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Indirect Biomimicry Impact on Form & Structure to Obtain Sustainable Architecture Biomimetic Model Case Study: Masdar Institute of Science and Technology [MIST]

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Abstract: Biomimicry is a new science that studies nature's models, processes, and systems to solve human problems. Nature has already found answers to all problems that we face today, it has developed systems and modified itself to adapt its environment and the different changes that happen around us. Therefore, nature holds the key to the chest of answers for achieving a prominent level of sustainability which has become the leading subject of the architectural design. Most previous studies regarding biomimicry methods are limited to the most known method, the direct method of applying biomimicry into the built environment. There is a lack of consideration for the indirect method in research. Therefore, this study was aimed to deduce a biomimetic model which can provide sustainable architecture by employing the natural principles into design. A study of the natural principles of the biological systems and discussing their application into form and structure in architecture, the indirect method. The Masdar Institute of Science and Technology [MIST] was selected for the study of this approach, analyzing its application's influence on the architectural aspects, function, form, structure, and technology, of the case study. The result of the study is guidelines for sustainable architecture which can provide an integrated relationship between the built environment and the ecosystems of which it is a part.

Keywords: *Biomimicry, Natural Principles, Architectural Aspects, Sustainable Architecture.*

1. Introduction

Throughout history, architects have considered nature as a great source of inspiration [1]. The main aim of biomimicry is the creation of great designs by imitating various living organisms that have evolved during the 3.8 billion years [2]. Biomimicry claims that nature is the most effective source of innovation for designers. Nature provides creative solutions for human problems and natural designs, processes and systems are wholly recyclable and environmentally friendly [3], so they ensure the greatest productivity for the least amount of energy and materials. The concept of biomimicry involves learning from nature in developing new products and methods which do not harm the nature but cooperates with it [4]. Biomimicry is an inspiration for intelligent and innovative engineering for minimizing or eliminating the negative impact of the construction industry on the environment and reaching overall sustainability of the buildings.

A growing body of international biomimicry research in relation to the built environment identifies many obstacles to the use of such an approach. One drawback worth noting is the lack of a clearly defined approach to mimicry that architectural designers can initially use. Therefore, the aim of the study is to provide sustainable architecture by employing the natural principles into design, to deduce a sustainable biomimetic model.

2. Materials and Methods

The nature of the study requires relying on the descriptive approach, the analytical approach, in addition to the deductive approach. A descriptive approach was considered studying the theoretical framework of Biomimicry in architecture, its levels and methods, sustainability, and architectural aspects. Then analytical study of biomimetic architecture and assessment of the extent to which the concept of sustainability has been achieved. Finally, deductive approach was used for deducing guidelines for designing sustainable Architecture using indirect method of biomimicry.

3. Biomimicry

Biomimicry derived from the Greek, 'bio' means life, and 'mimic' means imitation. Other terms used include biomimicry, bio-inspired designs, or bionics. In biomimetics, solutions are obtained by simulating the systems, mechanisms, and principles of ecosystems found in nature. Several benefits have been identified for applying biomimetics to solve design and construction problems, such as enhancing creativity and innovation [4]; Improving the use of resources (i.e., materials and energy) in buildings, reducing pollution, benefiting health, and providing a basis for environmentally responsive developments [3].

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Architects and designers have looked to biology for inspiration since the beginnings of science in the early 19th century. They sought not only to imitate the shapes of plants and animals, but to find ways of design similar to the processes of growth and development in nature. Biological ideas feature in the writings of many contemporary architects, the most famous **Le Corbusier** and **Frank Lloyd Wright**. Le Corbusier declared biology to be "**the great new word in architecture**".

An example of this approach is the **Daimler Chrysler** prototype **Bionic Car**. When looking for a compact, large wheelbase car, the design of the car was based on the boxfish (ostracion meleagris), a surprisingly aerodynamic fish. Because of its box-like shape. The vehicle's body is also biomimetic, having been designed using a computer modeling method based on how trees grow in a way that reduces stress concentrations. The resulting car body looks almost structural, with materials only being allocated to where they are most needed [5].

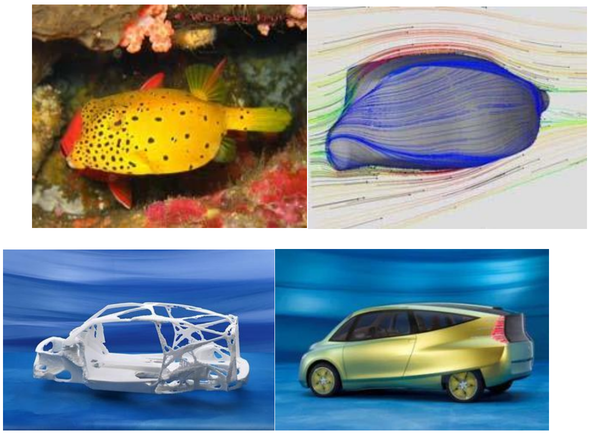


Fig 1. DaimlerChrysler's electric car is inspired by the growth patterns of trees and box fish [6]

3.1. Biomimicry Methods

3.1.1. Direct Method

The designer follows some steps to arrive at a biological solution to a given problem. There are two different approaches to this method: **A- a problem-based approach**, **B- solution-based approach** [6].

3.1.2. Indirect Method

No specific steps are specified for the designer to follow, but instead, the designer considers the principles of natural design during the design process, trying to achieve as many of those principles as possible in his designs [7].

3.2. Principles of Natural Design

"We do not seek to mimic nature, but to find the principles that she uses" (Buckminster Fuller quote) [8], successful biomimetics relies on mimicking a particular natural strategy that is imitated in a similar environment to achieve the same function using minimal effort [7], and thus it is possible to better design environmentally friendly architectural solutions by analyzing general principles of natural design, There are nine principles mentioned by Janine Benyus [4], and they are as follows :

1- Nature depends on sunlight.
2- Nature uses the energy it needs.
3- Nature suits form to function.
4- Nature recycles everything.
5- Nature rewards cooperation.
6. Nature depends on diversity.
7. Nature requires local expertise.
8- Nature limits transgressions from within.
9- Nature exploits the power of boundaries.

