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Role of Structures Inspired by Nature to achieve Sustainable Architectural Buildings Case Studies: National Museum of Qatar, El-Bahr Towers, Eden Project

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Abstract

The built environment is considered to be one of the major causes of the negative environmental impacts, consuming materials, using energy resources, and emitting green house gases. Therefore, architects and engineers are always seeking more sustainable design solutions. This is where biomimicry has a powerful role. Biomimicry is a science that studies nature to solve human problems as it has abundant structural solutions that can help in evolving a complex form which was the focus of this paper. This paper is seeking sustainable structural solutions by studying and analyzing sustainable architectural cases in which their structural systems were inspired by nature with less negative impacts on the environment. As a result of the study, some guidelines were concluded which can be employed into the design of the structural system to obtain sustainable architecture showing how nature can be a guide for a more sustainable environment in the future.

Keywords: *Architecture; Biomimicry; Bio-inspired design; Structural systems; Sustainability*

Introduction

In order to create more sustainable systems and designs, biomimicry studies the forms, functions, and ecosystems found in nature. Nature refers to the conscious thinking and active pursuit of nature's experiences before designing something (M.Benyus 2016). Biomimicry is a conscious simulation of the “genius of life.” The true genius of life lies in how its technologies contribute to the continuation of all life on Earth, including physiological, behavioral, and societal strategies (M.Benyus 2016). Our modern lifestyles have an impact on the environment, which causes climate change and a shortage of natural resources (Pedersen Zari 2010). By conserving nature's resources, or mimicking nature that is inherently sustainable. In order to meet the design challenges sustainably and more effectively, the built environment must be dealt with as a contract in an integrated periodic system, and the design process should be affected by mimicking nature as one of the basic approaches used to achieve sustainable architecture (Pedersen Zari 2007).

1.1 Research problem and objectives

Lack of using nature as an inspiration to reach structural solutions despite the sustainability existence of living organisms and their adaptation to nature. There fore this research aims to deduce the guidelines for sustainable design solutions by directing architects to discover the structural shapes in nature.

1.2 Methods

The nature of the study requires relying on the descriptive approach, the analytical approach, in addition to the deductive approach. First a descriptive approach was used for studying the theoretical framework of biomimicry in architecture, its levels and methods, and sustainability in architecture. Then analytical study of biomimetic architecture and assessment of the extent to which the concept of sustainability has been achieved. Finally deducing some guidelines for structural systems to obtain sustainable architecture.

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2 Theoretical approaches

2.1 Biomimicry

Biomimicry first appeared as a term in 1982 by "**Janine Benyus**" in her book "**Biomimicry: Innovation Inspired by Nature**" (Benyus 1997). She defined biomimicry as "a new science that studies models of nature and then imitates or draws inspiration from these designs and processes to solve human problems".

Janine affirmed sustainability as a biomimicry's goal. She suggested viewing *nature as a model:* it is a science that considers models of nature,then studies and imitates them or could help in solving human problems by inspiration of these designs and processes, for example a solar cell inspired by paper. *Nature as a measure*: it can use biomimicry as an environmental standard of our innovations "correctness judgement". *Nature as a mentor:* Biomimicry is a method to view and evaluate. It presents what we can learn from the natural world not what we can extract from it.

2.2 Biomimicry approaches

Some systematic steps can be followed by the designer to get a suitable biological solution. There are two different approaches:

A- Problem-based approach (design looks in biology): it is also called the **top-down approach** (Radwan and Osama 2016). An approach in which designers look to nature for by observing organisms that have solved similar problems. Defining the primary design goals and criteria is considered more effective.

b- Solution-based approach to design (biology influences design): it is known as Biological Impact Design, **bottom-up approach** and Biological Inspired Design (Radwan and Osama 2016). When biological knowledge affects human design, at the beginning this collaborative design process relies on biological or environmental research rather than identifying design problems.

2.2 Levels of biomimicry

An organism mimicry is by simulating a particular aspect of that organism which might be a shape or a function. This aspect is referred to as the "level of biomimicry." Two classifications of nature simulation levels are given by: (1) "Janine Benyus", (2) "Pedersen Zari".

1- Janine Benyus has pointed out that there are three levels of biomimicry:

(a) Form or Structure Level: nature was created in a comprehensive, rich, and varied form. These forms succeeded in surviving in the environment despite the different conditions. *(B) Process Level:* it is a mimicking of the natural process, organisms and humans are always having the same environmental conditions, but in most cases, organisms overcome their problems within the limits of energy and materials through a natural process to adapt to their environment. *(c) Ecosystem Level:* mimicking the characteristics of ecosystems such as food web, diversity, feedback loops and symbiotic relationships that take place in wetlands when wastewater is purified by living machines (Benyus 1997).

2- Pedersen Zari has set the biomimicry levels as follows:

(a) Organism Level: organisms that have survived on Earth for millions of years have evolved, and their survival mechanisms have evolved to withstand and adapt to the constant changes of the environment over time. Humans have a wide range of examples to draw from in solving societal problems, usually in energy- and material-efficient ways that living things have already addressed (Pedersen Zari 2007), (table 1).

Table 1 Organism level example

Inspiration from nature	Application example
"Namibia desert beetle" (fig 1), the beetle lives in a desert with little rain which picks up moisture from the fog that moves over the desert by sloping its body in the wind direction. The drops form on the beetle's back with rough surface helps in forming drops, until the water droplets roll into its mouth.	Inspired by the beetle, Matthew Parks demonstrates a biomimetic of the organism-wide process with his design of a fog catcher for the Hydrological Center in University of Namibia (fig 2), where fog is collected through its condensation, and when the wall becomes saturated with water gravity pulls the water into an underground tank.

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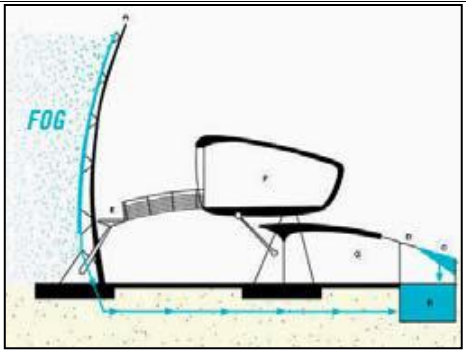
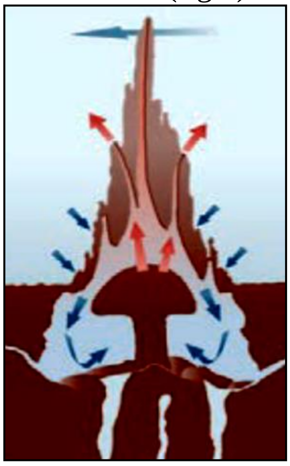
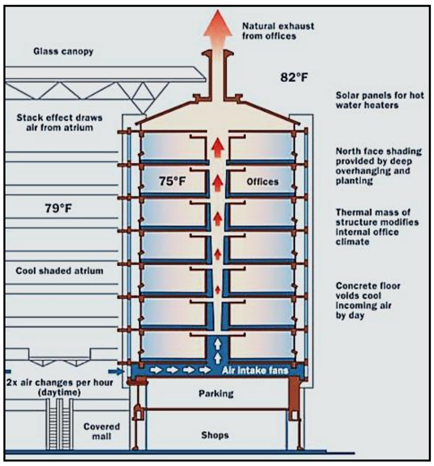
 **Fig 1** Namibia desert beetle (Pedersen Zari 2007)	 **Fig 2** Brickell office (Pedersen Zari 2007)

(B) Behavior Level: it's considered as a different term of the process level. Thus, the evolution of the behaviors of living organisms and patterns of relationship between organisms to adapt in the conditions of ecosystems (Reap and others 2005) and observing and following up those behaviors that are adaptive to certain environmental conditions and thus simulating them in a way that helps in solving human problems for the same environmental conditions. Table 2 illustrates an example of the behavior level.

