro structure according to the change in temperature as it becomes opaque with the increase in temperature and vice versa to achieve the thermal regulation efficiency (Khoo & Shin, 2018). |   Fig. 12- Reciprocal intervention structure Source: (Khoo & Shin, 2018) | | | | |
| | | 2- Environmental skeleton:<br>- It is a flexible structure system developed for a virtual rooftop glass dome.<br>- It was developed to improve the environmental response by reducing the heat gain and humidity of the existing building surfaces, thus reducing energy consumption (Khoo & Shin, 2018). |  Fig. 13- Environmental skeleton structure. Source: (Khoo & Shin, 2018) | | | | |
| | | 3- Soft responsive skin:<br>- It is a structural technique with flexible modules, which depends on the usage of passive sensors to achieve environmental adaptation. The size of their units shrinks or expands according to the temperature and solar radiation to regulate the heat exchange process (Khoo & Shin, 2018). |  Fig. 14- Soft responsive skin. Source: (Khoo & Shin, 2018) | In winter | | | In summer |

### *2.5. Architectural examples of biomimetic thermal regulation strategies:*

This part of the research includes a presentation and analysis of some architectural examples based on the principles of biomimicry in achieving thermal regulation between the building and the environment with variable climatic characteristics at the scale of building design, envelope, structure, building components, and material performance. The selection of these examples relied on the diversity of the climatic zones in which they are located to study the mechanism of dealing and inspiring by organisms to achieve thermal regulation efficiency in the building design according to environmental conditions. This study can benefit us for planning a group of strategies and techniques that can be applied in the different climatic zones in Egypt.

Table 3 - Presentation and analysis of Eastgate center, Zimbabwe, Source: researcher.

<table>
<tr><th>Project name</th><th colspan="4">Eastgate center</th><th>Site:Zimbabwe</th></tr>
<tr><td>Processing level</td><td>Design</td><td>Envelope</td><td>Structure</td><td>Component</td><td>Material</td></tr>
<tr><td>The thermal problem</td><td>Heat gain</td><td>Heat retention</td><td>Heat dissipation</td><td>Heat prevention</td><td>-</td></tr>
<tr><td>Result summary</td><td colspan="5">- The thermal regulation strategy in the building reduces costs that reduce the cost of energy consumption. It uses energy less than 10% of what is used in traditional buildings to reach the ideal temperature efficiency (ElDin et al., 2016).<br>- Reducing the percentage of carbon dioxide emissions by 100%, reducing the heat island phenomenon by 60% (Yousef Mohamed, 2018).</td></tr>
<tr><td>Building</td><td colspan="5">- Location: Harare, Zimbabwe<br>- Architect: Mick Pearce (ElDin et al., 2016).<br>- Year of establishment: 1996 (ElDin et al., 2016).<br>- Description of the building:<br>• A shopping center and offices, on an area of 32,000 square meters, consisting of two 9-floor buildings, with an inner atrium between them (ElDin et al., 2016) (Atef, 2013).<br>• The building envelope is characterized by hooded windows, variable thickness, and light-colored building materials as a part of a passive cooling system (Yeler & Yeler, 2017).<br>• The design of the building matches the architectural character of Zimbabwe.<br><br>Fig. 15- Eastgate center<br>Source: (ElDin et al., 2016)</td></tr>
<tr><td>Innovation & Mechanism</td><td colspan="5">- The building design mimicked the concept and mechanism of thermal control and ventilation in African termite mounds.<br><u>Adaptation strategies in termite mounds:</u><br>- The tropical climate of Zimbabwe is characterized by varying temperature ranges between ($3^o$:$43^o$) C. Despite the constant change in outdoor temperatures, termite mounds can adapt and keep the indoor temperature constant at the required thermal comfort limit of $30^O$ C (ElDin et al., 2016) (Yeler & Yeler, 2017).<br>- This mechanism progresses through the thick walls and a convection airflow from cold to warm air through<br><br></td></tr>
</table>

***Thermoregulation techniques***

the lower openings at the bottom of the mounds to the higher ones. This cycle continues until achieving the desired temperature. These openings constantly change (closing & opening) to achieve the optimum performance of ventilation and thermal regulation with the surrounding environment. The moist mud helps in this, which works to cool the mound and heat dissipation by evaporation (ElDin et al., 2016).

