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Biomimetic Architecture Towards Bio Inspired Adaptive Envelopes: In Case of Plant Inspired Concept Generation

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ABSTRACT

In recent decades, the value of architecture become more due to its importance for reducing detrimental effects on the environment and natural capital. To minimize the building's impact on the environment, architectural designs should be highly incorporated into the environment rather than behaving as a separate element focused on a single issue. To address this problem, different methods and design approaches have been introduced. However, exploring the natural solutions for survival can provide invaluable data which can address the human-caused problems. Throughout decades, nature has been survived and evolved. Biological solutions due to their adaptability and multi-functionality are great source of inspiration. This article with help of content analysis method aims to review the concept of biomimetic design in architecture. And proposes plant-inspired solutions for envelope design which can play significant role on buildings' energy efficiency. Thus, the plant-inspired concepts to be integrated on adaptive envelopes were studied. And a framework for concept generation introduced. Furthermore, a case study on an existing building envelope in the Mediterranean climate region presented and two plant-inspired techniques proposed and conceptually applied.

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1. Introduction

Environmental disruption and current climate change are closely linked to human activities. Social, ecological, and financial crises are becoming more frequent and severe, highlighting the new global vast range of challenges. Much of the world's population has experienced water shortages, lost living standards, and social and cultural instability. (Williamson, et al., 2003). Within this fact, in past years, one of the significant challenges in the area of architecture is the issue of energy efficiency and the effects of building construction on sustainability. After the 1970s energy crisis and till the 1992 Rio Earth Summit, sustainability in architecture eventually defined. Sustainable building has minimum impacts on the environment, increases energy efficiency, and decreases economic impacts (OECD, 2002). But, a question arises here, has the application of this concept to architecture been successful?

Ongoing architectural developments related to sustainability and green design is not enough yet to be effective. As Bill Reed in

2009 discussed, "we could have a world full of LEED platinum buildings and still destroy the planet". He explains that the green buildings have been developed regarding sustainability concerning the standards, but they are not fully fulfilling the green design criteria and are just simply "less bad" (kou, 2013).

However, biological evidence demonstrates the natural world's evolution, adaptation, and development over centuries, which is the basis for its survival. They can be used as a database to learn about and solve human-caused challenges in a long-term manner (Jin and Overend, 2014). Using the natural world as a source of inspiration and problem solving introduced new terminology to architectural design called 'biomimetic'. The biomimetic desgin main objective is to learn from nature and discover the solutions that nature employs. It does not have to be about repeating the concept but rather about being inspired by it and putting it to good use. These solutions will aid architectural design and research in different scales (Pedersen Zari, 2007).

In the other hand, the building envelope is one of the main components that biomimetic solutions can be applied to and enhance overall sustainability. Envelopes are among the most critical elements in architectural design because of their control of energy flow, extensive use of materials, high maintenance costs, and occupant satisfaction (Schittich, 2001). A recent suggested alternative for envelope design, represents a new approach based on successful examples found in nature. In this scope, one of the althernatives is plant-ispired envelope design which is the main focus of this study. Current construction methods and advancements in materials science open up a whole range of possibilities for an innovative plant-inspired building envelopes that will communicate more with the environment (Mlecnik et al. 2012). Thus, in this study it has been tried to:

- presents an in-depth literature review over theory of biomimetic design in architecture,
- presents a plant-inspired concept generation,
- presents two plant-inspired techniques for envelope design in mediterranean region to reduce energy consumption.

By covering the aims of the study, this article put forward an approach which can be used for furthur studies in this field both in practice and research.

2. Methodology and Scope of Research

The study with content analysis methodology presents a review of current studies concentrating on biomimetic architecture and envelope design. Through out the concent analysis within the first step of the study, the theory of biomimetic design approach for architeture been reviewed. With screening the main scholars works, the principles of biomimetic design been decussed, and accordingly biomimetic design approach as a promissing solution for energy efficiency of the buildings been highlighted. Since, building evnelopes play a major role in energy efficiency and overal sustainability of the building, in the second stepo, study been focused on evnelope design and biomimetic design. With furthur content analysis, plant-insipired approach as one of the biomimetic design methodes for envelope design been intoduced. The intoduced plaint-inspired adaptive envelope highlighted as one of energy efficient solutions. As one of the main outcomes of the study, after in-depth content reviews, a framework been proposed for concept development of plant-inspired adaptive envelope design. Lastly, through data collections (plant examples) data been evaluated according to mediterranean climatic characteristics and through a qualitative case study two solutions put forward for plant-inspired evnelope design in this region. Implementing the plant-inspired approach to the Faculty of Education and Central Lecture Hall building at the Eastern Mediterranean University in Cyprus aims to demonstrate the impact of this application on improving the building's energy efficiency and resource consumption. Following Figure 1, is illustating the stages of methodological approach.