Table 2 Behavior level example

Inspiration from nature	Application example
(passive ventilation techniques) in termite mounds (fig 3).  **Fig 3** Ventilation process in termite mound (ElDin and others 2016)	The Eastgate Building (fig 4) by **Mick Pierce** Architects in Harare, Zimbabwe, passive ventilation techniques were designed to provide a thermally stable indoor environment.  **Fig 4** The Eastgate building in Harare, Zimbabwe (ElDin and others 2016)

(c) Ecosystem Level: this term reflects a sustainable form of biomimicry. Design advantages at this level of nature simulation: 1- It can be used in conjunction with other levels, 2- interstitial or bio assisted systems by integrating human and non-human systems for the mutual benefit of both (e.g. **John Todd's Living Machine**) (John Todd 2003), as shown in table 3, 3- Possible positive effects on the overall environmental performance.

Table 3 Ecosystem Level Example

Application example

Biologist John Todd has developed a technology in environmental engineering called "living machine" (fig 5) that purifies sewage or other polluted water by mimicking the natural purification processes that occur in ponds and swamps. An "environmental purification system" with raw sewage water entering an external area containing tanks inhabited by a complex group of living organisms, and then connecting these tanks to a system of other tanks, which each have their own ecosystem and specialized in a certain stage of decomposition and separation of organic and non-organic materials Organic water, after ten days in a series of purification ecosystems, clean water flows to an external artificial swamp or wetland to be returned to the (local water hydrologic cycle), and the water can also be made potable using ultraviolet light or by passing water through a generator Ozone (Todd 2006).

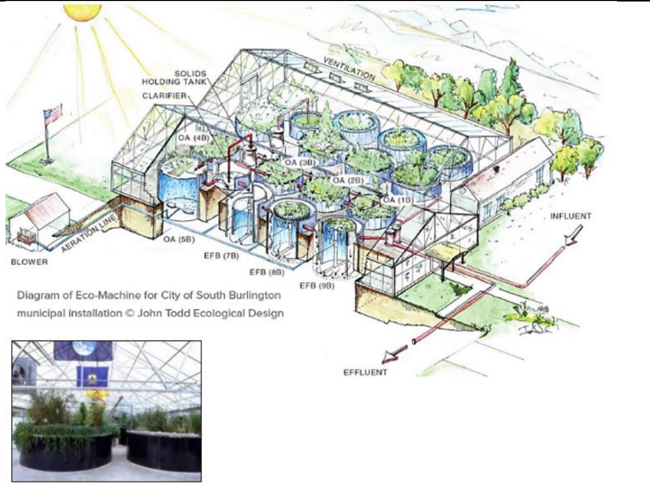


Fig 5 Natural purification processes by machine live in South Burlington, Vermont (Todd 2006)

3. Sustainability

Ensuring that our use of the resources that are currently available does not negatively impact our collective well-being or make it impossible to get resources for future uses is the notion behind sustainability, or environmental design. The goal of sustainable design is to satisfy present demands without depleting the natural resource base that will be available to future generations. Concern for the fundamentals of social and economic sustainability as well as particular issues with energy use and the effects of cities and structures on the environment should be included. The primary problems are low energy and efficient resource use (Clements-Croome 2004).

3.1 Sustainability in architecture

Sustainable design focuses on long-term effects on buildings, users, and the environment, preserving natural resources for future generations. Measures like LEED in the USA, NABERS in Australia, and BREEAM in the UK evaluate projects' success in balancing energy, environment, and ecology, considering social and technological aspects. These standards cover sustainable siting, water efficiency, energy, materials, and indoor environmental quality (Clements-Croome 2004).

4. Case studies

4.1 National Museum of Qatar [NMoQ]

In Doha, Qatar, the museum was founded as a center for culture and social interaction. Architect Jean Nouvel created it in 2002 (Nouvel 2019). After initiating work on the project in September 2011, Hyundai Engineering and Construction, a South Korean corporation, has already finished building the National Museum of Qatar. On March 28, 2019, the museum opened (Lee Ji-yong 2019).

4.1.1 General information

The 430,000-square-foot (52,000 m2) museum consists of several disk-shaped volumes interconnected to form a 350-meter-long ring-shaped architectural complex. The complex also includes the Royal Palace of Sheikh Abdullah bin Jassim Al Thani, a historic building from The twentieth century has been preserved and restored (Bianchini 2020). Fig 6 shows the plan and sections of the museum.

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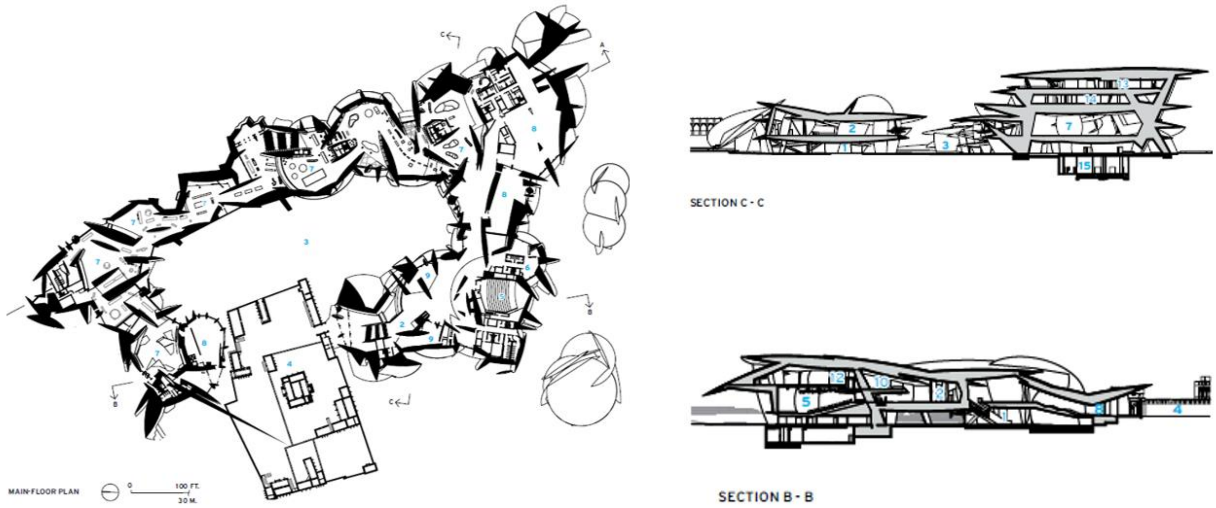


Fig 6 The plan and sections of the museum (Broome 2019)

4.1.2 Biomimicry analysis in the case study

Table 4 shows the biomimicry analysis of national museum of Qatar, mimicking the desert rose form into the shape of the museum's structural discs.