Fig. 16- Adaptation strategies in termite mounds
Source: (Atef, 2013)

- The building relies on passive design techniques that mimic the concept of the thermal control mechanism in termite mounds based on storing high temperatures during the day and losing them at night (ElDin et al., 2016).
- During the day: the building block with thick walls absorbs the high temperature from the external environment and the human activity inside the building (ElDin et al., 2016) (Atef, 2013).

- During the night, the cold air is allowed to flow from the openings in the bottom of the building (Atef, 2013).

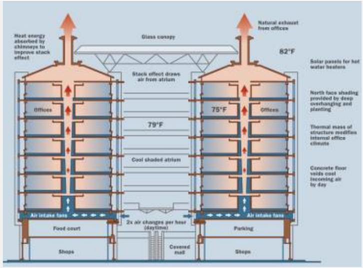


Fig. 17- Eastgate center section
Source: https://www.mickpearce.com/biomimicry.html

Table 4 - Presentation and analysis of (CH2) building, Australia, Source: researcher.

| **Project name** | **The Council House 2 (CH2) building** | | | | **Site**:Australia |
|---|---|---|---|---|---|
| **Processing level** | **Design** | **Envelope** | Structure | **Component** | **Material** |
| **The thermal problem** | Heat gain | **Heat retention** | **Heat dissipation** | Heat prevention | - |
| **Result summary** | - The thermal regulation strategy for the building reduces energy consumption by 20% compared to traditional buildings of the same size.<br>- Reducing the percentage of carbon dioxide emissions by 36%, reducing the heat island phenomenon by 87% (Yousef Mohamed, 2018). | | | | |

***Building***

- **Location**: Melbourne, Australia
- **Architect**: Mick Pearce & Designinc company.
- **Year of establishment**: 2004: 2006 (Radwan & Osama, 2016).
- **Description of the building**:
    - It is an extension of an Australian office building, consisting of 10 floors (Yeler & Yeler, 2017).
    - It is considered one of the best buildings in the field of environmental design and energy efficiency. The building received a 6-star rating from the Green Building Council of Australia.

Fig. 18- The Council House 2
Source: https://www.mickpearce.com/CH2

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*Innovation & Mechanism*

- The building design is based on achieving a connection and harmony between the building and the surrounding environment. The building achieved an almost complete response to the surrounding environmental conditions, as the designer resorted to achieve his goal of inspiration of the following techniques (Radwan & Osama, 2016):

1- Inspiration of the tree bark function and its adaptation to the surrounding environment for designing the building envelope.
2- Inspiration the thermal control and heat regulation mechanism in termite mounds for designing the heating and cooling system (explained earlier in the previous example).
**3-** Inspiration the soil function of the outer surface of the termite mounds in the design of the roof of the building, as it stores the thermal mass during the day, preventing it from penetrating the hill and replacing it at night with cold air to reach thermal comfort level.

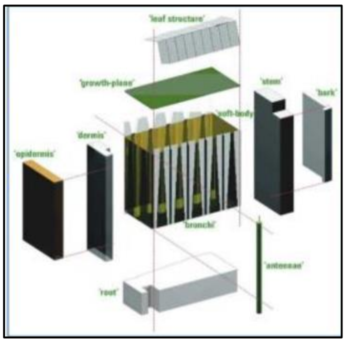

Fig. 19- CH 2 concept
Source: (Yousef Mohamed, 2018)

*Thermoregulation techniques*

- The building used many biomimetic techniques to enhance the thermal organization, based on inspiration from termite mounds, relying on natural resources to reach the required thermal comfort rates and within a limited range of mechanical intervention to reduce energy consumption.

**Biomimetic strategies in the building represent in:**

1- On the western façade, the tree's shell function mimicked to cool down the temperature (Radwan & Osama, 2016).
2- A group of ventilation chimneys continues along with the north and south facade designed in a strategic style that corresponds to the sun movement in Australia. The north façade is the most exposed to sunlight, while the south façade is the least exposed. So the hot air rises from the northern chimneys painted black for increasing the rate of performance as the temperature increases. It replaces by cold air entering from the southern openings painted with a light color to reduce the thermal gain to increase its efficiency (Radwan & Osama, 2016).
3- The Eastern core and the facade, its idea took inspiration from the function of the tree shell (bark) in filtering light, thermal regulation, and air movement (Radwan & Osama, 2016).
4- The design of a corrugated concrete roof mimicked the soil function of the termite mounds surface to achieve cooling requirements and improve thermal regulation efficiency. It can store the thermal mass during the day and replace it at night with cold air to

