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An Approach to Adaptive Sustainable Facades Inspired by Plants

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Abstract

Nowadays, and under the global warming circumstances we are facing, particularly those resulting from the building sectors, many directions for more sustainable and eco-friendly concepts have emerged. From these sustainability approaches is the “Biomimicry” approach. This approach represents the science of imitating and benefiting from nature’s principles. Nature has provided various strategies to adapt to the surrounding conditions. There are several methodologies and tools developed following the biomimicry approach and taking nature as inspiration. However, difficulties arise in collaborating more than one discipline, which consumes a lot of time and effort, consequently cost. Furthermore, the existing methodologies are still too generic for architects. Therefore, this paper aims at developing a platform that integrates different methodologies, approaches, and tools comprehensively.

In this paper, the focus would be on plant adaptations. A more focus would be on the building’s envelope specifically due to its valuable contribution to the building’s overall energy consumption. The paper seeks to integrate the plant’s adaptive strategies to the building envelope. The motivation is to tackle solutions for the building envelope environmental problems mainly for heat, water air, and light challenges.

Keywords

Biomimicry; Adaptation ;Plant strategies

1. Introduction

Biomimicry represents the science of imitating nature, where nature has proved to identify what survives, what lasts forever. Nature knows what works by developing lots of strategies to guarantee this survival. (Janine, 2002) Biomimicry has been classified into three levels which are according to the way of mimicking (Zari, 2007). Mimicking the behavior or physiological or even the morphological aspect of the living organism. In this section, the focus would be on the plant's features as an inspiration. Plants similar to buildings are static in their location, confronting various environmental challenges; however, plants can strive with these conditions through different adaptive means. Some designers consume a lot of time trying to figure out the most efficient plant solution that suits their design purpose. This is due to the diversity of these strategies and the variety in the building envelope’s demands. Therefore, in this paper, an overview of the plant’s adaptive strategies would be described. Several methodologies and other categorization systems similar to the one proposed in this paper are available, but in this paper, there is an emphasis on the building envelope. More focus on the environmental challenges the building envelope encounters in hot dry regions related to heat, water air, and light. The paper begins by identifying the main environmental challenges that face the building envelope, an initial selection of 200 research publications corresponding to 40 plant strategies, from which approximately 10 plants were selected for this paper and analyzed. The equivalent function and possible architecture application in the building envelope are then identified according to the hot dry context.

This paper would show a simplified methodology to this translation process from the plant's adaptive strategies which would help to assist the designer in decision-making in choosing the appropriate materials and methods suitable for a specific type of envelope regulation.

2. Biomimicry Overview

Nature has been a source of inspiration to many innovations till the 21st century, however they were mostly limited to imitating shapes and forms. However, lately, there was a paradigm shift in contemporary architecture, where mimicking nature became towards deep search in nature's function and the strategies it offers. There are several methods for implementing biomimicry in Architecture which will be discussed as follows:

2.1. Biomimicry Activities

There are two methods of applying biomimicry in architecture, either directly or indirectly. The "*Indirect*" approach, Figure 1, is concerned for two disciplines other than architecture, however, architects benefit from it indirectly. A kind of the " Gooey Mold" was observed as being able to discover the straight, shortest path for reaching its food. This behavior was mainly an inspiration to develop an algorithm that was more efficient than the conventional ones. It was capable to discover the optimum path in a network via a minimum number of nodes with a collaboration between biologists and computer scientists. This discovery inspired architects indirectly and urban planners with the assistance of computer scientists. They reused these algorithms to develop an efficient transportation network by using minimum lines to connect a city (Tero et al., 2010).

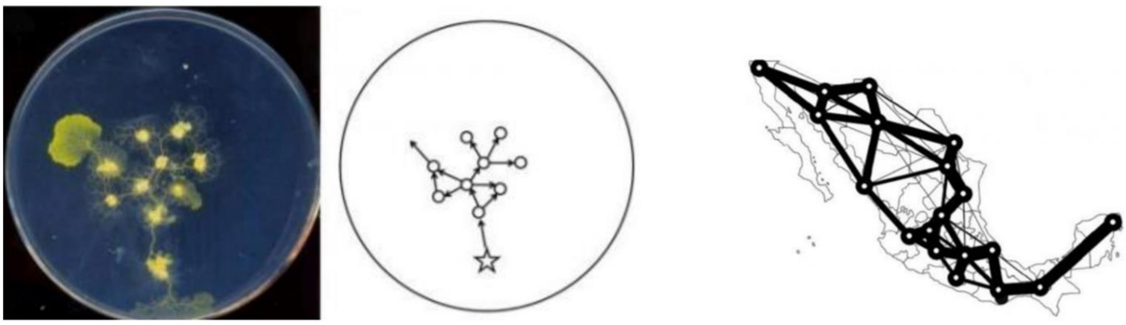


Figure 1: On the left: The behavior of Physarum Polycephal , on the right : The transport network in Mexico City