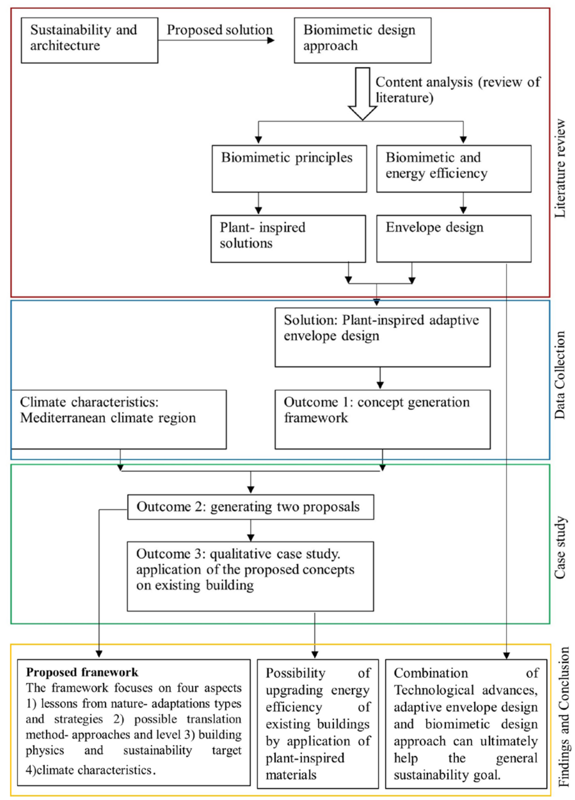

Figure 1 stages of methodological approach of the study

In order to carry out the content analysis of the study, the selected articles from online sources, had meet the scope of this study and fall into the focus of study. Following Figure 2, is illustating the scope of the study and main focus area. Aspects and researches not meeting the highlighted keywords are fall out of the scope of the study and has not been reviewed.

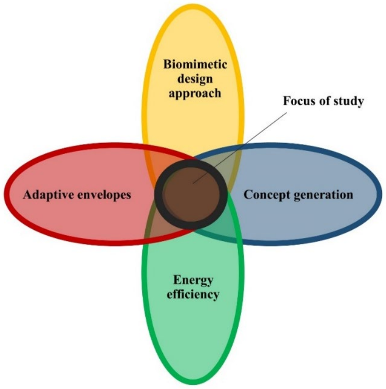

Figure 2 Scope of study

3. Literature Review: Biomimetic Design

Biomimetic is a recent discipline whose aim is to learn from nature and imitate it to discover solutions to human-caused problems. The literal translation of biomimetic terminology comes from the two Greek works of bios (life) and mimesis (imitating). The evolution and survival of the natural world over 3.8 million years is proof of natural solid ecosystem adaptation to change, and this is the most critical lesson for sustainability. While biomimetic is a new term that has only recently been applied to architecture, the use of this approach dates back a long time. Nature has long been a source of inspiration for humans, as shown by human history. Later architects, such as Antonio Gaudi and Frank Lloyd Wright, used a similar style in their designs, but this time with more abstract context and complexity. The principle of biomimetic design has emerged in architecture due to such designs (Vincent et al., 2006).

According to the Biomimicry Institute, biomimicry can be defined as "an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies. The goal is to create products, processes, and policies—new ways of living—that are well-adapted to life on earth over the long haul."

Biomimetic is a multidisciplinary methodology at the intersection of three disciplines, possibly requiring knowledge from biologists, biophysicists, and material science. Communicating between these disciplines provides enlightenment about the challenges and potential answers. The method of simulating a natural world is similar to that of translation. Nature's necessary solutions for survival should be translated to suit the human-made environment. The end product of this translation method does not necessarily provide the exact and equivalent impression of the organism that inspired it. Still, it does have a functional concept that is similar (Pedersen Zari, 2007).

Due to its complexity and multidisciplinary, the biomimetic design approach presents many barriers that should be studied to translate the natural solutions to architectural designs. Thus, understanding biomimetic design principles; 1) adaptation types, 2) design approaches, 3) adaptation levels, and 4) strategies (illustrated in Figure 3) has extra importance (Feuerstein, 2002; Aldersey-Williams, 2003).