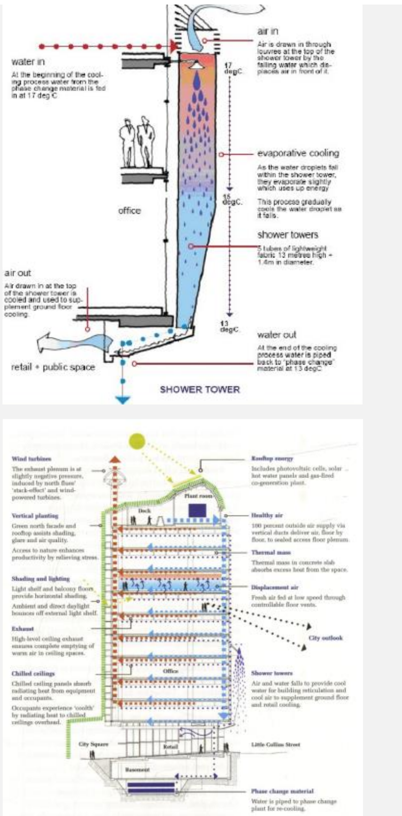

Fig. 20- CH 2 sections
Source: https://www.mickpearce.com/CH2

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reach the desired thermal comfort (Yeler & Yeler, 2017).
5-The envelope idea took inspiration by mammalian skin. It consists of a double envelope. One of which is external with direct contact with the surrounding climatic conditions and is permeable. The second is internal and is responsible for protecting the building elements as it controls by closing or opening as needed (Radwan & Osama, 2016).

Table 5 - Presentation and analysis of Minister of Municipal Affairs & Agriculture building, Qatar, Source: researcher.

| **Project name** | **Minister of Municipal Affairs & Agriculture building** | | | | **Site:** Qatar |
|---|---|---|---|---|---|
| **Processing level** | Design | **Envelope** | Structure | Component | Material |
| **The thermal problem** | Heat gain | Heat retention | **Heat dissipation** | **Heat prevention** | - |
| **Result summary** | - Enhance thermal regulation efficiency & reduce energy consumption. | | | | |

***Building***

- **Location**: Doha, Qatar
- **Architect**: Aesthetics Architects Go Group (Atef, 2013).
- **Description of the building**:
  - An administrative building designed for the Ministry of Municipal Affairs in Doha.
  - The building is located in a hot, dry climate. It exposes to harsh climatic conditions represented by intense solar radiation, thermal mass, and a high temperature with an average of 43°C (N. Charkas, 2019).

Fig. 21- MMAA building
Source: (Atef, 2013)

***Innovation & Mechanism***

- The design idea of the building depends on the inspiration by the shape and function of the cactus plant and the botanical dome at the end of the building to achieve adaptation to harsh climatic conditions (N. Charkas, 2019). The adaptive mechanism depends on how the cactus retains water during the transpiration process, provides adequate moisture, and reduces the air temperature in contact with the outer surface (N. Charkas, 2019). The thorns that cover the cactus shade the plant and reduce the thermal gain due to the intense solar radiation, as the thorns trap hot air away from the outer surface, which keeps its coolness (Atef, 2013).

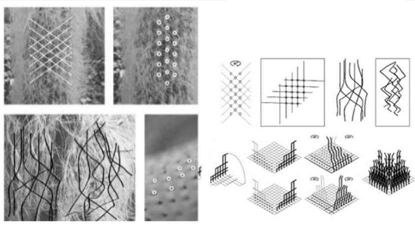

Fig. 22 - Cactus design structure
Source: (Arbabzadeh et al., 2017)

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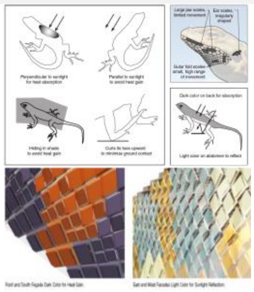
| | | |
|---|---|---|
| ***Thermoregulation techniques*** | - The dominant idea in the building design is the thermal control of the amount of heat gain due to harsh climatic conditions to achieve the thermal comfort requirements of the users. The building design depends on achieving the principles of thermal dissipation, regulating the amount of heat gain, solar radiation, and controlling the rate of heat convection (N. Charkas, 2019).<br>- The adaptation mechanism in the building depends on the inspiration from the function of cactus thorns in developing an intelligent shading system that adapts to the amount of solar radiation and the outside temperature. The shading system is able to change (open & close) automatically during the day according to the change in the external conditions (N. Charkas, 2019) (Atef, 2013). | <br>Fig. 23 - MMAA building<br>Source: https://inhabitat.com/qatar-cactus-office-building/ |