On the other hand, the "*Direct*" approach, is an approach designed specifically for architects (Mazzoleni, 2013; Badarnah, 2020). It is a collaboration between the biologists and architects directly to discover solutions to architectural problems. "Architecture follows nature" is an example to direct biomimicry in architectural design activity. Architect Ilaria Mazzoleni along with biologist Shauna Price searched solutions of twelve animal skins behaviors. Those behaviors were analyzed in terms of communication, thermoregulation, water balance, and protection. Those principles were inspirations for the design building envelope.

2.2. Biomimicry Approaches

There are two main biomimetic approaches, Figure 2. First, the "*Problem based*" approach. It was also termed "top-down" (Knippers, 2009) or " Design looking to biology" (Zari and Storey, 2007). They all lead to the same meaning; wherein the "problem based " approach, designers initially tackle a particular problem, goal, and parameters by searching biological analogies. On the contrary, the "Solution-based" (Bottom-up) approach seeks nature Solutions to be applied to suitable problems (Vincent et al., 2005). For this paper, the focus would be on the "Direct", "Top-Down " approach, as it is most commonly used by designers. This approach is different than the "Solution-based" which requires people with previous biological knowledge.

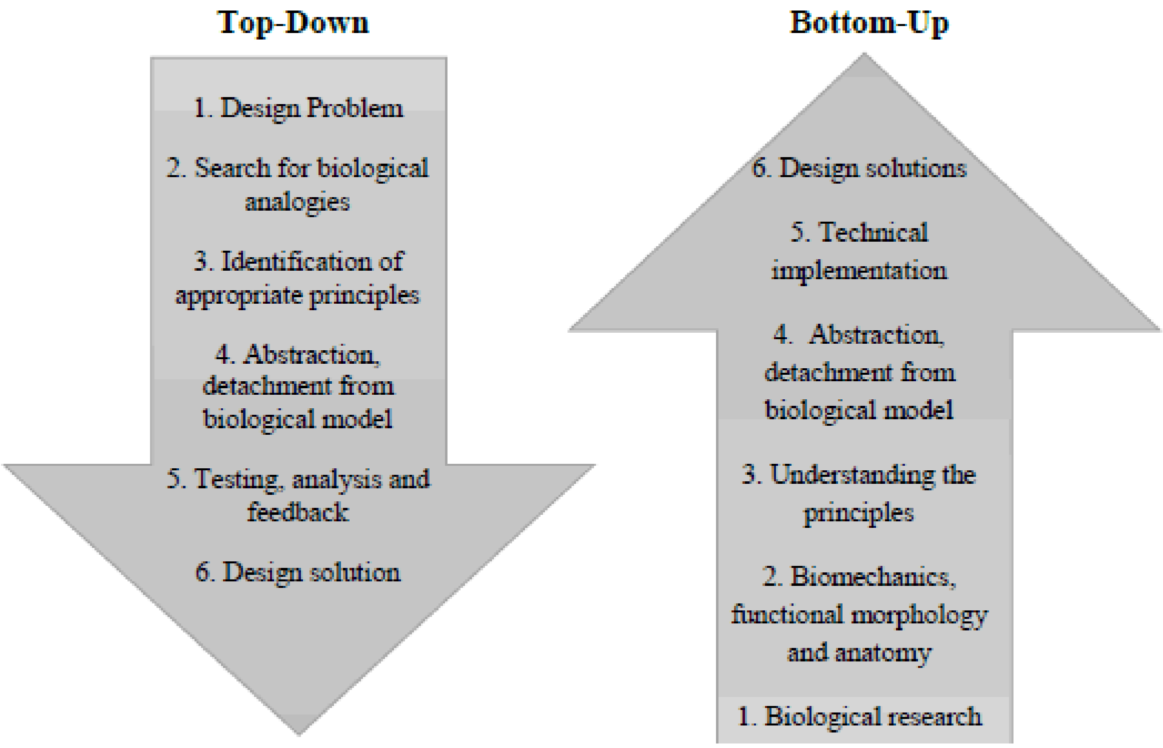


Figure 2 : The Biomimicry Approaches

2.3. Biomimetic Tools

There are several tools to assist the biomimetic design process. The most commonly used is "*Ask nature*", (Deldin and Schuknecht, 2015) which is a large online database that contains biological information ."*Functional Modelling*" (Nagel et al., 2010) uses functional models to represent biological systems. " *Bio-TRIZ*". (Vincent et al., 2006) Simulate a contradiction matrix based on biological phenomena and "*SAPHIRE*" (Sartori et al., 2010) which is intended to recognize biological systems. However, those tools are generic for architects to efficiently benefit from it.