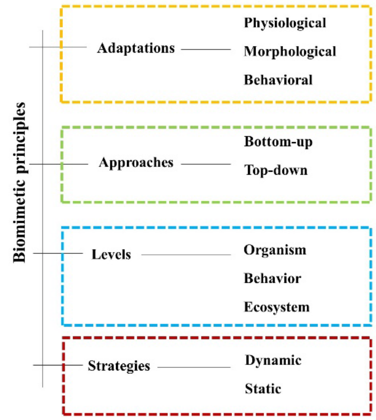

Figure 3 biomimetic principles (authors, 2021)

3.1. Biomimetic Principles

Principles of biomimetic method within various scales were developed by studies such as Zari in 2007 biomimetic architecture. These studies provide a greater understanding of the working mechanisms of the natural world. It is possible to provide architectural design solutions only if we have explicit knowledge of the natural world.

Nature adaptation- Natural adaptation is the phase by which species conform to their surroundings to survive. This adaptation can be perceived within three scales of morphological, physiological and behavioural. Morphological or structural adaptation refers to the changes in the organism body. In contrast, the physiological adaptation focuses on 'how' the changes happen, which refer to chemical changes. Lastly, behavioural adaptation refers to how an organism responds to the environment to help them survive (Kuru, et, al., 2018).

Biomimetic approaches- To transfer the knowledge from nature to architectural design, two primary approaches have been proposed in the literature. In a top-down or problem-based approach, the design process begins by identifying the problem. In this approach, the planner or architect identifies the problem and searches for a solution in nature; as they discover an organism that has solved a similar problem, they abstract the solution and apply it to their design problem. The method is reversed in a bottom-up or solution-based approach. Designers of this approach have experience of specific biological researches, which influences their design. So, aside from specifying the issue, their initial design is based on their biological understanding (Zari, 2007). The two approaches and examples of them illustrated in Figure 4.

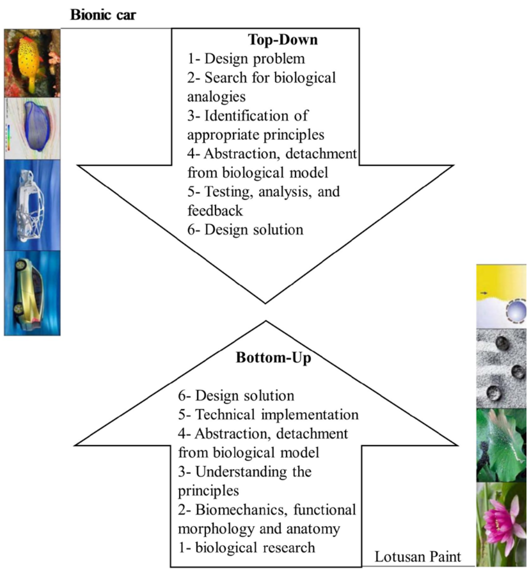

Figure 4 Biomimetic approaches and examples of each (Aziz, 2016)

Biomimetic levels and dimensions- Organism or structure' is the first level of biomimetic architecture. Nature creates a complete picture of rich and diverse forms. These forms can survive the environment's changing conditions. Structures are designed to replicate a single entity at the organism level. At the behaviour level, the action of the individual is mimicked, not the organism itself. Similarly, it might be possible to replicate the relationships between organisms or species. Ecosystems mimicry (or eco-mimicry) is an essential aspect of biomimicry(Figure 5). The benefit of designing at the ecosystem level is to combine the other two levels of biomimicry. These three levels can be applied to different dimensions (sub-levels) of design; From, Material, Construction, Process, Function (Zari,2007)

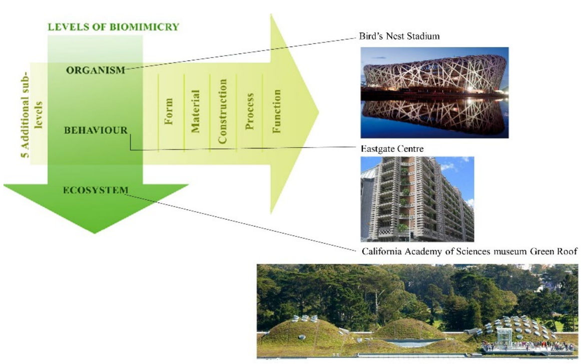

Figure 5 Levels of biomimetic (Zari,2007, ammanded by authurs, 2021)

Biomimetic strategies- natural environment has two strategies or techniques for adaptation, dynamic or static. The two strategies can happen on two scales of macro or micro. The dynamic adaptation is usually in macro-scale presents a motion. On the other hand, the static adaptation strategy happens in the properties of materials that are micro-scale (López, et, al., 2017).