Table 6 - Presentation and analysis of S.C.A.L.E.S., California, Source: researcher.

| **Project name** | **S.C.A.L.E.S. (Smart, Continuous, Active, Layered, Environmental, System)** | | | | **Site**: California |
|---|---|---|---|---|---|
| **Processing level** | Design | **Envelope** | Structure | **Component** | **Material** |
| **The thermal problem** | Heat gain | **Heat retention** | Heat dissipation | **Heat prevention** | - |
| **Result summary** | - Achieve thermal regulation efficiency and reduce energy consumption. | | | | |
| ***Building*** | - **Location**: Palm Springs, California (Mazzoleni, 2013).<br>- **Architect**: Ilaria Mazzoleni and her students (Mazzoleni, 2013).<br>- **Description of the building**:<br>• It is a one-floor residential building and located in California state, which has a desert climate (Mazzoleni, 2013). | | | <br>Fig. 24 - S.C.A.L.E.S. building<br>Source: (Nessim, 2016) | |
| ***Innovation & Mechanism*** | - The building design idea depends on mimicking the behavioral and physiological characteristics of the skin of the lateral macula lizard (Uta Stansburiana) in designing the building envelope to achieve efficient thermal regulation in the desert environment (Mazzoleni, 2013) (Nessim, 2016).<br>**<u>Adaptive strategies for a lateral macula lizard:</u>**<br>- The lizard skin is distinguished by its diversity in its properties to reach the optimum thermal regulation with the surrounding environment due to the color pattern variation of the leather layer (Mazzoleni, 2013). | | | a<br>b<br><br>Fig. 25 – (a) Lateral macula lizard adaptation mechanism; (b) S.C.A.L.E.S. skin material<br>Source: (Mazzoleni, 2013) | |

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***Thermoregulation techniques***

- The envelope design is a fixed steel grid where a group of modular panels is suspended and movable, covering all parts of the building with different methods depending on the building's orientation and function. For example, three different types cover the southern facade (opaque insulation, photovoltaic, and operable window) (Nessim, 2016).
- The insulating panels used are hollow and contain material capable of changing its vital properties to control the internal temperatures constant at the rate of thermal comfort. The building envelope stores the heat during the day while maintaining the desired coolness inside the building, and then it is released at night regularly to warm the building. All units operate on a unified system with different configurations depending on their function and the amount of exposed heat to them (Mazzoleni, 2013) (Nessim, 2016).
-The building rests directly on the desert floor, with a slight inclination in the roof and the southern façade to improve thermal performance in line with the angle of incidence of solar radiation (Mazzoleni, 2013).

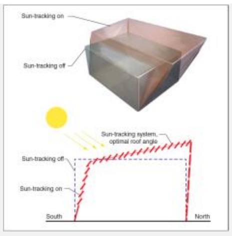
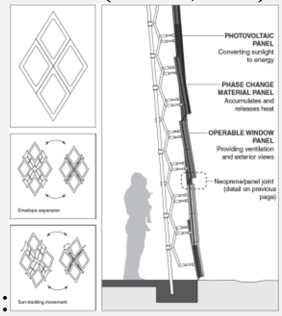



Fig. 26 –The operable windows for the sun tracking system
Source: (Nessim, 2016)




:
Fig. 27 – S.C.A.L.E.S. building envelope & adaptation mechanism
Source: (Mazzoleni, 2013)

Table 7 - Presentation and analysis of Esplanade art center, Singapora, Source: researcher.

| **Project name** | **Esplanade art center** | | | | **Site:** Singapora |
|---|---|---|---|---|---|
| **Processing level** | Design | **Envelope** | Structure | Component | Material |
| **The thermal problem** | Heat gain | Heat retention | Heat dissipation | **Heat prevention** | - |
| **Result summary** | - Reducing the heat gain from the external environment.<br>- Reducing reliance on mechanical HVAC systems, thus reducing energy consumption. | | | | |

***Building***

- **Location**: Marina Bay, the historic Singapore River.
- **Architect**: Michael Wilford, Atelier one.
- **Year of establishment**: 2007 (Radwan & Osama, 2016) .
- **Description of the building**:
    - The building represents a cultural center for the city of Singapore, and it consists of two gigantic buildings, each of them containing a theater hall, outdoor theaters, apartments, and administrative offices.