Fig 2. Natural Design Principles [4]

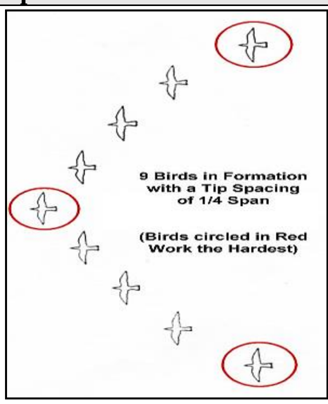
3.3. Levels of Biomimicry

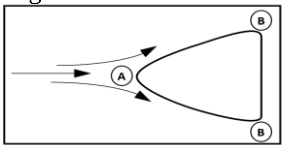
Mimicry of an organism, for example, is actually the imitation of a particular aspect of that organism, this aspect may be the shape of the organism, or the way that enables the organism to accomplish a function, the aspect that is being simulated is referred to as the "**level of biomimicry**", Janine Benyus has pointed out that there are three levels of mimicry of nature:

3.3.1. Form or Structure Level

Nature was created in a comprehensive and varied form. These forms succeeded in surviving in the environment despite the different conditions, as the following example illustrates:

Table 1. Form or structure level example

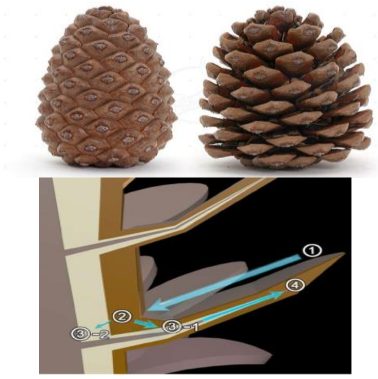
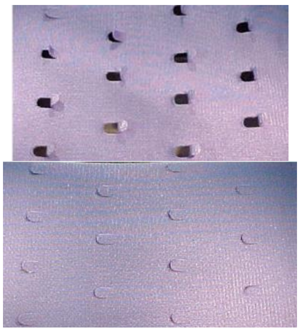
	Inspiration from nature
Form or Structure Level	Forming the flight in a V-shape reduces the drag forces each bird in the group  experiences compared to the amount of force each bird experiences when flying alone. **Fig 3.** Birds fly in the V-shape [9]

	Application example
	The formation of the office building Brickell [1450 Brickell] in the V-shape, which helped to reduce the forces of the winds faced in the distribution on the outside surface of the entire building.   **Fig 4.** Brickell office building [10]

3.3.2. Process Level

It is a mimicking of the natural process, a large number of living organisms face the same environmental conditions as humans, but these organisms are trying to solve their problems within the limits of the availability of energy and materials through a natural process to adapt to their environment, and continue to develop solutions even as the challenges of conditions change surrounding environment, as the following example illustrates:

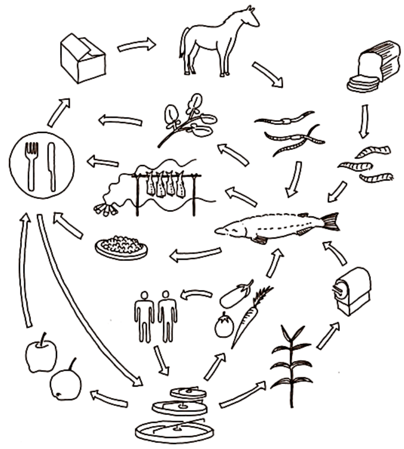
Table 2. Process level example

	Inspiration from nature
Process Level	The husks of seed-bearing pinecones move in response to changes in relative humidity. When dry, scales open, releasing cone seeds, and when wet, scales close (Dawson et al., 1997).  **Fig 5.** Movement of pinecone scales with change in humidity [11]
	Application example
	The process has been mimicked to produce the fabric with pores that open on their own in response to moisture when the wearer sweats.  **Figure 6.** Multi-layer fabric that opens automatically in response to humidity [7]

3.3.3. 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.

Table 3. Ecosystem level example

	Application example
Ecosystem Level	The **Cardboard to Caviar** project founded by **Graham Wells** in Wakefield, UK is a closed cyclic system that uses waste as a nutrient. The idea of reusing one's excrement as nourishment for the other has the potential to translate into whole cities, which has evolved over time to follow nearly all of the basic principles of ecosystem thinking [12]  **Figure 7.** Food web diagram for the [Cardboard to Caviar] project [12]

3.4. Biomimicry in Architecture- Architectural Aspects

Inspiration from nature and its application in architecture affects one or all aspects of the architectural work, and this may vary in relation to the level of biomimicry, or the appropriateness of the inspired idea with the surrounding environment. Any architectural output consists of four basic elements that integrate and produce an architectural work that is evaluated. First comes the **function** and then translates it into a **form** that serves its requirements and then a **structure** that achieves this form using **technology** [13].

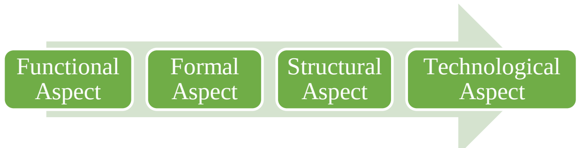


Fig 8. Architectural Aspects [13] (edited by authors)

4. Sustainability

Sustainability means "meeting our own needs without compromising the ability of future generations to meet their own needs" [14].

4.1. Sustainable Architecture

Sustainable design can be defined as "environmental design" design that integrates seamlessly with ecosystems in the biosphere over the entire life cycle of the built system. Building materials and energy are combined, with minimal impact on the environment [15].

Sustainable engineering is the process of designing or operating systems so that they use energy and resources sustainably, in other words, at a rate that does not harm the natural environment, or the ability of future generations to meet their own needs. Her areas revolve around water supply, production, sanitation, clean-up of pollution and waste sites, restoration of natural habitats, and more [14].

4.2. Sustainable Architecture Evaluation Systems

Rating systems have been developed to measure the level of sustainability of buildings. With the specified standards, the design, construction, and operation of sustainable buildings are approved. Using many of the standards compiled in the guidelines and checklists, these standards either cover only aspects of a building's approach to sustainability, such as energy efficiency, or they cover the entire building approach by determining performance in key areas such as sustainable site development, human health and the environment, and water savings., material selection, indoor environmental quality, social aspects, and economic quality [16].

5. Case Study: Masdar Institute of Science and Technology [MIST]

5.1. General Information

The Masdar Institute of Science & Technology is located in Masdar City, 17 km from the Emirate of Abu Dhabi, the capital of the United Arab Emirates, and is part of the Khalifa University of Science and Technology. A research-driven institute that addresses issues of regional and global importance through a specialization in clean and renewable energy, water, environment, and sustainable technologies. The design of the institute began in 2007 by architect Norman Fosters + Partners [17]. The first phase [A1] of the Masdar Institute of Science and Technology [MIST] campus with six buildings covering 65,073 square meters was officially opened in November 2010 [18].