3. Biomimicry and plants

Throughout history, architects have been inspired by plant strategies as shown in the following, Figure 3. Though, most inspirations were either structural, ornamental, or aesthetic functions, despite the variety of the strategies they perform on other levels.

A brief timeline presenting the plants as a source of inspiration throughout history. The "*Egyptian column*" inspired by the "*lotus plant*", the "*Greek column*" was inspired by the "*Acanthus plant*". We could also see the "*Gothic fan vaults*" inspired by the "*tree structure*", similar to the "*tree trunk*" which was also an inspiration to "*Sagrada Familia*" columns. The "*Crystal Palace*" also was inspired by the "*lily plants*" and finally, the well-known "*Fibonacci spiral*" was a source of inspiration for many architects.

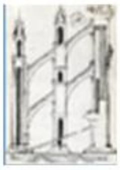
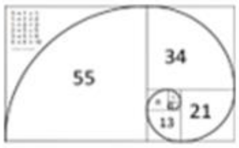
6th Century	9th Century	12th Century	19th Century	19th Century	20th Century
					
					

Figure 3: Timeline summary to plants as inspiration to architecture throughout history

3.1. lant's adaptive strategies

Plants are capable of adapting different environmental challenges on different adaptive levels. Those adaptations are either static (related to morphological adaptations) or Dynamic (related to behavioral and physiological mechanisms). "*Morphological*" adaptations are related to the plant's shape, pattern, or structure. "*Cactus*" undergoes a variety of morphological adaptations in response to harsh environments, like having ribs, spines, and its spherical shape in some cactus species. "*Behavioural*" adaptations are those actions and acts that are taken by the organism in an interaction with the environment to survive. "*Mimosa Pudica, Sp*." (Badarnah, 2017) is an example of this type of adaptation, where it closes its leaves inwards as a result of a physical contact stimulus. The third adaptive level represents the "*Physiological*" adaptations, which is the plant's response to the external stimuli through chemical processes to maintain its homeostasis. Most of the "CAM" plants undertake the photosynthesis process to adapt to dry conditions for increased water efficiency, like in the "*Ezcurra, Sp*." plant. (Ezcurra et al., 2006) Figure 4.

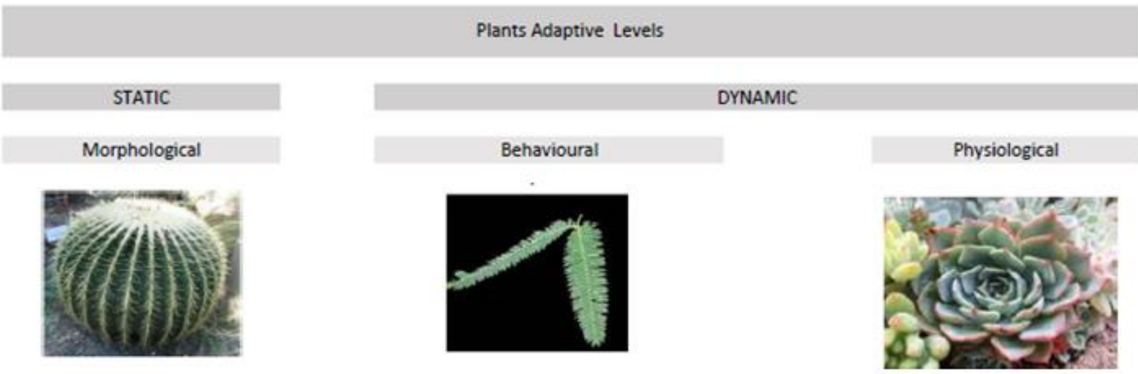


Figure 4 : An example to Plant's adaptive levels

Plants are good candidates for adaptations; they are capable of a variety of adaptations. The following table is an example of plants' adaptive strategies to different environmental conditions. The characteristics of 10 plants are shown in the following table. In the type of adaptation M: Morphological, P: Physiological, B: Behavioral. The performance: H: Heat, L: Light; W: Water; A: Air. Table 1.