Fig. 28 – Esplanade art center
Source: https://www.pond5.com/stock-footage/item/18286955-singapore-esplanade-performing-art-center-night

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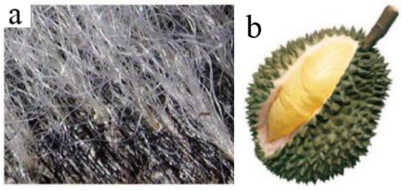
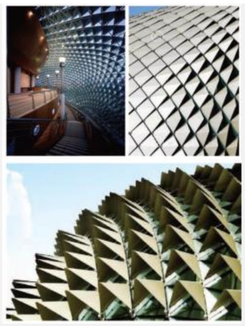
|---|---|---|
| ***Innovation & Mechanism*** | The envelope design idea mimics the structure and function of two main elements to adapt to the nature of Singapore's tropical climate (Atef, 2013):<br>1- The durian fruit (a local fruit): It is characteristic of thorns on the plant's surface that act as umbrellas to protect the inner seeds from high temperatures.<br>2- The polar bear (does not belong to the building site): The building mimics the adaptive mechanism of the polar bear in a reverse way. The polar bear is characteristic of its white fur consist of transparent hair follicles and black skin. During sun shining, the hair follicles erect to allow the sun rays passage through the black's skin. Since the heat is not desirable in this building, follow a reverse adaptation mechanism for the polar bear to reduce the thermal gain (Atef, 2013). | <br>Fig. 29 – (a) The polar bear skin; (b) The durian fruit<br>Source: (Atef, 2013) |
| ***Thermoregulation techniques*** | - The thermal regulation techniques in the building envelope depend on a smart shading system connected to photoelectric sensors to adapt to the sun's movement.<br>- The shading system is double and curved. It was made of aluminum inspired by the durian plant's thorns to shade the facade. It can move according to the sun's movement during periods of the day to achieve a minimum thermal gain as the polar bear. That contributes to reducing the cooling capacity by 30% compared to traditional buildings (Atef, 2013) (Radwan & Osama, 2016). | <br>Fig. 30 – Esplanade art center envelope. Source: (Atef, 2013) |

Table 8 - Presentation and analysis of The (Water – Cube), Beijing, Source: researcher.

| **Project name** | **The (Water – Cube) National Aquatic Swimming Center** | | | | **Site**: Beijing |
|---|---|---|---|---|---|
| **Processing level** | Design | **Envelope** | **Structure** | Component | **Material** |
| **The thermal problem** | **Heat gain** | Heat retention | Heat dissipation | Heat prevention | - |
| **Result summary** | - The use of energy saving equivalent (ETFE) in the envelope led to the absorption of 90% of the solar energy required for heating.<br>- Reducing energy costs by 30% compared to traditional buildings.<br>- Reducing the percentage of carbon dioxide emissions by 100%, reducing the heat island phenomenon by 100% (Yousef Mohamed, 2018). | | | | |
| ***Building*** | **-Architect**: Chriss Boss, Tristam Carfrae, PTW Architects, CSCEC, CCDL.<br>**- Year of establishment**: 2004: 2007.<br>**- Description of the building**:<br>• The building design takes the cube shape with straight linear faces. Its dimensions are (177*177*30) meters, and it consists of four floors as the headquarters of the Beijing Olympics, 2008 (Radwan & Osama, 2016). | | | <br>Fig. 31 – The National Aquatic Swimming Center.<br>Source: (Radwan & Osama, 2016) | |