Table 4 Biomimicry analysis of national museum of Qatar

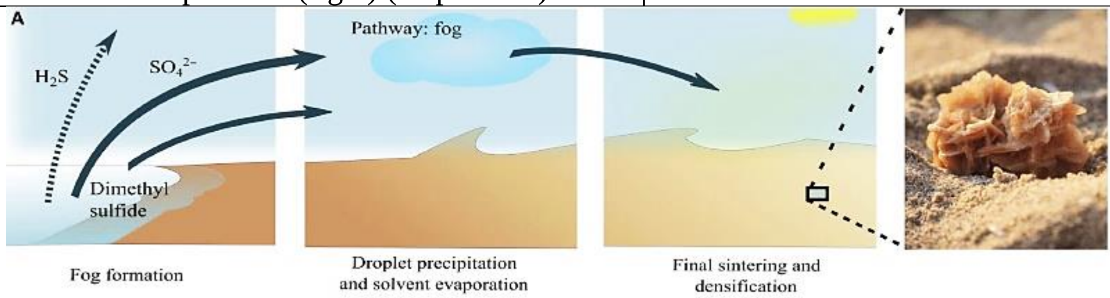
<table>
<tr><td>Biomimicry level</td><td colspan="2">Form or structure level</td></tr>
<tr><td>Inspiration from nature</td><td colspan="2">Desert rose</td></tr>
<tr><td>Biomimicry approach</td><td colspan="2">Solution-based approach</td></tr>
<tr><td colspan="2">The French architect Jean Nouvel inspired the design of the museum (fig 7) from the desert rose, similar to crystals, with a series of intertwined reproduction (fig 8), to take the external appearance of the museum in the form of several disk-like structures intertwined together, the desert rose (Wikiarquitectura 2020), The damp sand forms desert roses. Crystals are formed when water with dissolved calcium sulfate flows across it, balanced by the flow of water due to evaporation (fig 9) (Hope 2015).</td><td>
Fig 7 National Museum of Qatar design inspiration (Broome 2019)</td></tr>
<tr><td colspan="3">

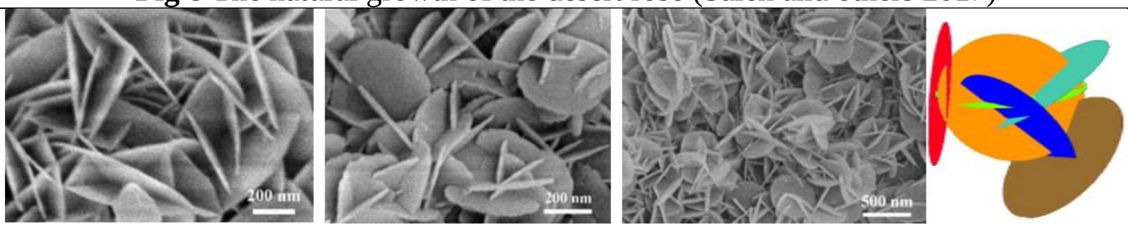
Fig 8 The natural growth of the desert rose (Saleh and others 2017)</td></tr>
<tr><td colspan="3">

Fig 9 High-Magnification SEM images of the Desert Rose (Min Wang and others 2014)</td></tr>
</table>

4.1.3 Structure analysis

The core structure was developed by[Arup]. The structural solution relied on radial or perpendicular steel frames, which supported Fiber Reinforced Concrete side panels to achieve the desired aesthetics and performance of the building envelope (Wikiarquitectura 2020).

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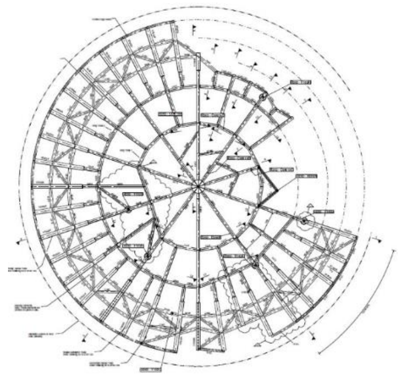
Primary structure: the primary steel structure is the supporting structure of the structure. The spherical disks are formed by a steel structure radially with different diameters and variable bends, whose radii range from 10 to 43 m, so that they can be adjusted to suit the loads by means of beams down to the bottom plates (Wikiarquitectura 2020). **The link between the primary and secondary steel structure:** which supports the cladding is secured with screws. These studs control the curved formation of the disc. It consists of two different types: **ceiling discs and vertical discs**, where the remaining loads are transferred to the base by the vertical discs, which serve as the project support, as shown in table 5.

Table 5 Structural discs of national museum of Qatar

Structural discs		
Number	539 discs of 30 different sizes, cross an astounding number of knots (fig 10).	 **Fig 10** Primary Structure's Discs (Wikiarquitectura 2020)
Usage	It was used to create the ceilings, panels and walls of the museum.	
Description	Spherical-section discs are formed by a radially steel structure of various diameters and variable curvatures, which range in radius from 10 to 43 meters, so that they can be adjusted to suit loads by means of beams down to the bottom plates (fig 11), (fig 12) (Wikiarquitectura 2020).	
Types	Two different types: ceiling discs and vertical discs.	
Vertical discs	They support the project and transfers the rest of the loads to the base.	
 **Fig 11** Primary structure installation at the site (Trimble-Co 2020)	 **Fig 12** Primary structure installation at the site (Alpin-Co 2020)	

Secondary structure: the secondary structure is made of steel profiles. They are curved structures to fit an axially symmetric concrete slab installation. The secondary steel structure consists of supporting beams with a maximum distance of 3 meters between them. They are secured with screws at the ends, one with a regular hole and the other with a rectangular hole. Therefore, the force transfer between the secondary and primary structure due to thermal motion is limited (Wikiarquitectura 2020).

Table 6 illustrates the cladding panels of national museum of Qatar**. Cladding installation:** (1) Metal frame installed on the main steel structure, (2) Insulating and waterproof membrane supported by the structure, (3) Welded beams to the main steel structure, (4) Secondary steel structure supported by bolts. (5) Concrete sides installed on the secondary steel structure (Wikiarquitectura 2020).

Table 6 Cladding panels of national museum of Qatar

Cladding panels		
Material	The building is clad in ultra-high performance precast concrete panels (UHPC) reinforced with pink fiberglass [Glass-Fiber Reinforced Concrete (GFRC)] (fig 13) (Wikiarquitectura 2020).	
Number	76,000 units of the cladding are produced from 3,000 master molds, approximately 2 square meters each (Broome 2019).	

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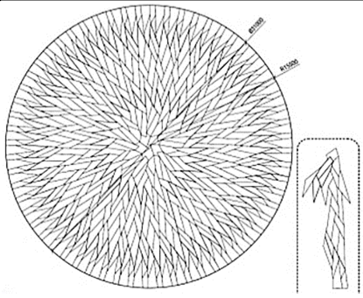
Description	Despite the obviously random layout, a recurring radial pattern has been constructed and adjusted to fit various disk sizes, covering an area of 120,000 square meters (fig 16).	 **Fig 13** Concrete Cladding Panels shape (Wikiarquitectura 2020)
Support	Mounted to a steel frame that spans over a water-repellent upper structure. (Wikiarquitectura 2020) Stainless steel ties molded into the panels connect them to the infrastructure (fig 14). The thickness of the plate around the circumference is increased to 60 mm to allow for the placement of the mounting bracket, which is a steel Z plate that is fixed with four bolts in the secondary structure and ensures the cutting resistance of the anchor point. An expansion joint is created between each concrete slab, (fig 15), (fig 17).	