Understanding the biomimetic principles is the first step towards generating concepts for problem-solving. The second step is formulating the purpose of concept generation. Biomimetic can respond to different problems such as global warming and climate change, economic enhancement, energy consumption reduction, etc. This study has focused on the energy efficiency goal for building design with a biomimetic approach.

3.2. Energy Efficiency And Biomimetic Design

Buildings account for over half of all energy consumption, according to the International Energy Agency. This reality emphasizes the importance of proposing approaches that reduce building energy use and contribute to the ultimate sustainability target. Nature seems to use low-energy methods, implying that various biological species could be investigated as a source of novel strategies for minimizing Operational Energy. Biomimicry has been recognized as a ground-breaking design method for enhancing energy-efficient design in the same way (Herring and Roy, 2007). Together, recent technological advancements and nature as a source of problem-solving will offer architectural solutions to solve the high energy consumption challenge.

Termite mounds are a well-known natural example of energy efficiency that their air conditioning units circulate hot and cold air between the mound and the outside environment. Mick Pearce built Eastgate Centre (Figure 6) in 1990, based on the termites' Process. It has about 350,000 square feet of office space and shops. It consumes 90% less energy than a building of comparable scale in the same climatic condition. This natural example suggests that other species could be better builders than humans. The Eastgate Center, for example, demonstrates that biomimetic can be a viable option for improving building energy usage (Annon, 2005).

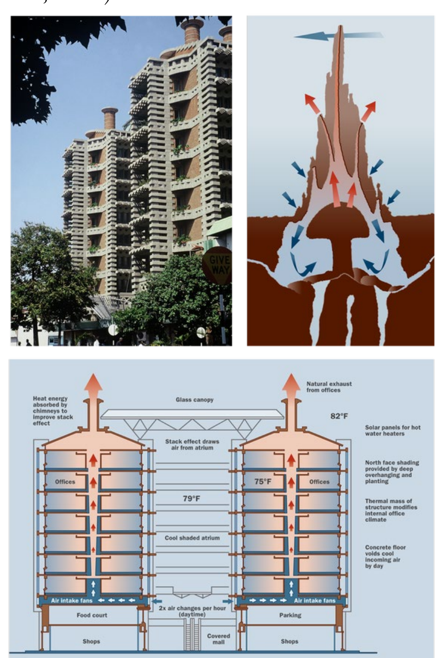

Figure 6 The Eastgate Center and inspiration from Termites mounds (Annon, 2005).

Natural lighting, natural ventilation, heat gain, and heat loss can be improved with biomimetic solutions. Not only can a building's energy performance change as a result of these solutions, but the quality of the indoor environment would also improve, which would have a significant impact on occupant satisfaction. Building envelopes are the essential factor for a building's energy efficiency. The use of biomimetic solutions on building envelopes will improve the building's energy efficiency.

3.3 Adaptive Envelopes

According to Ferguson et al. (2007), adaptability is described as a tool that can provide a particular purpose based on a set of parameters and can adjust physically with time. The ability of the building envelope to adapt and respond to changes in its environment, such as solar radiation, wind, temperature, and rainfall, is unique among building elements. Compared to buildings with static design envelops, this capability can reduce energy consumption and increase energy efficiency (Loonen et al. 2011).

The definition of adaptive envelope defined by Loonen et, al in 2013; 'adaptive envelopes can repeatedly and reversibly change its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions. By doing this, the building shell effectively seeks to improve overall building performance in terms of primary energy consumption while maintaining acceptable thermal and visual comfort conditions.'

The adaptable envelope not only serves as a barrier between the inside and outside of the building, but it also serves as a temperature arbitrator and balancing interior comfort (Wigginton and Harris 2002). The building envelope should respond as a solution for the whole year; it might not have the best performance, but it should solve a wide variety of problems (Bakker et al. 2014).

Many different types of adaptive envelopes with different adaptation scales developed in recent years due to technological advancement. A wide range of adaptive envelopes include; kinetic, dynamic, intelligent, and so on. Biomimetic or bio-inspired envelopes are one of the adaptive envelope varieties. The bio-inspired envelopes and concept generation from plants are the subject of this research.