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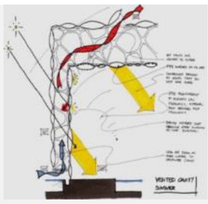
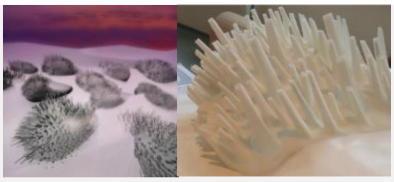
| | | |
|---|---|---|
| ***Innovation*** | - The building envelope design mimics the structure of forming arrays of soap bubbles. The main goal is to design an external envelope that can absorb as much as possible from solar radiation for heating (Radwan & Osama, 2016) (Öztoprak, 2018). The studies of the Belgian scientist Plateau proved that soap films formed from bubbles could reduce the surface area and reduce the surface energy amount for studying how the envelope of the facades and the roof of the building form with a linear shape (ElDin et al., 2016). |  Fig. 32 – (a) The National Aquatic Swimming Center skin Source: http://funfav.blogspot.com/2008/06/national-aquatics-center-china.html |
| ***Thermoregulation*** | - The envelope structure design is based on forming a group of bubbles in a specific direction and then discharging the mass of these bubbles to create the building structure that achieves the minimum self-weight. The building structure represents a group of regular repetitive units for its reliance on mathematical procedures in a three-dimensional space that can adapt and rotate around its axis to achieve adaptation with external conditions for allowing the transfer of heat gain through the structure to the internal environment (Radwan & Osama, 2016) (Öztoprak, 2018). |  Fig. 33 –The National Aquatic Swimming Center section Source: (Radwan & Osama, 2016) (Yousef Mohamed, 2018) |

Table 9 - Presentation and analysis of Proto–Project, arctic region Source: researcher.

| **Project name** | **Proto–Architectural Project** | | | | **Site**: arctic region |
|---|---|---|---|---|---|
| **Processing level** | Design | **Envelope** | Structure | Component | **Material** |
| **The thermal problem** | **Heat gain** | Heat retention | Heat dissipation | Heat prevention | - |
| **Result summary** | - The thermal regulation efficiency between the units and the environment. Increase the thermal absorption efficiency. | | | | |

| | | |
|---|---|---|
| ***Building*** | - **Location**: Arctic region.<br>- **Architect**: Ilaria Mazzoleni and her students (Yeler & Yeler, 2017).<br>- **Description of the building**:<br>• It is a project to design housing units in the Arctic region with harsh climatic conditions (temperature is 0 degrees Celsius in summer, -34° C in winter (Yeler & Yeler, 2017).<br>• The units are partly buried in the ground (Yeler & Yeler, 2017). |  Fig. 34 – Proto–Architectural Project Source: (Mazzoleni, 2013) |

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***Innovation & Mechanism***

- The design idea of the project mimics the physiological behavior of polar bear skin and its adaptation to harsh environmental conditions (Nalcaci & Nalcaci, 2020) (Yeler & Yeler, 2017).

**Adaptation strategies in the polar bear:**

- The transparent hollow hair layer protects from cold weather, (Nalcaci & Nalcaci, 2020).
- White fur contains protective membranes that reduce heat loss (Mazzoleni, 2013).

The subcutaneous fat layer represents an insulating layer of the polar bear from the lower external temperatures (Mazzoleni, 2013).

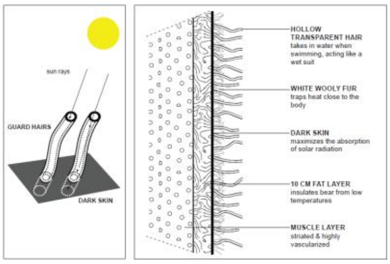


Fig. 35 – Polar bear fur (structure & details)
Source: (Nalcaci & Nalcaci, 2020)

***Thermoregulation techniques***

- The architect inspired the white fur of the polar bear and its ability to change and orientation according to the sun movement to design the envelope of units for creating an active dynamic envelope that can collect solar rays (light and heat) (Yeler & Yeler, 2017) (Nalcaci & Nalcaci, 2020). The envelope consists of a group of active glass tubes controlled by sensors to track the sun's movement to increase the thermal regulation efficiency and thermal absorption (Nalcaci & Nalcaci, 2020) (Yeler & Yeler, 2017) (Mazzoleni, 2013). These tubes deliver light and heat gained through them to the insulating layers of the units' envelope, where they are stored and then slowly re-fired to warm these units (Yeler & Yeler, 2017).

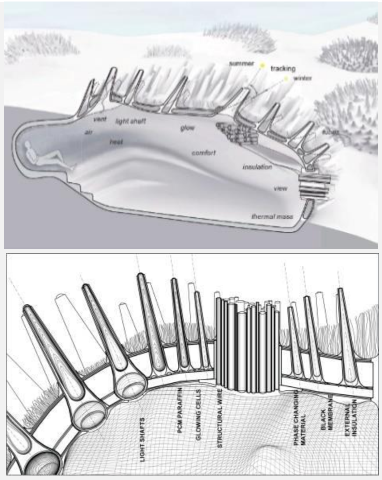

Fig. 36 – Proto Project envelope (structure & details)
Source: (Mazzoleni, 2013).