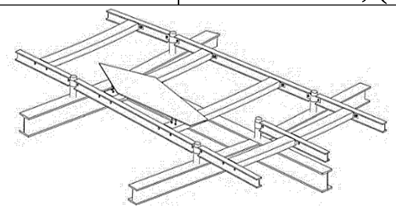


Fig 14 Install supporting panels to cover the structural structure (Wikiarquitectura, 2020)

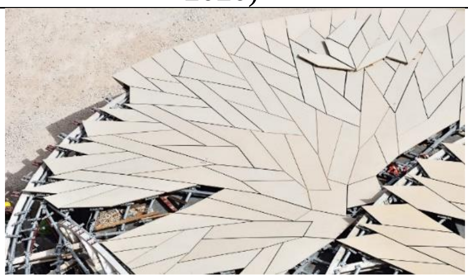


Fig 15 The cladding panels on site (Dunmall 2014)

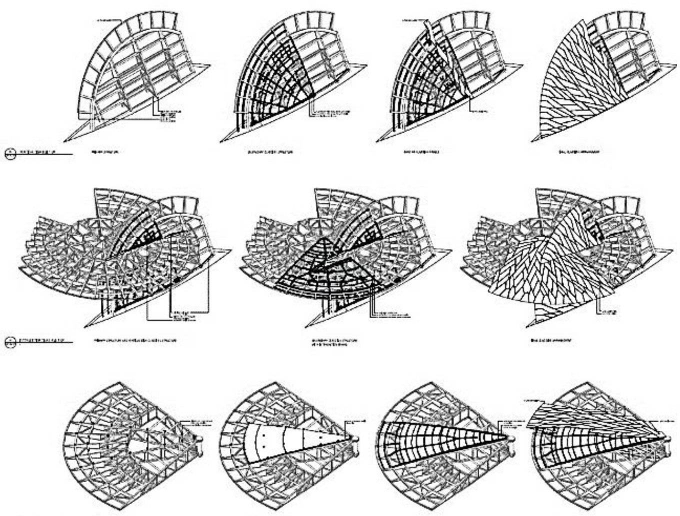


Fig 16 Installation of cladding panels on structural disks (Nouvel 2019)

Fig 17 Installation of cladding panels on site (Wikiarquitectura, 2020)

4.2 El-Bahr towers

Designed by global architecture firm Aedas in collaboration with consultant Arup, Al Bahar Towers (fig 18) creates an impressive facade that pays homage to traditional Arab architecture and design in the

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Emirate of Abu Dhabi in the United Arab Emirates. The project brief required two 25-storey towers to create an iconic building that would offer contemporary design using modern technology while keeping in mind the architectural heritage of the area. Fig 19 shows a section in El-Bahr Towers.

Fig 18 El-Bahr towers layout (LINE 2020)

Fig 19 A section in El-Bahr towers (LINE 2020)

4.2.1 General information

The building consists of two towers, one of which includes the offices of the Council's headquarters and the other includes the headquarters of Al Hilal Bank and other departments, in addition to a separate structure for car parking.

4.2.2 Biomimicry analysis in El-Bahr towers

Arup Architects have turned to the natural world for inspiration on practical design principles that allow forms to adapt to their surroundings, and this is demonstrated through design ideas inspired by nature:

A- Mimicking the structural system of **honeycomb**, (table 7).
B- Mimicking the form and behavior of **Oxalis**, (table 9).

Table 7 Mimicking the structural system of honeycomb in El-Bahr towers

<table>
<tr><th colspan="3">A- Mimicking the structural system of honeycomb</th></tr>
<tr><td>Biomimicry level</td><td colspan="2">Form or structure level</td></tr>
<tr><td>Inspiration from nature</td><td colspan="2">Honeycomb</td></tr>
<tr><td>Biomimicry approach</td><td colspan="2">Solution-based approach</td></tr>
<tr><td>Mimicking the structural system of honeycomb, where the designer created the external structural structure of a hexagonal mesh, (fig 20), derived from the formation of nested honeycomb, (fig 21), in line with the architectural idea of the building’s shape (Arup 2014).</td><td>
Fig 20 Al-Bahr towers mimicry of honeycomb (AHR 2020)</td><td>
Fig 21 Hexagonal composition of honeycomb (Mangum 2020)</td></tr>
</table>

The hexagonal structure fits the design idea, where a circular horizontal plan (fig 22) was designed based on six transverse arches, starting with three geometric circles to reduce the sunlight, with an oval shape narrower at the base than the top (fig 23) (Arup 2014).

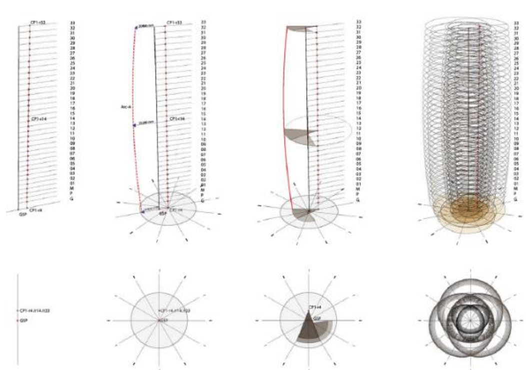

Fig 22 Formation of Al-Bahr towers floor slabs from transverse circuit arrangements

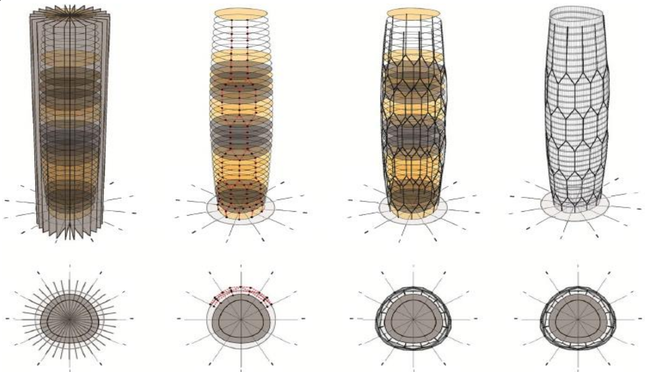

Fig 23 Structuring the honeycomb in Al-Bahr towers by connecting nodes resulting from the transverse circles intersection and the basic radial network extrusion (Karanouh and Kerber 2015)

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through a radial grid (Karanouh and Kerber 2015)

4.2.3 Structure analysis

The towers have a cylinder form and an oval shape. Each tower is given lateral stability by the 20-meter-diameter core that sits in the center. To fit the architectural concept, the perimeter structure is composed of steel columns that have a honeycomb geometry. A repetitive core design enhances efficiency and facilitates construction (Arup 2014).

About 10% of the superstructure's overall lateral stiffness comes from the surrounding structure's truss design. Additionally, the perimeter structure's shape increases flexibility under transverse loads by giving neighboring perimeter columns alternative loading routes.

Table 8 shows the analysis of the main structural system of El-Bahr towers. The main beams of steel extend in a radial direction between the core and the columns of the surrounding structural system (fig 24), extending with the supporting arms of the mashrabiya (Arup 2014). Figs 25 and 27 show the towers' construction work.