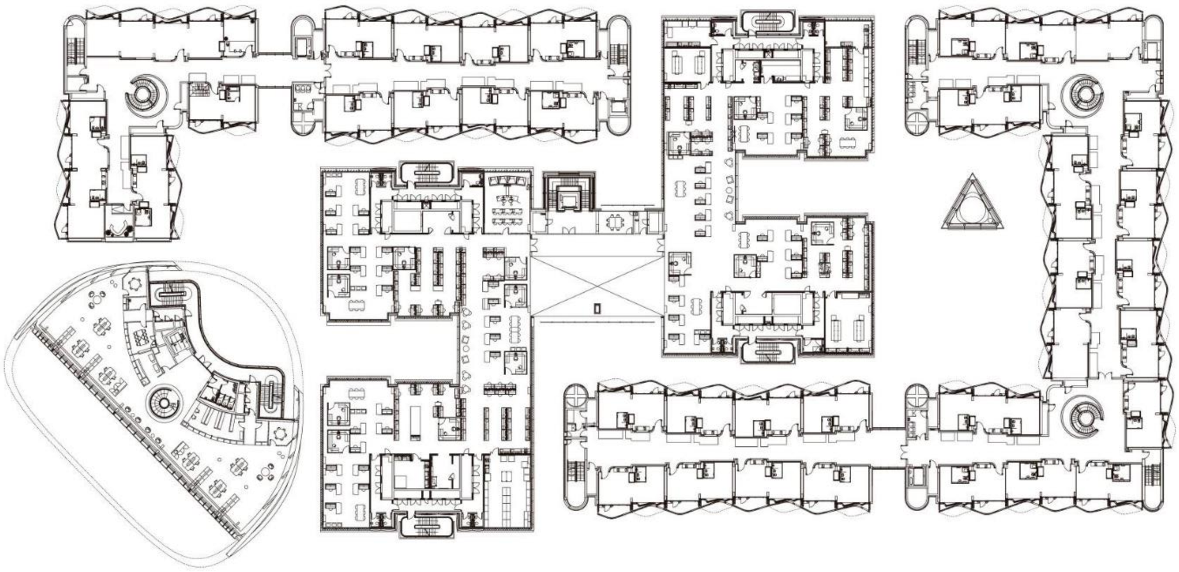


Fig 9 Masdar Institute plan [19]

Residential Units: Phase [A1] of MIST campus opened with four housing blocks surrounding a central laboratory and knowledge center, comprising 102 one, two and three-bedroom apartments, located in low-rise, high-density buildings [18].

Fig 10. Residential Units [20]

Laboratories and Research Center: Laboratories offer flexibility to change "plug and play" services designed to encourage interdisciplinary research [18].

Fig 11. Laboratory [21]

Knowledge Center: The interior of the slightly flattened spherical (helmet-shaped) Knowledge Center 'Library' covers a flat of 900 m² and is divided into a vertical hierarchy of spaces, which concludes gathering, group study spaces, and quieter private research areas [22].

Fig 12. Knowledge Center [23]

The public spaces: Street spaces and courtyards are designed with different regional themes [24]. The public spaces are designed to be naturally cooled by shading and contain a small number of water features [25].

Fig 13. The public spaces [20]

Rapid transit cars: The Masdar Institute is accessed by 10 Personal Rapid Transit (PRT) vehicles that run as a pilot project from the city perimeter down under the building [26].

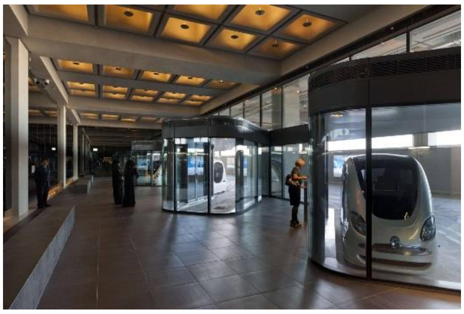


Fig 14. Rapid transit cars [19]

5.2. Biomimicry analysis of the case study

Table 4. Biomimicry analysis of MIST

Biomimicry Level	Eco-system level
Inspiration from Nature	Principles of Natural Design
Biomimicry Method	Indirect Method
Successful biomimetics relies on the simulation of a particular natural strategy that is imitated in a similar environment to achieve the same function using minimal effort [7], and thus it is possible to design better environmentally friendly architectural solutions by analyzing the general principles of natural designs.	

The following shows how [Principles of Natural Design] had been applied into MIST design:

5.2.1. Nature runs on sunlight

All energy used is renewable energy: Energy is generated through a solar plant, where about 30% of the campus energy is covered with solar panels on the roof, and 75% of the hot water is heated by the sun [26].

Fig 15. Solar panels on the roof [20]

5.2.2. Nature uses only the energy it needs

Use the energy and resources you need: The institute consumes only 40% of the solar energy generated on top of the institute's buildings, while 60% is sold to the neighboring buildings. Also, the buildings are equipped with water-saving fixtures, smart water reduction and control technologies, and efficient washing systems. Wastewater, which is recycled in the city's treatment plant (used to irrigate plants), is also reused, as the institute uses

51% less energy and 54% less drinking water compared to a typical building in the UAE [24].

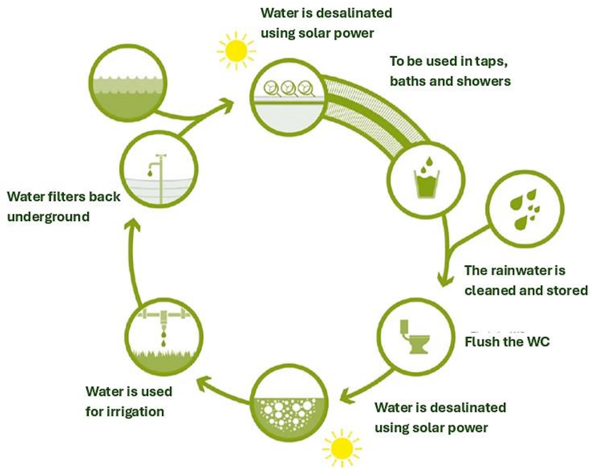


Fig 16. Water treatment and recycling strategy used in the institute [27]

Multifunctional is better than monofunctional (building skin): Buildings are designed to provide optimum shade, reduce cooling loads, and podium level shade poles benefit from high insulation and exposed thermal mass [26].

Fig 17. The laboratory building facade and its blinders [18]

5.2.3. Nature fits form to function

The residential buildings were provided with windows supported by contemporary forms of the traditional mashrabiya, a type of grille in the form of a prominent balcony, which was designed using sustainable cement and glass-reinforced before being painted with sand color to facilitate its integration and the desert and to reduce maintenance operations.

Fig 18. Residential building [28]

5.2.4. Nature recycles everything

- All wastewater is treated on site and recycled, which is used to irrigate plants.
- The wood used comes from sustainable forests.
- 95% of the aluminum used in construction in source comes from recycled aluminum where the carbon produced is 90% less than raw aluminum.
- Green Concrete uses 40-60% less embodied carbon than regular concrete [29].