Table 10 - Presentation and analysis of The BIQ House, Hamburg, Source: researcher

| **Project name** | **The BIQ House at the International Building Exhibition** | | | | **Site**: Hamburg |
|---|---|---|---|---|---|
| **Processing level** | Design | **Envelope** | Structure | Component | **Material** |
| **The thermal problem** | **Heat gain** | Heat retention | Heat dissipation | Heat prevention | - |
| **Result summary** | -The bio-envelope contributes approximately (30 kWh / m2 of biomass, 150 watt / m2 of thermal energy). -Reducing carbon dioxide emissions by an estimated 6 tons annually (Tokuç et al., 2018). | | | | |

***Building***

- **Location**: Hamburg.
- **Architect**: splitterwerk, Graz, and Arup.
- **Year of establishment**: 2013.
- **Description of the building**:
  - It is a five-floor residential building built within the framework of the International Building Exhibition in Hamburg (Tokuç et al., 2018).

Fig. 37 – The BIQ House
Source: (Tokuç et al., 2018)

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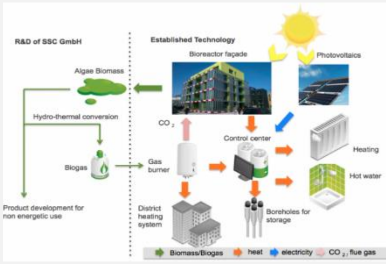
| | | |
|---|---|---|
| ***Innovation*** | - The envelope design was inspired by the functions of vital skin systems as both sides of the building represent a "bio-envelope" inside which microalgae grow (Öztoprak, 2018).<br>- The envelope design aims to design a system that can produce energy, control the amount of solar radiation acquired, and shade the facades (Öztoprak, 2018). | <br>Fig. 38 – The envelope of BIQ<br>Source: https://www.architonic.com en/project/arup-biq-house/5101636 |
| ***Thermoregulation techniques*** | -The Architect relied on adaptive materials in developing bio-envelope systems linking between the inside and outside of the building. It is working to provide heating and the building's biomass. The bio-structure consists of 129 bioreactors that contain microalgae (They are constantly supplied with liquid nutrients and carbon dioxide gas via feeding lines in the building envelope) constructed on a secondary structure separate from the main envelope of the building. Bioreactor panels absorb solar rays with a similar mechanism as thermal units, and the resulting heat is either used directly for heating or stored in underground wells. These microalgae work on biogas production. (Öztoprak, 2018) (Tokuç et al., 2018). | <br><br>Fig. 39 – The BIQ house adaptation mechanism<br>Source: https://www.buildup.eu/en/ practices/cases/biq-house-first-algae-powered-building-world |

## 3. RESULTS AND RECOMMENDATIONS:

Living organisms and ecosystems have proven their efficiency in providing strategies based on physiological and morphological characteristics to achieve efficiency in the thermal regulation processes with the surrounding environment without causing any harmful effects (Garcia, 2015) (Margariti, 2020). Due to the diversity of climatic and thermal conditions of the environmental regions, organisms have provided a remarkable difference in adaptation strategies according to the thermal properties of their sites. Biomimicry in architecture requires studying the climatic and thermal properties of the region to understand its thermal issues and design requirements to create solutions that depend on mimicking the organisms of the region itself or any climatic regions with similar thermal properties.

Due to the variety of thermal properties of Egyptian climatic zones, the design requirements of each zone differ from the others to reach the optimum thermal performance. Each of Egypt's climatic zones provides the required thermal comfort levels inside buildings only during certain months of the year and often in the autumn and spring seasons (Mahmoud, 2011) (Saleem et al., 2016). Therefore, it is necessary to recommend a group of strategies that can be applied to enhance the thermal regulation of buildings with the environment to reach the required thermal comfort rates in the warmer or colder months.

We have used some strategies from the analyzed experimental techniques and architectural examples applied in climatic regions similar to the properties of the climatic zones of Egypt to plan a biomimicry strategies guideline matrix for enhancing thermal regulation efficiency in different Egyptian climatic zones.