Table 8 Analysis of the main structural system of El-Bahr towers

The core	Reinforced concrete
Perimeter columns	Steel
Slabs	Steel composite floor decks with concrete poured over it (fig 26)

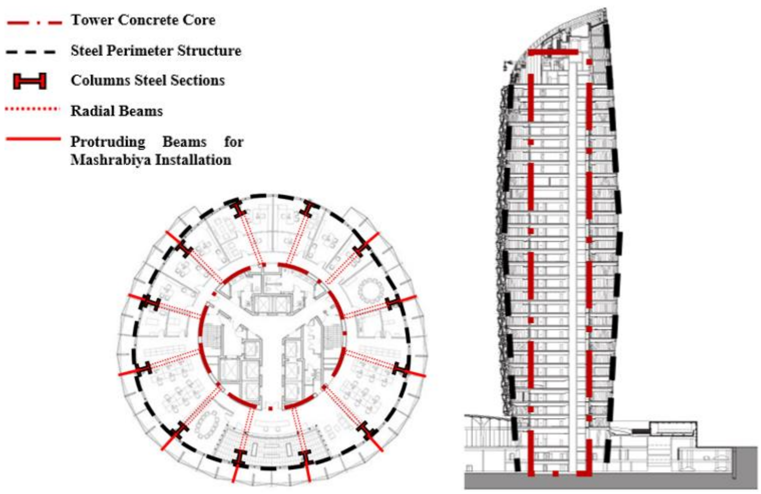

Fig 24 Components of the structural system of the tower (LINE 2020) (Edited by Author)

Fig 25 Tower construction work (Arup 2014)

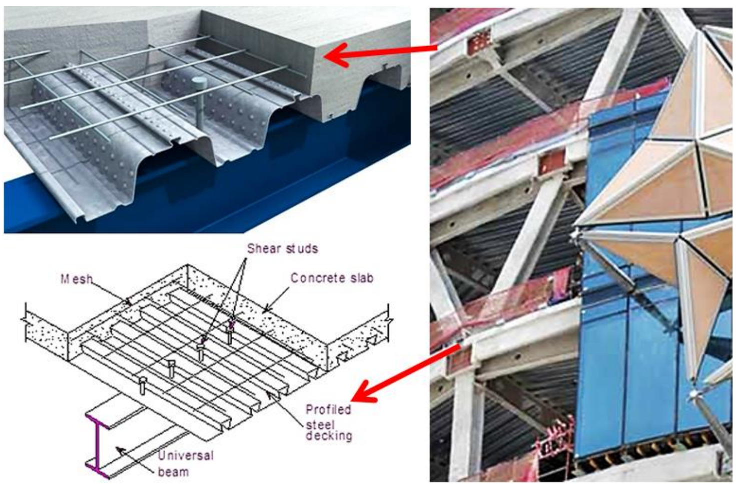

Fig 26 Composite slabs on site (MGS 2020) (Mediawiki 2012)

Fig 27 Almost finished installing the curtain wall (Yacoubian 2020)

Table 9 Mimicking the form and behavior of Oxalis in El-Bahr towers

B- Mimicking the form and behavior of Oxalis		
Biomimicry level	Form or structure level	

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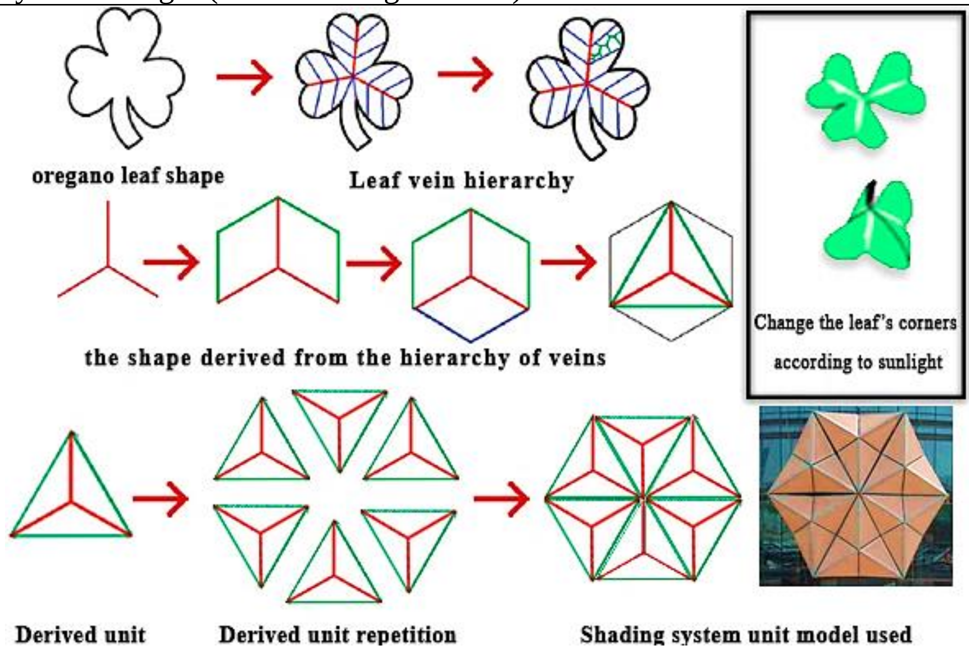
<table>
<tr><td colspan="2"></td><td>Behavior level</td><td rowspan="5">
Fig 28 Oregano leaves (Sheikh and Asghar 2019)</td></tr>
<tr><td colspan="2">**Inspiration from nature**</td><td>Oxalis oregana</td></tr>
<tr><td colspan="2">**Biomimicry approach**</td><td>Solution-based approach</td></tr>
<tr><td colspan="3">Two levels were mimicked (organism and behavior) (fig 29):</td></tr>
<tr><td colspan="2">**Organism level**</td><td>**A. Mimicking oregano leaves [Oxalis] shape (fig 28):**
1- The primary, secondary, and subordinate vein hierarchy in leaves.
2- Different angles of veins.</td></tr>
<tr><td rowspan="2">**Behavior level**</td><td colspan="3">**B. Mimicking the behavior of oregano leaves [Oxalis]:**
1 -Adjusting the angles of the leaf according to the intensity of the light: Oregana can track the intensity of sunlight through photoreceptors and change its angle.
2 -Detecting and tracking the changing path of the sun: When too much light is present, the plant can sense it and adjust its orientation to avoid it vertically for photosynthesis or horizontally for low light (Sheikh & Asghar 2019)</td></tr>
<tr><td colspan="3">

Fig 29 The shading unit shape was inspired by the oregano leaf (Sheikh and Asghar 2019) (Edited by Author)</td></tr>
</table>

The exterior facade was designed by Aedas Architects, a dual facade system of sea towers, in a kinetic way of opening and closing responding to the the sun. Aedas integrates principles of bioinspiration, regional engineering, and performance-oriented technology with core performance criteria, grid proof, and engineering configuration (Karanouh and Kerber 2015). Fig 30 shows the integration of building systems in the design phase.

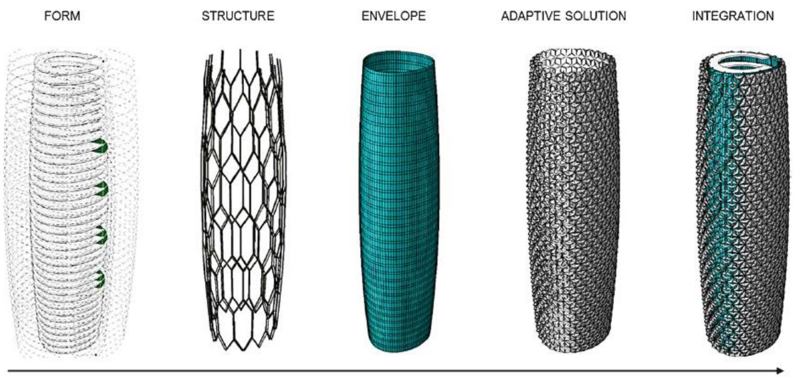


Fig 30 Integration of building systems in the design phase (Karanouh and Kerber 2015)

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How it works: The dynamic mashrabiya is installed in each of the towers on the eastern, southern, and western facades. To offer shade for the building's internal glass cover, the Mashrabiya units in the facade area are closed when it is exposed to direct sunlight (Karanouh and Kerber 2015).