Table 1: Plants adaptive strategies

Plant name	Adaptability	Level of adaptation	Strategy Summary
Sunflower (Badarnah, 2017)	L	B	Sunflower track sun path throughout the day by bending towards light and maintaining radiation perpendicular surface
Pinecone (Krieg, 2004)	W	B	The pine cone opens and closes in response to humidity allowing air to pass through
Grape leaves	A	M	Grape's vines morphology allows air to pass between.
Lotus leaf (Mauseth, 2003)	W	P	The hydrophobic leaf is covered in papilla, which are small bumps or ridges covered in a thin layer of wax. Thus rolling water off the leaf's surface.
Tree bark (Baumeister, 2007)	H, L	M	a)A waxy thick layer of cork plays a very crucial role in preventing water loss in plants. b)The round cross-section dissipates heat and light, thus stays cool. (c) Rough and peeling crusts provide shade.
Phragmites (Valk, 2006)	A	B	Stems move air, generate/use air pressure difference, or temperature difference for ventilation.
Cactus (Pohl, 2011)	L,H,W	M	a)The outer skin of the stem of the Barrel Cactus is covered by a thick waxy coating to reflect the solar radiation, b) Densely spaced spines provide shade skin of a cactus and reflect and diffuse the direct incident solar radiation. c) Ribs and folds provide shade to combat heat radiation cool down the skin.
Venus flytrap (Schleicher, 2015)	Other	B	Sudden deformation due to the structural element, altering its properties to a deformed geometric structure, less strained instead of high tensile or compressive stresses. It was described as a failure made due to amplifying small stimuli to vast movements beyond the limits through simple hydraulic mechanisms.
Mimosa Pudica (Guo et al., 2015)	Other	B	Closing its leaves and bending its "pulvinus". The ventral and dorsal side of the leaf consists of flexor and extensor cells (motor cells), shape, and volume are changed according to the applied turgor pressure.
Strelitzia reginae (bird of paradise) (Schleicher et al., 2011)	Other	B	Bending motion to the bottom two petals due to bird's weight when lands on it when a bird lands.

3.2. Plants and building envelope

Plants like buildings remain static in their place confronting environmental challenges, unlike animals that could move and search for shelters. Accordingly, this paper will be concerned with the plant's adaptive strategies as they would always be good candidates for inspiration for an adaptive building envelope.

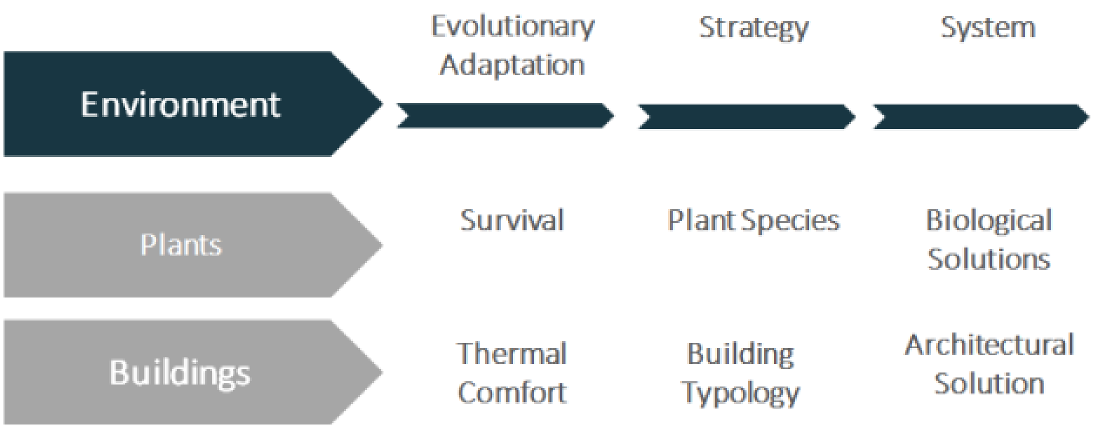


Figure 5: Concept scheme showing the main objective of the study (The researcher, 2020)

Building envelopes are similar to nature's skin, where they perform almost similar functions. They remain both barriers to secure the inside from the outside, tend to maintain the inner comfort. Both face the same environmental challenges, thus developing strategies and methods to mitigate those conditions and adapt to it. Accordingly providing thermal and light comfort, as well as suitable air and moisture content. Figure 5, indicated the similarities between the building envelope and nature, specifically plants.

The following Figure 6, demonstrates a comparison between the “Man-Made” construction versus “Nature’s” creations. The comparison is in terms of complexity, cycle, using resources, interconnection with the surroundings, multi-functionality, and dependence on renewable energy.

Man –Made	Nature
Simple	**Complex**
Linear	**Closed loop**
Use global resources	**Use local resources**
Wasteful	**Zero - waste**
disconnected	**interconnected**
Mono functional	**Multi-functional**
Fossil fuel dependent	**Renewable energy dependent**

Figure 6: Comparison between Man Made and nature’s constructions

4. Current problems with the building envelope

The building envelope contributes to the building’s overall energy consumption to reach the indoor thermal comfort, thus more attention should be taken to the façade’s design. In this paper, the focus would be on solutions corresponding to environmental challenges that were classified into four categories, heat, light, water, and air regulations.