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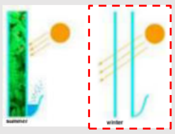
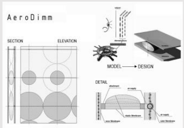
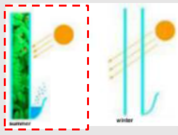
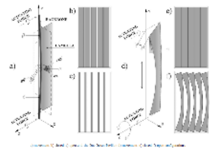
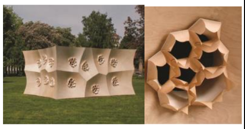
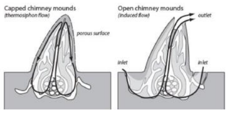
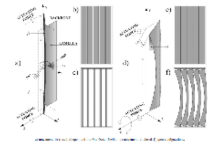
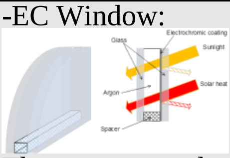
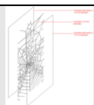
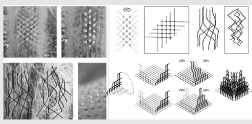
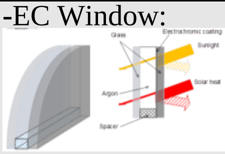
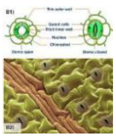
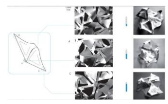
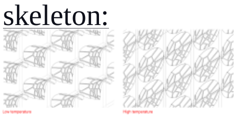
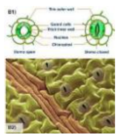
Table 11 - Biomimicry Design Strategies guideline matrix for enhancing thermal regulation efficiency in different Egyptian climatic zones, Source: researcher.

| Guidelines | Thermal (Heat) regulation mechanisms | | | |
|---|---|---|---|---|
| | **Heat gain** | **Heat retention** | **Heat dissipation** | **Heat prevention** |
| | -Foliage Facade:<br><br>Plant leaves fall to allow the sun's rays to penetrate. | -Aero Dimm:<br><br>The radiative heat exchange rate depends on the temperature. | - Stoma Brick:<br><br>Achieve thermal regulation by the evaporative - cooling system. | -Foliage Facade:<br><br>Leaves prevent the sun's heat from penetrating. |
| | -Flectofin ™:<br><br>Unit displacement is activated to increase heat gain. | -Hygroskin:<br><br>Cones close and open according to the humidity & temperature. | -Termite mounds:<br><br>Control of airflow rate & heat dissipation by evaporation. | -Flectofin ™:<br><br>The units are closed to achieve heat prevention. |
| | -EC Window:<br><br>The outer layer becomes clear to increase heat gain. | Hydrogel Structure:<br><br>Provides passive shading devices with variable thermal properties. | -Cactus inspiration:<br><br>Reduce the air temperature in contact with the surface. | -EC Window:<br><br>The outer layer becomes dark to prevent heat. |
| | -Stomata:<br><br>Envelope units open to increase heat gain. | -BiMetal:<br><br>A curve forms according to the temperature to complete the heat exchange. | -Environmental skeleton:<br><br>reducing the heat gain & humidity of the existing building surfaces. | -Stomata:<br><br>Envelope units are closed to achieve heat prevention. |
| 1-North coast | In winter | | | In summer |
| 2-Delta & Cairo | | | | In summer |
| 3-Northern upper Egypt | | | | |
| 4-Southern upper Egypt | | | In summer | |
| 5-Eastern Coast | | | | |
| 6- Altiplano (Highlands) | | | In summer | In summer |
| 7- Desert region | | | In summer | |
| 8- Southern Egypt | | | In summer | |

## 4. CONCULSION:

Living organisms and ecosystems provide an infinite source of strategies for different thermal regulation functions (heat gain, heat retention, heat dissipation, heat prevention) (Badarnah, 2015) (Widera, 2016). They depend on the physiological and morphological characteristics of the organisms and can be inspired in architectural design at the level of building design, envelope, structure, components, and building materials (Badarnah, 2015).

The primary objective of this paper is to map the classification of some strategies & techniques that can be applied in different climatic zones in Egypt as a guiding approach to the design process. To achieve this objective, we could analyze experimental techniques & architectural examples depended on biomimicry principles for achieving thermal regulation efficiency. That would facilitate the understanding of the inspiration mechanism of the living organism strategies in different regions to enhance thermal regulation efficiency in the building.

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