As shown in table 10, the mashrabiya structural system consists of (fig 32): (1) To support the dynamic components, cantilever trusses that are part of the building's main structure extend through the curtain wall, (2) the mashrabiya has stainless steel support frames, aluminum dynamic frames and fiberglass mesh, (3) six triangular frames of each unit which open and close through a central actuator and piston. Fig 31 shows the structural components of the mashrabiya system on site (Karanouh and Kerber 2015).

Table 10 Mashrabiya structural system in El-Bahr towers

Number	There are 1,049 units installed in each of the towers.
Distance from the curtain wall	It's at a distance of 2 m from the surface of the curtain wall, and 2.8 m from the main structure (Arup 2014).
Unit dimensions	Each parachute-like device was assembled as a unified system with a height of 420 cm and a width ranging between (360 - 540) cm.
Weight	Each weigh about 600 kg (1.5 tons with steel supports) (Arup 2014).

Fig 31 The structural components of the mashrabiya system on site (Al-Khalidi 2018)

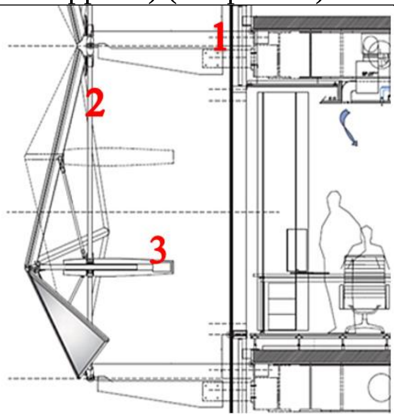

Fig 32 Mashrabiya connection with the tower (Karanouh and Kerber 2015) (Edited by Author)

Transmission of loads

The loads are transmitted from the mashrabiya and the engine through the [Y] steel frames, then to the cantilevered trusses on the main structure of the building (fig 34), (fig 35). Fig 33 shows the mashrabiya mechanism test on site.

Fig 33 The mashrabiya mechanism test on site (MGS 2020)

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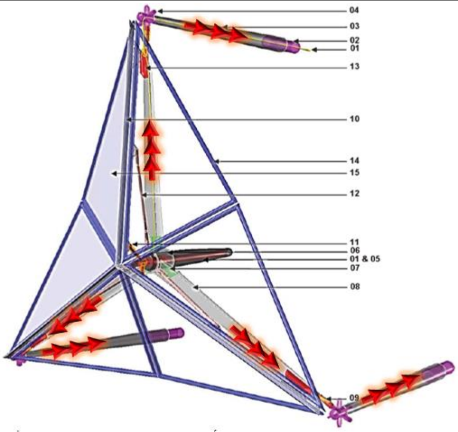

Fig 34 Transfer of loads through the mashrabiya unit (Karanouh and Kerber 2015) (Edited by Author)

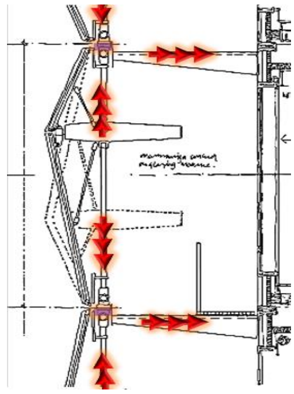

Fig 35 Transfer of mashrabiya loads to cantilever supports (Karanouh and Kerber 2015) (Edited by Author)

4.3 Eden project biomes

The world's largest botanical garden, which is located in Cornwall, England, in the United Kingdom. It is a scientific experiment that uses highly innovative technology to provide different climates, combining ecology, gardening, science, art and architecture. The project includes more than 5,000 species of plants. From different regions around the world (Eden-Project-Co 2020).

The initial idea of the project was started by Grimshaw Architects in 1996, construction phases started in 1998. The project was fully opened to become one of the most prominent attractions in the United Kingdom on 17March2001 and contributed more than one billion pounds sterling to the economy of England.

4.3.1 General information

The Eden Project is considered a multifunctional project. In addition to being an international botanical garden, it is considered a cultural, educational, and recreational center with its multiple services. Master Plan [Layout] (fig 36) contains biomes, outdoor gardens, the core building, visitors center, the stage & the arena (Eden-Project-Co 2020).

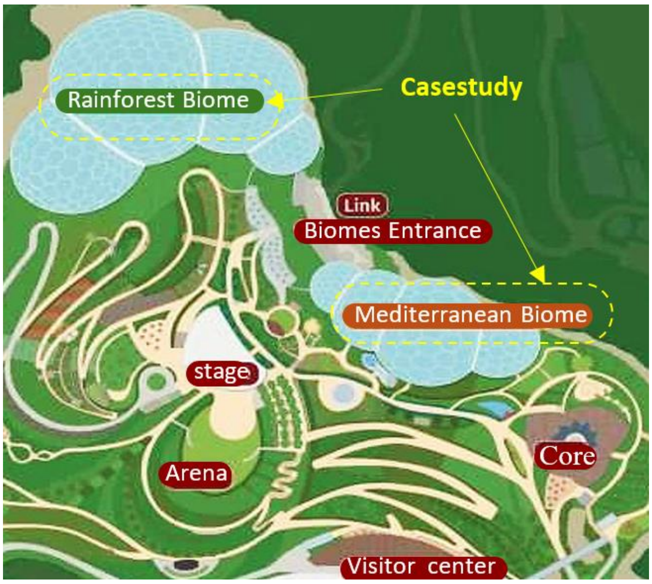

Fig 36 The general outline of the Eden project (Eden-Project-Co 2020)

4.3.2 Biomimicry analysis in the case study

The site of the project was an unstable deep mud hole with an irregular topography, David Kirkland proposed a shape for the construction inspired by Soap Bubbles (fig 37) (which may rest on any surface), where the idea was a series of bubbles [Bubbles Necklace] of various diameters to provide appropriate mounting heights in different parts of the building (fig 38), which can be arranged to suit the approximate terrain (fig 39) (Eden-Project-Co 2020). Table 11 shows mimicking necklace of bubbles in Eden project biomes.