“*Heat*” regulations require multiple methods like prevention, dissipation, retention, or gaining. The aim of “*light*” regulation within the envelope is to reduce or manage the amount of light incident, adjusting the amount of light, upon a surface to improve the comfort of the space for users or improve the functionality of the building.

“*Water*” regulation is related to heat regulation by using evaporative cooling to cool the envelope. Water conservation in hot dry regions and preventing water loss could be through reducing the evaporation process by regulating the temperature, SV ratio, or permeability, or water transportation. The fourth regulation of the building envelope could perform is "*air*" regulation. Air regulation could be either by air exchange through diffusion or air movement. Air movement could be fulfilled as a result of natural convection like temperature gradients or pressure differences. This pressure difference could be due to a variation in volume or velocity gradient.

5. Methodology Motivation

As discussed earlier, there are several methodologies and approaches developed to assist nature inspiration. They all share the sustainability and energy efficiency concepts, they all agreed on the potential of mimicking nature.

However, it was observed that they are generic; disciplines fit several professions with different design approaches, Sims, scales, and projects; Figure 7. It was also harder to find personnel experienced with all competent knowledge. Therefore, this methodology is developed to be tailored to architects, specifically environmental designers, specialized in building envelope adaptation inspired by plants.

	Biomimicry traditional approach	Proposed methodology
Scale	Generic	Specific
Aim	Seeking "Nature" inspiration	Seeking "Plants" inspiration
Solutions	Seeks solutions to all problems	Focused on Architecture discipline, specifically building envelope
Process	A team of Architects, biologists and other disciplines	Only Architects as it is designed to gather all data from other disciplines in one place
Approach	Could be direct or indirect	Direct approach only (designed specifically to architects)

Figure 7: Showing the differences between Man-made constructions and nature's strategies

5.1. Research Approach

From the previous table, we could deduce that there is an interrelation between three factors, which represent the plant's adaptive strategies, environmental challenges; and building envelope. Remarkably, they share similar factors offering interesting solutions and a variety of options for building adaptation. Accordingly, they are considered as the main pillars of the methodology generation. Figure 8. The methodology correlates between those key components. Each plant performs a certain adaptive strategy that is correlated to the environmental challenge (Heat, water, air, and light) it tackles at a certain level of adaptation (behavioral, morphological, and physiological).. Those strategies are thus categorized, classified , and organized to be easily translated to the building's envelope for its adaptation.

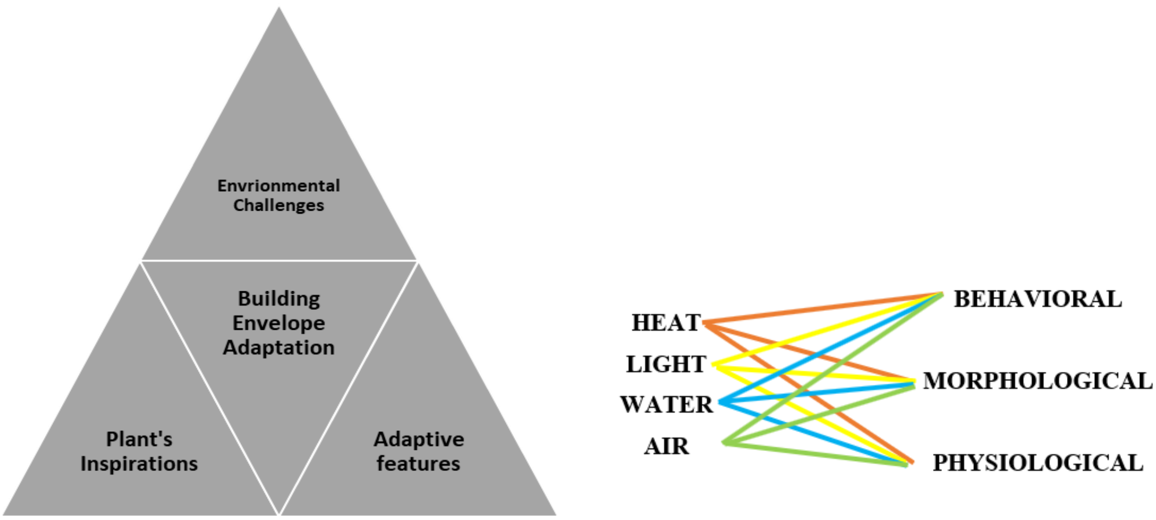


Figure 8 : The interrelation between the methodology pillars (The researcher, 2020)

5.2. Methodology generation

The proposed methodology was a correlation between the x-axis, y-axis, and z-axis as follows The database in Table 1, could be represented in a 3d matrix. This 3D heuristic model was developed combining the three pillars, where every two axes are interrelated as shown in Figure 9.