5.2.5. Nature rewards cooperation

The direction of the streets is affected by the flow of prevailing winds in the area. City street networks are formed with limited width, resulting in shaded and cool lanes on hot days. A step back designed under the columns at the edge of the short streets turns and changes direction on the ground floor of the buildings, speeding up the air movement [30].

Fig 19. Shaded Street design between the institute buildings [24]

5.2.6. Nature banks on diversity

Energy sources used in the building: solar energy and wind energy.

- **Solar energy:** The station above the institute generates approximately 10 megawatts, which covers about 30% of the campus energy with solar panels on the roof and is used to heat 75% of the hot water [26].

- **Wind energy:** a strategy for street ventilation and night cooling with wind towers [26].

Fig 20. Wind Tower [18]

- **The use of the mashrabiya:** Relating to traditional Arab architecture, the shaded openings of the mashrabiya allow maximum natural light while providing privacy [26].

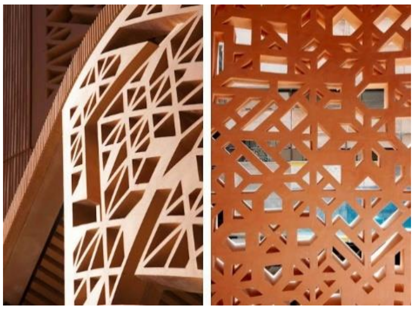


Fig 21. The mashrabiya cladding [31]

- **Wind tower:** An essential element of local architecture is the traditional air tower. The new iron tower allows diverting the wind flow to the road level for cooling [32].

5.2.7. Nature demands local expertise

- **Responding to local climatic considerations:** Vibrant social spaces, cooled by shading, green farming, and several water features are designed to mitigate the effects of the local climate.

5.2.8. Nature curbs excesses from within

The laboratories are at the heart of the development process and are designed to provide the largest flexible shaft free surface area within stringent loading and vibration parameters. The support facilities are arranged in a linear layout which is functionally efficient [26].

5.3. Architectural Analysis of MIST

5.3.2. Function Analysis (Biomimicry's effect on the functional aspect)

Table 5. Function analysis of MIST

Light Comfort	**Outdoor:** the solid areas are covered with thin patterns of aluminum and silver to reflect the light on the pedestrian streets [24].	 **Fig 22.** Shaded Street between buildings [24]
	Laboratories: they are protected from the sun by cornices and horizontal blinds (Indirect Light) [18].	
	Residential Units: The mashrabiya-type shielded apartment windows allow maximum natural light from indoor and outdoor patio [24].	
	Knowledge Center: it is helmet shaped zinc-coated flat and folded to provide breathable shading [24].	 **Fig 23.** Interior of laboratory [18]
Thermal & Air Comfort	**Outdoor:** The heat transfer spaces and facades are adapted with two systems, natural ventilation and thermal mass on the other, which was confirmed that a significant decrease in radiation temperatures in the campus environment by the research team. • The grouping of **wind towers and courtyards** are street-level night ventilation and cooling strategies, where pedestrian traffic occurs. • Cooling the air currents that pass through the public spaces using contemporary wind-collecting towers in the region. These spaces are further cooled by landscaping, including designs with greenery and water. These two methods are not only used for cooling outdoor spaces, but also they help to reduce thermal mass that enters the buildings [18].	 **Fig 24.** Residential mashrabiya units [28]
	Laboratories: These interior spaces are protected from the sun by cornices and horizontal blinds and have high thermal insulation through the fronts of inflatable mattresses, which remain cool to the touch even in the harshest desert sun [18].	

<table>
<tr><td rowspan="2"></td><td>Residential Units: (The use of the mashrabiya) a type of bay window that was usually surrounded by carved wooden latticework, referring to traditional Arab architecture, where the shaded openings of the mashrabiya allow maximum natural light while providing privacy [26].</td><td rowspan="2">

Fig 25. Helmet Shaped Knowledge Center [33]</td></tr>
<tr><td>Knowledge Center: The distinctive zinc cladding hangs prominently and covers the northeastern side of the building to provide shading and reduce internal cooling loads and direct sunlight, which reduces cooling loads [34].</td></tr>
</table>

5.3.2. Form Analysis (Biomimicry's effect on the formal aspect)

Table 6. Form analysis of MIST

<table>
<tr><td rowspan="3">Form fits to function</td><td>Laboratories: The facade has windows that allow daylight and outside views. They are shaded with fins to keep out the angled sunlight [25].</td><td rowspan="8">

Fig 26. Laboratories [21]

Fig 27. Southwestern facade of MIST [19]

Fig 28. Northern facade of the knowledge center [19]

Fig 29. Residential Units' Mashrabiya [28]</td></tr>
<tr><td>Residential Units: Mashrabiya shaded windows allow maximum natural light from the indoor and outdoor courtyard while also providing privacy [25].</td></tr>
<tr><td>The knowledge center (library): is a helmet shaped that provide well-ventilated shade [25].</td></tr>
<tr><td rowspan="3">Lighting & Shading</td><td>Laboratory: it has windows that are shaded by breakers to get rid of the angular sunlight.</td></tr>
<tr><td>Residential Units: Shaded mashrabiya windows allow maximum indirect natural light from the indoor and outdoor courtyard while providing privacy.</td></tr>
<tr><td>Knowledge Center: The distinctive veneer hangs prominently and covers the northeastern side of the building to provide shading, reduce internal cooling loads, and direct sunlight, which reduces cooling load [34].</td></tr>
<tr><td>Variation & Diversity</td><td>The openings in the facade are variable, with the upper floors being more solid up to 25% glass, while the lower shaded floors have about 45%. The solid areas are covered in thin silver patterns of aluminum to reflect light onto pedestrian streets [25].</td></tr>
<tr><td>Environmental Adaptation</td><td>Mashrabiya has been colored with local sand to give a desert context and reduce maintenance [25].</td></tr>
</table>

5.3.3 Structure Analysis

Table 7. Structure analysis of MIST (Sub-Structure and The Podium)

A- Sub-Structure

1. Piles

The loading analysis indicated that the foundations would be formed from the perforated piles. The required substrate diameter is likely to be from 600mm to 1200mm in diameter . The length and diameter of the outriggers are dependent on the loads applied and the availability of outrigger platforms [35].