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Table 11 Mimicking necklace of bubbles in Eden project biomes

A- Mimicking necklace of bubbles	
Biomimicry level	Form or structure level
Inspiration from nature	Necklace of bubbles
Biomimicry approach	Problem-based approach

Fig 37 The shape of soap bubbles (Faithtwins 2011) (Nitze 2012)

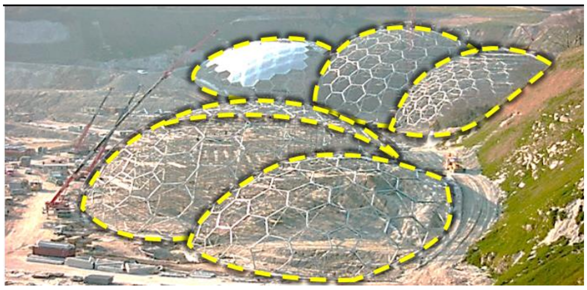

Fig 38 Domes under construction against one of the side walls of an old clay quarry (Eden-Project-Co 2020) (Edited by Author)

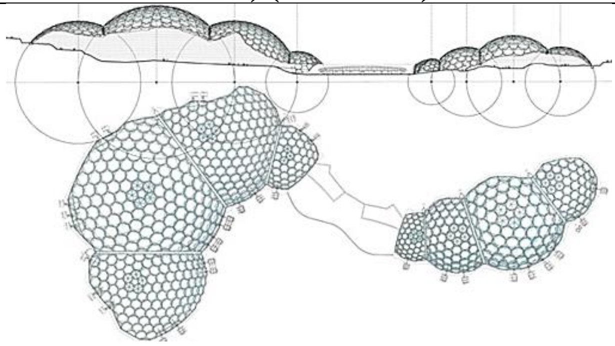

Fig 39 The geodesic domes shape that looks like a series of bubbles (GRIMSHAW 2020)

B- Mimicking the Geodesic systems in Eden project biomes

Mimicking the hexagonal structures of the biomes from the geodesic structure of cellular structures in nature, the design team was aware that there are many effective solutions in nature, from cell membranes to spider webs "The Geodesic System" (fig 40), (fig 41), The structural lattice resembles the molecular organization of some minerals, such as silicates (SiO_4) (fig 43) (Knebel and others 2001), as shown in table 12.

Table 12 Mimicking Geodesic systems in Eden project biomes

B- Mimicking the geodesic systems in nature	
Biomimicry level	Form or structure level
Inspiration from nature	Geodesic systems in nature
Biomimicry approach	Problem-based approach

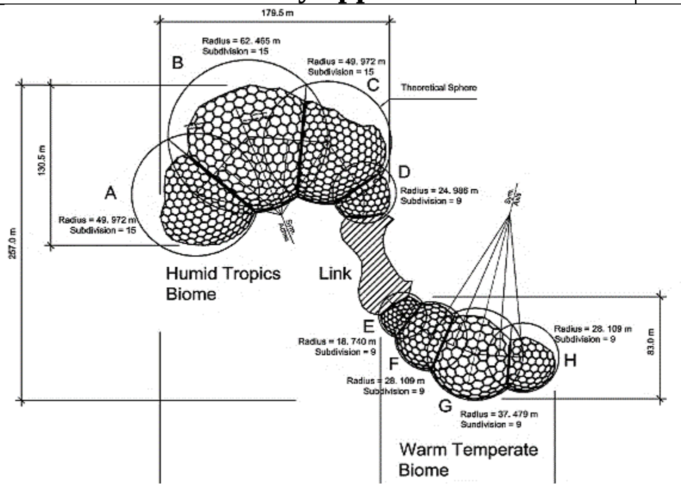

Fig 40 The Geodesic domes (Eden-Project-Co 2020)

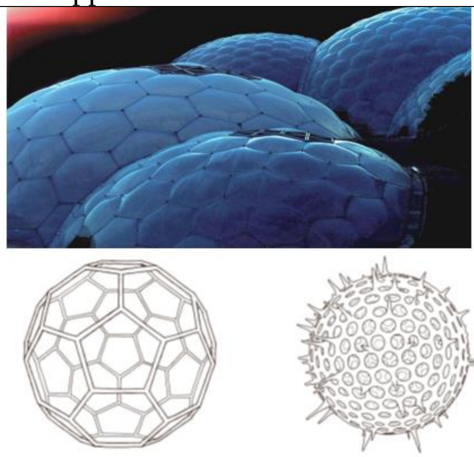

Fig 41 Mimicking the structure of domes geodesic shapes in biology (Eden-Project-Co 2020)

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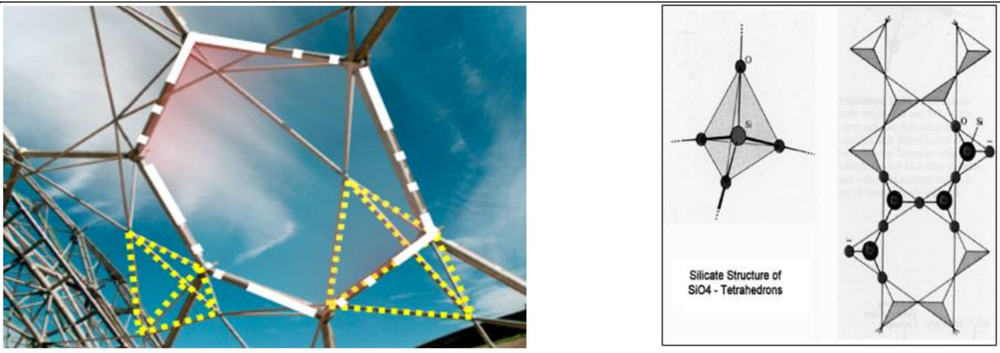

Fig 42 Application of the silicate molecule shape in the [Hex-Tri-Hex] structural system (Knebel and others 2001) (Edited by Author)

4.3.3 Structure Analysis

Space frame of galvanized steel tubes with a Hex-Tri-Hex profile (fig 43), which is two layers (Knebel and others 2001): *(1) The outer layer* consists of hexagons (the largest of which is 11 meters in diameter) as well as individual pentagons. (*2) The inner layer* consists of hexagons and triangles held together, the steelwork weighing slightly more than the weight of the air contained in the domes inside.

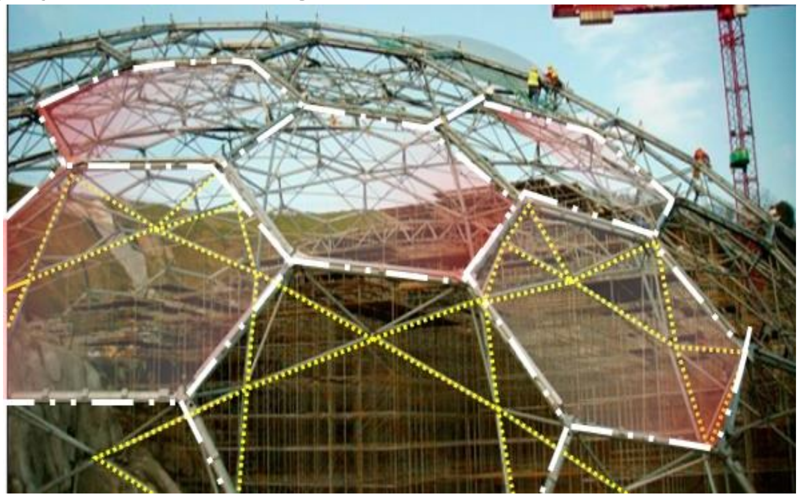

Fig 43 Hex-Tri-Hex modulation of the space frame forming dome structures (Knebel and others 2001) (Edited by Author)

Arches: Truss arches with a triangular section were constructed along the intersection of the domes, and some more cables were added to support the cushions there (fig 45). The arches' hinged support was provided by substantial foundation concrete blocks (fig 44) (Knebel and others 2001). Table 13 shows the cladding panels in in Eden project biomes.