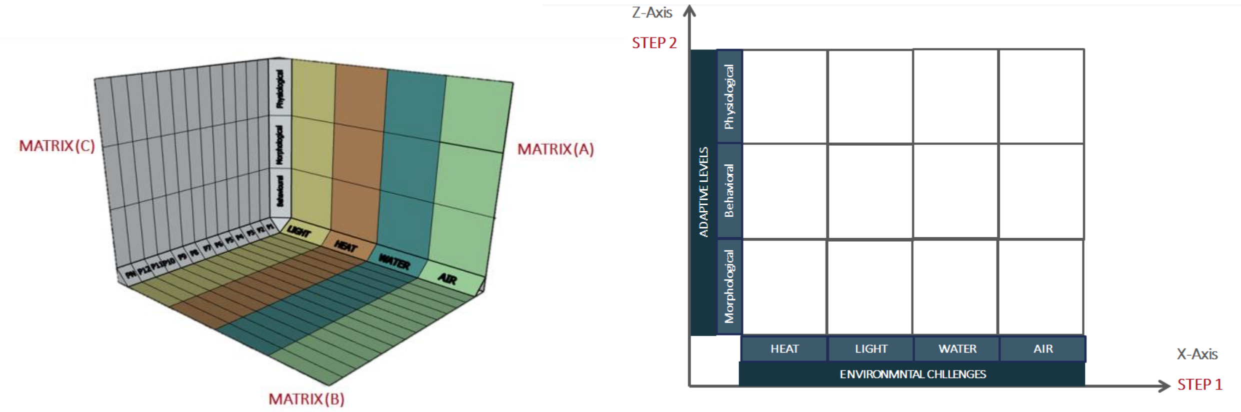


Figure 9 : on the left: 3d Heuristic Model proposal, On right : Matrix A: The relation between the desired type of regulation, and the desired adaptive level (The researcher, 2020)

This design methodology is formed out of two main layers discussed earlier. Each layer consists of a series of steps that are interconnected where each step leads to the step that follows.

Layer 1 is related to the environmental factors that need to be regulated within the envelope, Figure 10. This layer is formed up of two steps which are as follows:

- ***Step 1***: Defining the environmental regulation, which is categorized into the four key environmental factors that we focused on earlier.
- ***Step 2***: Specifying the adaptive level desired according to the designer's preferences, building typology, and scale of application.

The second layer***, Layer 2***, is specified with the plant's adaptive methods, it consists of four steps which are as follows:

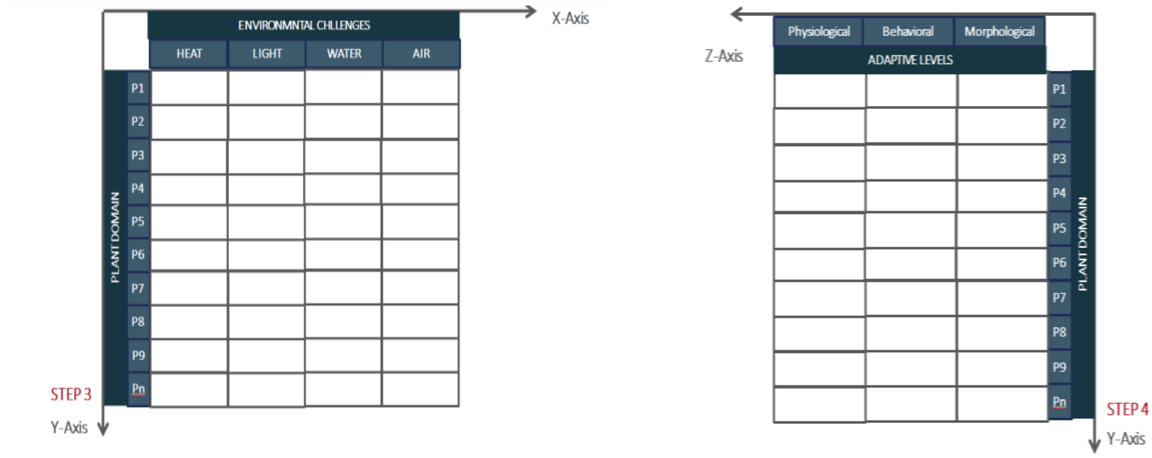


Figure 10 : On left: Matrix B: Describes the relation between the desired environmental regulation and the Plant's adaptive strategies. On right: Matrix C: Shows the relation between the plant domain and the adaptive level (The researcher, 2020)

- ***Step 3:*** Defining the adaptation type, whether it is a Macro level: morphological (static) /behavioral (dynamic) or micro level: psychological. (static)
- ***Step 4***: Afterwards, datasheet for the available plant domains that are relevant to the selected type of environmental challenge, the designer subsequently the adaptive and most suitable strategy for the desired project.