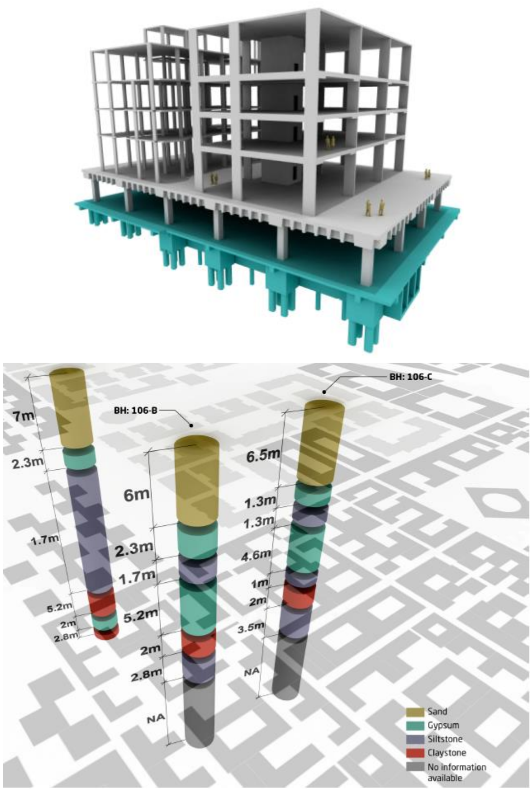


Figure 30. Site soil tests and the Masdar Institute substructure [35]

2. Service Trench/PRT

The Personal Rapid Transit (PRT) system has been integrated into the lower level of the institute's development and a service tunnel running directly under a "road" (PRT) where services will be distributed to the entire city will be integrated. The [PRT] system and service trench had to be designed as structurally independent and isolated from the main structure adjacent to the development of the institute, with reduced risk of transmitting vibrations [35].

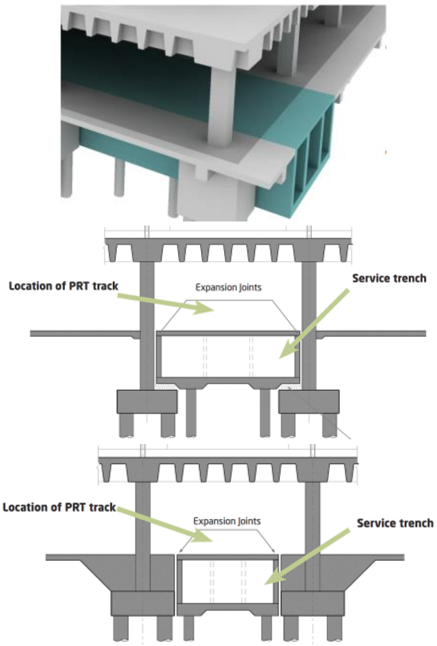


Figure 31. Design choices for the [PRT] service trench (narrow or wide) [35]

3. Ground Floor

- Hanging beams in two directions [2 ways Beams] spanning a 5.25 m x 5.25 m grid isolated from the adjacent board, 400 mm thick board [35].

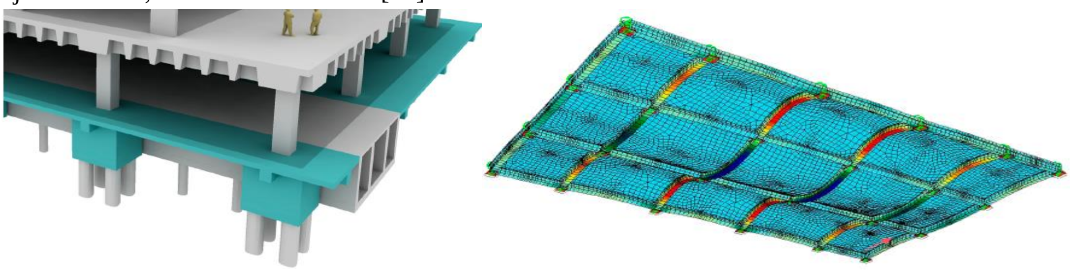


Figure 32. The ground floor slab [35]

<table>
<tr><td>B- The Podium</td><td>The main feature of Phase [A1] was the fact that the buildings were constructed on a 7-meter platform, with services such as MEP underneath, for pedestrian-friendly streets and public transportation. (Construction.Week, 2018), The podium structure is designed to be street level. Waffle slab (reinforced in situ concrete), 1.5 m deep within 10.5 x 10.5 m holes [35].

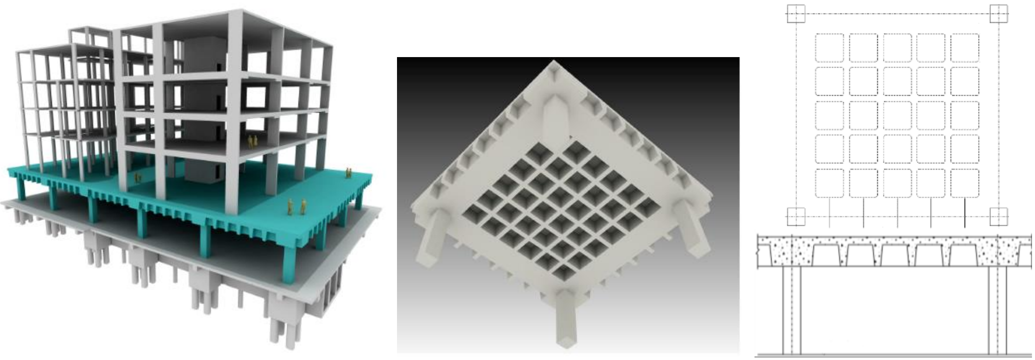



Figure 33. The podium waffle slab [35]</td></tr>
</table>

Table 8. Structure analysis of MIST (Super-Structure)

<table>
<tr><td rowspan="4">C- Super-Structure</td><td>1. Laboratories Building</td><td>2. Residential Units</td></tr>
<tr><td>Ribbed slab with down stand beams (reinforced in situ concrete), using some precast columns in some areas of laboratories to reduce construction times [35].

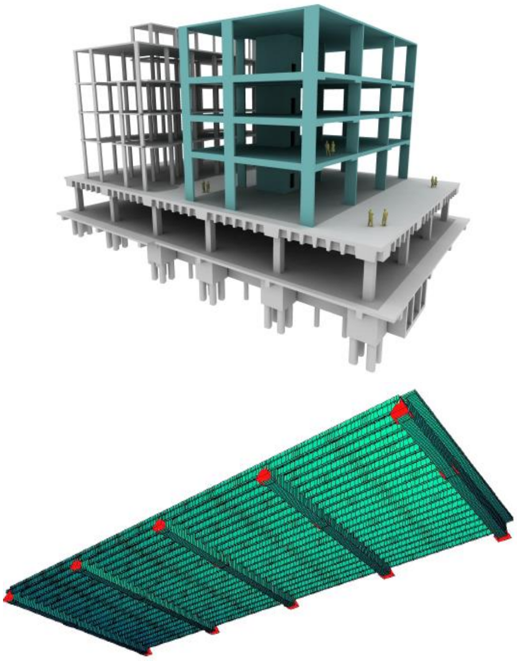



Figure 34. Laboratories Ribbed slab [35]</td><td>Flat slab of reinforced concrete 225 mm thick, Reinforced concrete beams, 5.25 m in size, 1 m deep. with some voids, which may be filled with ready-made panels, to turn the void into a laboratory [35].