Fig 44 Support construction (Knebel and others 2001)

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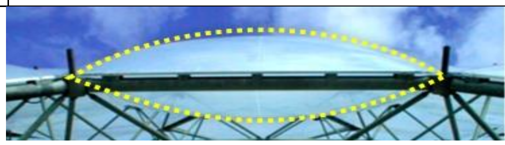
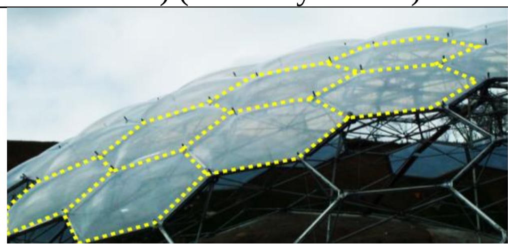
Fig 45 Steel arches between geodesic domes (Knebel and others 2001) (Eden-Project-Co 2020)

Table 13 Cladding panels in in Eden project biomes

<table>
<tr><th colspan="4">Cladding panels</th></tr>
<tr><td colspan="3">Mimicking geodesic systems that use elastic materials in tensile forces instead of solid materials in compression or bending forces (fig 46), it was suggested using of transparent films of ETFE (Knebel and others 2001).</td><td rowspan="4">
Fig 46 Elastic materials of geodesic systems in nature (Eden-Project-Co 2020)</td></tr>
<tr><td>Material</td><td colspan="2">Ethylene Tetrafluoroethylene Copolymer [ETFE].</td></tr>
<tr><td>Amount</td><td colspan="2">800 inflated membrane cushions, equivalent to 30,000 square meters.</td></tr>
<tr><td>Panels Thickness</td><td colspan="2">It varies between 5mm, 15m in width.</td></tr>
<tr><td colspan="3">Three layers make up the cushion (fig 47): the top and bottom layers hold the carrier in place while creating a cushion; the middle one works to enhance thermal insulation and also divide the airspace in the event of a leek. Figs 48 and 49 shows the ETFE pillows on site.</td><td>
Fig 47 An ETFE pillow (Eden-Project-Co 2020) (Edited by Author)</td></tr>
<tr><td colspan="3">
Fig 48 Installation of the ETFE pillows (Bissegger 2006), (GRIMSHAW 2020)</td><td>
Fig 49 The ETFE pillows (Eden-Project-Co 2020) (Edited by Author)</td></tr>
<tr><td colspan="4">[ETFE] features:
1- The material is weight (1% of the weight of glass) and is strong, providing a frame of structures [the metal frame] that is lighter and provides great savings in construction.
2- It allows more sunlight to pass through and reduces the heat that will be required in winter.
3- The full cost of the solution costs of treatment.
4- It is a material with a smooth surface and is self-cleaning (dirt is washed outside by rain).
5- Life expectancy is 25 years (Eden-Project-Co 2020).</td></tr>
</table>

5. Sustainability in case studies

(1) National museum of Qatar: The museum was regarded as the first national museum in the world to be awarded **a 4-star GSAS (Global Sustainability Assessment System)** sustainability rating in addition to **a LEED Gold** certification (Staff 2019). **(2) Al-Bahr towers: t**he project has been awarded **a [LEED] silver Certification** for sustainability, according to the [LEED] rating system of the US Green Building Council (Karanouh and Kerber 2015). **(3) Eden biomes: t**he project has been awarded the sustainability certificate [**The Planet Mark**], after conducting an environmental performance audit in all our operations to measure the use of carbon, energy, water, and waste, as the project has become a close partner of [The Planet Mark] since its launch in 2012 (Eden-Project-Co 2020).

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6. Results & Discussion

After the analytical study of the case studiin sustainableing these structure systems and forms which were inspired by nature, and how it could result a sustainable architecture. As a result of the study, it has been deduced some guidelines for achieving sustainable structure, as shown in table 14:

Table 14 Sustainable Structure Guidelines

		NMoQ	Al-Bahr Towers	Eden Project biomes
Case Studies		 **Fig 50** National Musuem of Qatar (Lee Ji-yong 2019)	 **Fig 51** Al-Bahr towers (AHR 2020)	 **Fig 52** Eden Project biomes (Eden-Project-Co 2020)
Sustainable structure guidelines	**Provide stability and balance**	The structural solution relied on radial or perpendicular steel frames, which supported the fiber-reinforced concrete side panels.	Use flexible joints that are resistant to vibrations.	The structure is made of a space frame consisting of two layers of Galvanized Steel Tubes with a "Hex-Tri-Hex" profile.
	Mimicking structural systems in nature	Mimicking the desert rose shape into the structural discs that support the museum.	Mimicking the honeycomb into the external structural structure of the towers.	Mimicking the hex-tri-hex biomes structures from the geodesic structure of cellular structures in nature.
	Using sustainable materials in the structure	To reduce the carbon footprint during the construction phase, 20% of the project's building materials were extracted, processed, and manufactured regionally, specifically within 800 km of the museum site.	All exposed/visible fixed main support components have a sandblasting-like finish. This hides the dust and sand particles that are deposited on the surface of the steel.	- [EFTE]: It is a material with a completely smooth surface and is self-cleaning (the dirt outside is washed away by rain), its life span is 25 years. - The steel frame was galvanized to prevent corrosion and is intended to require no maintenance for thirty years.
	Use of environmentally friendly materials	NMoQ used materials that were low in the concentration of volatile organic compounds (VOCs).	Made of DGU, the curtain wall sight glass has an 18% external light reflection, 0.28 G-Value, and 40% visible light transmission.	Super Insulation: Using a really good insulating material [ETFE] in the hexagonal air traps that act as a thermal blanket to keep plants warm in the biomes.
	Use suitable materials in the envelope	The cross-linked [NMoQ] tablets give a lighter color that reflects more sunlight and absorbs less heat.	PTFE Coated Fiberglass Mesh was shown to be the most effective and long-lasting option.	The use of a material from [ETFE] in the pillows that traps the air inside and is transparent to allow light to pass through to the plants.
	Use recycled or	Concrete mix, steel, gypsum board, and metal items made	Use of [PTFE] (can be recycled) in the mashrabiya units.	Use of [ETFE] (can be recycled) to cover biomes.

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	reused materials	up half of the project's construction components.		
	Achieving economic efficiency	Construction phases was followed up through the introduction of 3D Building Information Modeling (BIM), which resulted in cost savings and shortened construction period.	15% savings on both capital costs and plant size overall. 20% less weight overall and in materials thanks to the extremely efficient and well-designed design.	[EFTE]: Lightweight material (1% by weight of glass), about one-third of the cost of a conventional solution of glass, life span of 25 years.

7. Conclusions

A variety of feedback mechanisms are used by nature's design process to guide an organism's development and creation in response to internal and external forces operating on and inside it. At various stages of development, all systems work together to offer the best functionality. Buildings that are influenced by and connected to their surroundings may be created if this were applied to architecture. Understanding form, substance, and structure as intricately intertwined concepts rather than as discrete elements is necessary for this. It’s recommended that architects should consider and use the guidelines deduced to mimic nature, to build sustainable architecture.

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E.A.A. (Ph.D. candidate) conceived the presented idea and wrote the initial version of the manuscript. F.M.A. (Associate professor) provided critical feedback and helped shape of the research, manuscript and supervised the findings of this work. All authors discussed the results and contributed to the final version of the manuscript.

Competing Interests

The authors have no conflicts of interest to declare that are relevant to the content of this chapter.

Ethics Approval

No ethics approval was required.

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