- ***Step 5:*** Once the designer set their preferences and entered the inputs as well as chose the suitable strategies that fit the building's typology; another database with possible architectural application relevant to this strategy would be suggested. Figure 11.

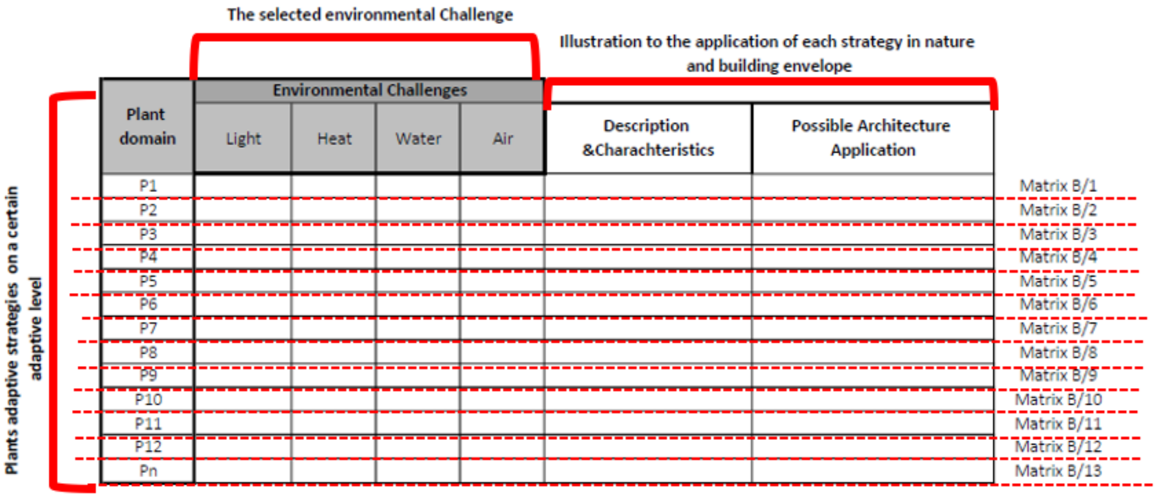


Figure 11 : Matrix (B) description and segmentation (the researcher, 2020)

6. Case Studies

The following section shows an example of the utilization of the proposed methodology in generating solutions inspired by plants. Two scenarios for three building types, each tackling an environmental challenge on a certain adaptive level through navigation within this 3d-heuristic model.

6.1. Scenario 1

Assuming that the building typology is an office building that requires "light" regulatory solutions. The architect subsequently starts navigation according to the aforementioned steps. First, selecting "light" as an environmental challenge. Second Choosing "physiological" as the adaptive level. If "Ivy Plant " was chosen, a corresponding datasheet to this choice, with a description of strategies developed by Ivy plants, an example of a project that adopted a similar adaptive strategy for the same purpose, Figure 12.