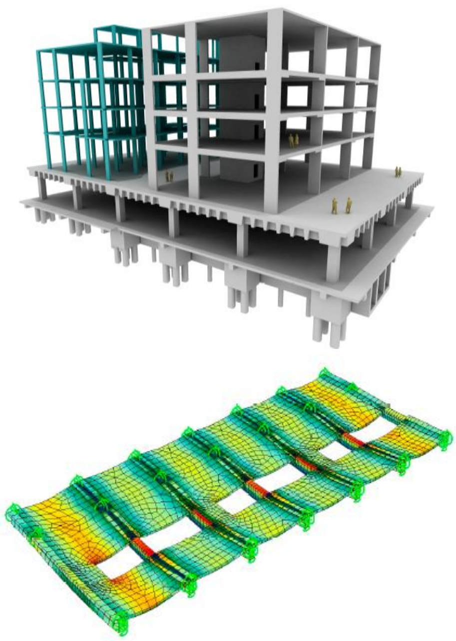
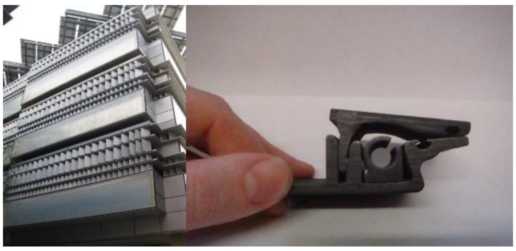



Figure 36. Residential Units flat slab [35]</td></tr>
<tr><td>Cladding: Coating of [Texlon® ETFE] on a high-performance perforated, self-supporting insulated aluminum system [36].
</td><td>Cladding: The mashrabiya-type shielded apartment windows are made of Glass Reinforced Concrete [GFRC] [18].

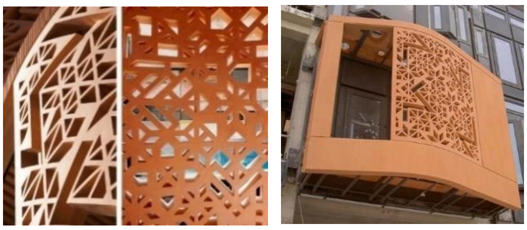



Figure 37. [GFRC] units in the mashrabiya</td></tr>
</table>

	Figure 35. Self-supporting covering panels for a laboratory building [37]	facades [31]
	3. Knowledge Center	
	Timber Glulam Truss, lightly flat spherical in shape [34].  **Figure 38.** Construction work for the knowledge center [33]	
	Cladding: The panels are covered with a flat, foldable zinc, the cladding supports the photovoltaic panels that provide a lot of electrical power for the facility [34].  **Figure 39** Zinc cladding panels for the Knowledge Center [38] [20] [39]	

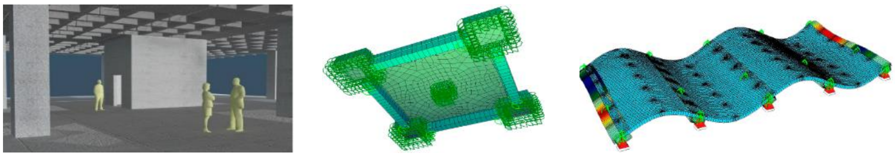
Table 9. Structure analysis of MIST (Economic Efficiency)

Economic Efficiency		
Infrastructure	The ground floor is built of sulfate-resistant concrete and the use of 'tanks' with a membrane, in order to achieve sufficient resistance against pollution [35].	
Green Concrete	Concrete that uses 40-60% less embodied carbon has been used compared to regular concrete and is 1.5 times stronger. which are sourced and manufactured locally (Construction.Week, 2018).	
In-Situ Concrete	Cast-in-Site Concrete This is due to the ability of Cast-in-Site Concrete to meet vibration standards with the most efficient use of materials [35].	
Pre-Cast Concrete	The use of pre-cast concrete either through precast elements such as the use of pre-cast columns in some places, or precast panels or walls (modular construction) or through fully formed structural units (Volumeric construction). Moreover, non-structural units such as bathroom hoods are regularly used to take advantage of the advantages of volumetric construction, due to the ability of volumetric forms to achieve the required acoustic and thermal properties and significantly reduce the construction program and waste [35].	
	 **Figure 40.** Precast wall panels on site [35]	 **Figure 41.** Installation of volumetric construction [35]
GFRC	GFRC Mashrabiya was tinted with local sand to give a desert context and reduce maintenance [18].	
Aluminum Panels	Approximately 95% of the aluminum used in construction at source comes from recycled aluminum where the carbon produced is 90% less [29].	

Glulam Wood	Glulam was chosen as the knowledge center's structure, due to its embodied low carbon footprint which is further reduced due to locally manufactured timber [34], and has been installed on site with minimal tolerance for repair issues [33].
Zinc Cladding	Zinc was chosen for the knowledge center roof cladding because it had the lowest overall environmental footprint [34].

5.3.4 Technology Analysis

Table 10. Technology analysis of MIST

Design and Analysis Techniques	The development of design and analysis methods during all stages of design, implementation and construction**.** **Execution accuracy:** A series of studies of different structural alteratives, different materials and joints, further investigations and analyzes to determine the most efficient structural form of concrete slabs, and detailed finite element analysis was conducted to ensure that they are able to meet the stringent vibration standards [35].  **Figure 42.** Design and analysis techniques using computers [35]
Building Materials Technology	The use of fair-faced concrete reduces the need for finishing materials, with the adoption of fuel ash powder to replace cement, the relative density of which has allowed it to comply with requirements for vibration mitigation throughout the building [20].
[C3] Energy Management Technology	**[C3] Energy Management Technology** is being used to monitor and optimize energy, water, sustainable transportation, and waste [29]. The buildings are equipped with water-saving installations, smart water reduction and control technologies, and efficient washing systems [24].
Central Ventilation Technology [Aircuity]	**Aircuity Technology** helps implement Centralized Demand Controlled Ventilation (DCV) in university hostels, classrooms, laboratories, conference rooms and library areas, where the air in is constantly monitored and the amount of outside air brought in is adjusted, saving an estimated 55% annually Total energy consumption for heating, ventilation and air conditioning (HVAC) [40].

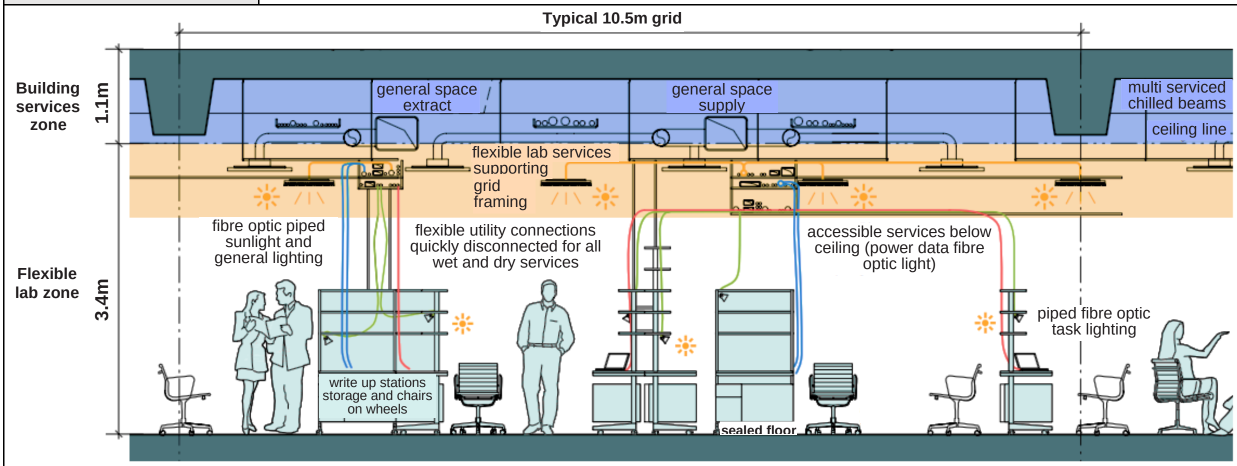


Figure 43. Technology for energy management and ventilation and lighting regulation [41]

Personal Rapid Transit (PRT)	The campus uses electric **Personal Rapid Transit (PRT)** vehicles for transportation. Driverless cars can travel at a speed of about 40 km/h [24].

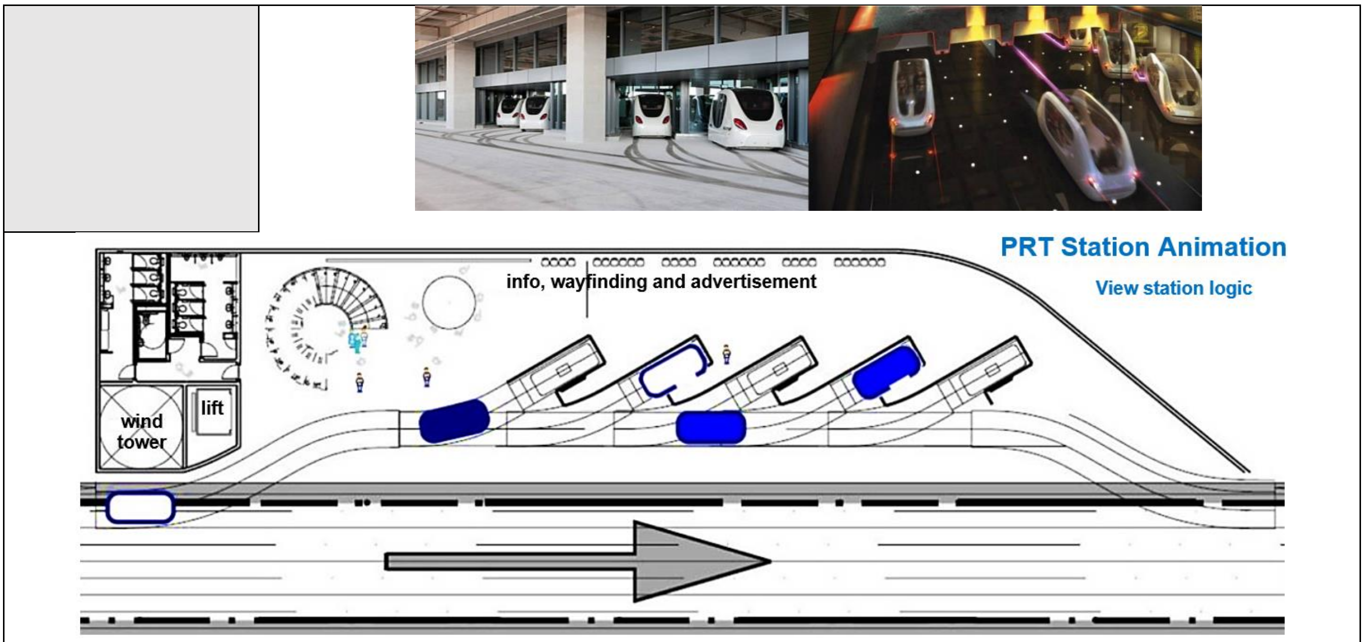


Fig 44. Rapid transit cars [19]

5.4. Sustainability in MIST

The first sustainable community to obtain a degree **(4 pearls)** from the certificate and evaluation system with pearl degrees in the United Arab Emirates.

Transportation: Electric **Personal Rapid Transit (PRT)** vehicles are being used for transportation. Driverless cars can travel at a speed of about 40 km/h [24].

Energy Efficiency: MIST campus is powered entirely by renewable solar energy, producing 60% more energy than the institute consumes, the rest of which is fed back into the Abu Dhabi grid. The institute uses **51% less energy and 54% less drinking water** than a typical building in the UAE. About 30% of the campus' energy is covered by solar panels on the roof, where **75% of the hot water is heated by the sun** [25].

Water Efficiency: Wastewater, which is recycled at the city's treatment plant, is reused for irrigation. The buildings are also equipped with water-saving installations, smart water reduction and control technologies, and efficient washing systems [24].

Indoor Environment Efficiency: Aircuity helps implement Centralized Demand Controlled Ventilation (DCV) in university hostels, classrooms, conference rooms and library areas to diversify outdoor ventilation based on occupancy sensing and indoor environment quality (IEQ) [40].

Building Operating Efficiency: Masdar City is using **[C3] Energy Management Technology** to monitor and optimize energy, water, sustainable transportation, and waste. [C3] analysis confirms that residential buildings in Masdar City are highly efficient [29]. The buildings are equipped with water-saving installations, smart water reduction and control technologies, and efficient washing systems [24].

Social Efficiency: The public spaces within the project are designed as vibrant social hubs, naturally cooled by shading, green farming, and a few water features, to mitigate the effects of the intense microclimate [25].

Environment Adaptation: The mashrabiya was made of reinforced concrete and colored with local sand to integrate with the desert environment and to reduce maintenance. Styles found in local traditional architecture. Building facades are designed to mitigate heat transfer, while also being sealed to reduce the internal cooling load [25].