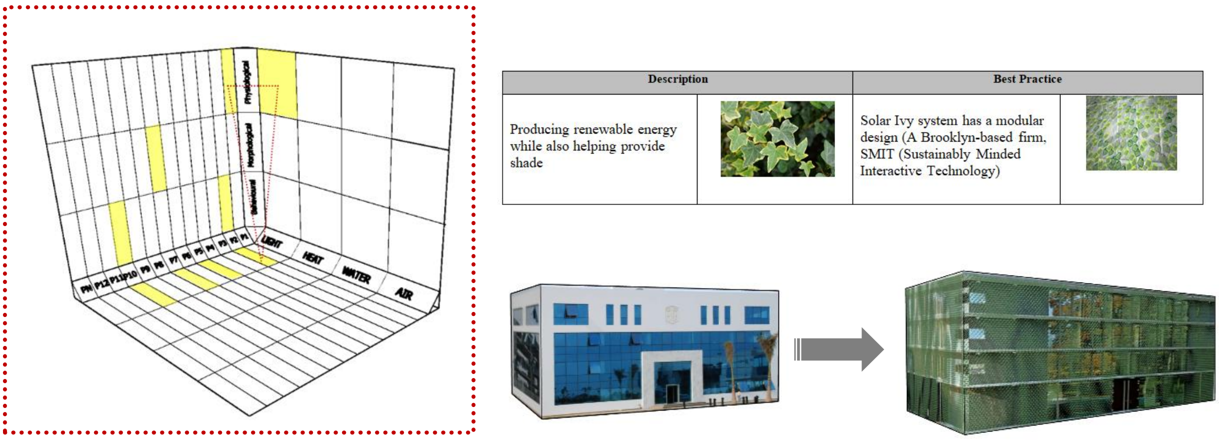
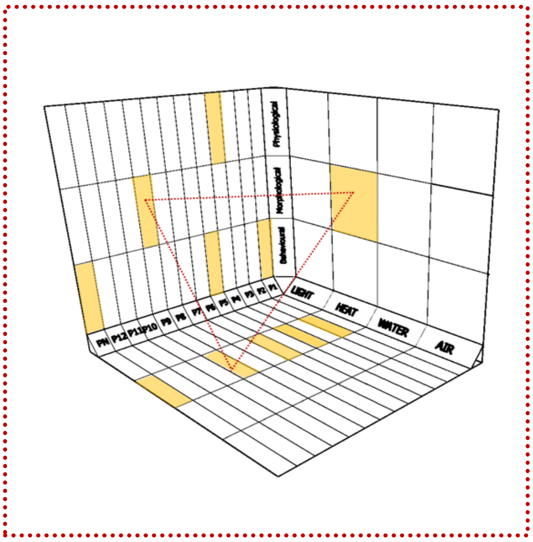


Figure 12 : Example to Utilizing the use of solar ivy in renovating an office building for light regulation on the physiological level

6.2. Scenario 2

The researcher assumed that the architect has chosen “ Heat” regulation on the “ Morphological” level. Out of the resulted plant strategies, it was assumed that the architect chose “Treebark’s” solution for example. The corresponding existing project mimicking tree bark strategies is CH2 building as shown in Figure 13.



Description		Best Practice	
During the growing process of the tree, xylem tissues push the circumference outwards which causes the outer layer of the bark to tear and die. Some barks form peeling crusts, while others react by forming deep cracks		CH2 (Council Building) Inspired by the aesthetic and function of bark which protects and houses the tree, the eastern façade houses the service core and toilets to the building. The bark façade was conceived as a second skin, or protective layer assisting with the natural ventilation of the wet area spaces. The final solution consists of two overlapping layers of perforated metal with polycarbonate walling and fixed metal louvres. (https://www.melbourne.vic.gov.au/SiteCollectionDocuments/ch2-snapshot-11-biomimicry.pdf)	

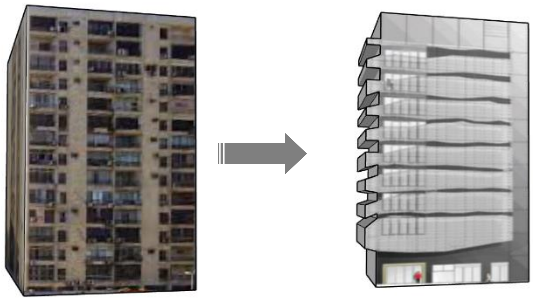


Figure 13: Example to Utilizing the use of tree bark strategy in renovating residential building for heat regulation on the morphological level

7. Findings

It could be observed that the methodology could assist the idea generation process and allowing the architect to visualize the building’s ideas either for renovation or new buildings. The generated ideas would contribute to the outcome of the total energy savings of the building. For instance, the adapted strategies would contribute to visual comfort, total energy savings, HVAC savings, natural lighting.

The proposed scenarios indicate the difference between conventional building and a biomimetic building applying plant’s adaptive strategies. It also minimizes the search process where all the abundant information is classified in a systematic methodology.

8. Conclusion

Mimicking plants offers a comprehensive database for building envelope adaption. Therefore, this paper has shown and analyzed selected plant’s strategies with proposed solutions that offer opportunities that could be implemented. However, there are still some unexplored areas for future research that could be following the same methodology.

As it could be observed, plant’s inspirations are available to be used by the architect directly without the need for any biologist's experience or multi-discipline team in the design process.

It was also observed that each plant could have more than one biomimetic strategy, thus the database was necessary to facilitate and simplify the selection process. It as well contributions to deciding which strategy and which plant could be further explored.

This paper has investigated simplified plant’s problems and challenges to assist understanding and underlying their main concepts and translate them to corresponding architectural applications depending on the building’s typology. This methodology acts like an “idea generation” a tool to the designer’s aiming at overcoming environmental challenges facing the building envelope.

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