Materials and Resources: The focus on selecting sustainable materials and products for the Institute's buildings meant that they were sourced and manufactured locally where possible. The wood used is sourced from sustainable forests. Approximately 95% of the aluminum used in construction at source comes from recycled aluminum where the carbon produced is 90% less than raw aluminum. Green Concrete uses 40-60% less embodied carbon than regular concrete [29].

Technology Integration Efficiency: Low flow water installations reduced drinking water consumption by up to 54%. Energy and water metering systems monitor consumption and produce data that is easily accessible to students and faculty [29].

6. Results & Discussion

After the analytical study of [MIST] and analyzing how the principles of natural system applied into architectural design could affect the architectural aspects, and how it could result in sustainable architecture. As a result of the study, it has been deduced some guidelines for achieving sustainable architecture. As shown in the following table:

Table 11. Guidelines for Sustainable Architecture using indirect biomimicry

Nature's Principles application	Guidelines for Sustainable Architecture	Sustainability Categories
Nature uses the energy and resources it needs. Nature recycles everything. Nature avoids excesses and excessive construction. Nature rewards cooperation. Nature harnesses the power of boundaries.	• Shared use of facilities with the community, by directing development to urban areas that already have infrastructure. • Seeking to adopt the same environmental and geographical priorities for the region, and to make optimal use of the characteristics and advantages of the region. • Use of finishing colors appropriate to the local environment, such as the local sand color, to give context to the desert and reduce maintenance. • Formation appropriate to site conditions. • Providing small car parking spaces (environmentally friendly). • Providing connections to public transportation. • Increasing open spaces: increasing green areas and pedestrian paths, which reduces the structural ratio. • Increasing green areas (biodiversity), using native plants, increasing shaded areas using seasonal trees. • The design of the facilities in a way that supports the effect of shadows more within the site. • The use of solar panels as a structural covering for roofs. • The use of materials with a good thermal reflection coefficient. • The use of light colors for ceilings and exterior finishes.	**Sustainable Site**
Nature uses the energy and resources it needs. Nature recycles everything.	• Employing strategies to reduce the use of potable water in the building. • Non-use of potable water in plant irrigation works, reusing treated water in bathrooms' waste bins, and water-cooling systems channels. • Using high-efficiency and low-water consumption sanitary equipment and fixtures, using water-conserving irrigation systems, using high-efficiency cooling systems, and providing systems for detecting water leaks.	**Water Efficiency**
Nature uses the energy it needs. Nature recycles everything. Nature requires local expertise. Nature depends on sunlight and renewable energies.	• Pre-planning the project's energy supply, evaluating its performance, and preparing periodic reports on the building's operational energy performance. • The minimum energy efficiency of the building is determined, while maintaining the performance and efficiency of the building's operation. • Using the computer to determine the level of energy consumed and reducing it to a minimum, using energy-efficient systems. • Designing the exterior perimeter of the building to achieve the insulation standards for moisture and heat for external surfaces and walls, to ensure the best performance of energy systems. • The use of cooling and heating devices that are less harmful to the environment, and do not contain compounds that harm the ozone layer in the atmosphere. • Contemporary use of traditional wind collector towers for cooling. • Employing renewable energy sources and integrating them into the building design, to generate clean energy without harming the environment, such as solar energy, wind energy. • Study the energy used in the building at the design stage and reduce the level of energy consumed through optimal use of lighting and natural ventilation, and other strategies that may contribute to reducing energy consumption in the building.	**Energy and Atmosphere**
Nature uses the energy and resources it needs. Nature recycles everything. Nature harnesses the power of boundaries. Nature requires local expertise.	• **Life Cycle Cost (LCC)** analysis for the materials used in the project. • Storage and collection of recyclable materials, to reduce waste generated by building occupants, provision of waste dumps in an accessible area. • **Reuse of basic elements** such as walls, floors and ceilings, reuse of structural and non-structural elements of the building. • Use of materials that have been salvaged, recycled, or used, such as (recycled steel, recycled steel, green concrete, aggregate, recycled timber, recycled aluminum).	**Materials and Resources**

	• The use of local building materials that are extracted or produced within the region, which reduces the pollution caused by their means of transportation and supports the local use of materials. • Use of materials manufactured on site, use of materials in a way that minimizes waste generated, use of prefabricated components. • The use of materials suitable for the local environment, environmental treatments, and external cladding for the building, and the use of appropriate finishing materials such as (FGRC).	
Nature rewards cooperation. Nature harnesses the power of boundaries. Nature requires local expertise. Nature depends on sunlight and renewable energies. Fit form to function.	• The design of the building to provide as much natural light as possible for the interior space. • Increasing the rate of fresh air ventilation (improved ventilation), by setting a minimum level for the performance and quality of indoor air, whether natural or mechanical ventilation. • Contemporary use of traditional wind collector towers (to aid in the ventilation and cooling of spaces). • The use of response systems to control the degree of ventilation in the spaces according to the number of users. • Using techniques to reduce heat transfer through moving curtains and using solar panels to control the amount of light entering the building. • The difference in the percentage of glass surfaces according to the prevailing climate and the facade, with the use of heat-insulating glass and appropriate light retractors to provide the greatest degree of visibility and contact with the external space. Using the mashrabiya element in a modern, static, or mobile way for shading. • Using sensors to collect data on the internal and external environmental weather, and to control the movement of solar panels according to the angle of inclination of the sun. • Providing a connection for the occupants with the nature by regularly seeing the external landscapes along the building. • Optimizing the sound quality of each function.	**Indoor Environment Quality**
Nature harnesses the power of boundaries. Nature rewards diversity. Nature depends on sunlight and renewable energies. Nature uses the energy it needs. Nature recycles everything.	• Protection of water sources from pollution, proper disposal of waste. • Providing **a Building User Guide**, which includes technical and non-technical information for users, to achieve effective operation, including the following: (the energy and environment strategy used in the building, follow-up and targeting, a presentation of the services available in the building, the connection of the building with transportation, and an explanation of those services, Construction Materials and Waste Policy). • **Building Management System (BMS)** is a comprehensive integrated system for managing and controlling all building systems such as: (energy management, ventilation and lighting, site coordination control systems and irrigation systems). • Provide a comprehensive **periodic schedule for the maintenance** of the building, updated regularly.	**Management**

7. Conclusions

A building that mimics nature, which provides a productive and suitable environment through the integration of aspects of architectural work (function, formation, construction, technology) achieves higher levels of sustainability. Mimicking nature indirectly by applying the principles of natural design in architecture is one of the most important successful ways to achieve sustainability in architecture. Adapting the uses of technology gave designers the opportunity to innovate and be able to apply ideas inspired by nature in their designs. It is recommended that architects should consider and use the guidelines deduced to mimic nature, to build sustainable architecture.

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