3.3.1 Biomimetic/ bio-inspired adaptive envelope

Both research and architecture practice show a need for further projects based on the bio-inspired envelope definition. Braun is one of the pioneers who researched a wide variety of bio-inspired building envelops design, over 45 models. Still, because of their multi-functionality and sustainability, the skin of plants and humans remain the most upstanding models and sources of inspiration. Plant and human's skin is the most straightforward imitation source for adaptive envelopes. Skin is an organism of the natural world that responds to various factors, has various functions, and is self-regulating. It is admired, but also tricky, to transmit these properties as metaphors to building envelopes.

Biomimetic methods are most often used in nature to regulate adaptation by using intrinsic properties of materials as actuators and are restricted to responding to environmental stimuli beyond those thresholds rather than the indoor environment or user experiences (Tabadkani, et,al, 2021). Bio-inspired adaptable envelope configuration can be viewed on three different scales and functional stages. Bio-inspiration can occur at various spatial scales, ranging from material, envelope components to the whole structure. According to biomimetic literature, bio-inspiration can be categorized into three aspects: form, function, and Process (Loonen et al. 2014).

Since it explicitly identifies with replication of the morphological appearance of the natural structure or living organism, form is the most straightforward type of bio-inspired architecture. Then there's the function, which mimics the simple organic framework in that it's more concerned about what the envelope does than with how it looks. Finally, Process, the third aspect of bio-inspiration, is an essential component in many biomimicry highlights. However, it is most often seen in building relationships on the urban or regional scale rather than individual buildings (Pedersen Zari 2010).

As mentioned earlier, the inspiration for a biomimetic envelope can be from any biological species. For this study, exclusively plants have been selected as an inspiration source. The study tries to understand the adaptation solutions from plants and later presents a framework for generating applicable adaptive concepts for building envelopes from plants' adaptation solutions.

3.3.2 Plant-inspired adaptation solutions

The static position of plants forced them to develop a protection structure against harsh environmental conditions such as temperature change, extensive sun direction, rain, etc. Due to the climatic changes, natural adaptation occurred over time to respond to critical environmental changes. Therefore, evolvability and adaptation are essential characteristics of plants for survival. In the sense of immobility and being exposed to various environmental conditions, buildings and plants share the same identity. Thus, understanding the adaptability of plants can propose methods and techniques to help buildings be more responsive to environmental conditions and more sustainable (Mazzoleni 2010).

As discussed in the biomimetic principles 3.1 section, adaptation in nature, including plants, can perceive in three levels; morphological, physiological and behavioural. And two strategies of dynamic or static. Studying plants based on biomimetic principles allows generating concepts to build adaptive envelope design (López, et, al., 2017). Following Table 1 is presenting studies on plants based on adaptation types and strategies. Understanding these two aspects is the first step towards concept generation. After studying adaptation and strategy types, it is possible to propose the level and approach type to translate the natural solution to architectural element. Such study is the first step towards working with the concept generation framework.

Table 1 adaptation types and strategies in plants (López, et, al., 2017)

plant	description	Adaptation type	strategy	picture
Gynandriris setifolia Common name: Thread iris	Hairs on the plant used to reflect sunlight	Morphological	static	
Echeveria Glauca Common name: blue echeveria	Phase Change materials	Physiological	static	
Leaves of Mimosa pudica Common name: humble plant	Folds inward as a reaction to contact	Behavioural	Dynamic	

Understanding plants adaptation towards the environmental condition and their strategies bring us one step closer to concept generation for adaptive building envelopes.

4. Plant-Inspired Proposal Development

Developing proposals from the plant for adaptive building envelopes can be defined as a framework in four phases (Figure7). Phase (1) is the analytical phase that studies the plant adaptation towards environmental conditions. Study in phase (1) is based on two biomimetic design principles, a) adaptation types b) biomimetic strategies. In this phase, a general understanding of the working mechanism of plants will be highlighted. Phase (2) of the proposal development framework focuses on the first transition stage from natural strategy to the architectural solution. Based on biomimetic design principles, the design approach and level of biomimetic design will be defined. Throughout phase (1) and phase (2), the initial proposal from plants translated to architecture will be introduced. Phase (3) of the framework, specify the purpose and target of the new proposal and which building component it will apply. In phase (4), the last variable of the framework, 'climate,' will be added. Each climate region has its characteristics that require specific solutions. Thus, considering the climatic factors is critical for developing a proposal.

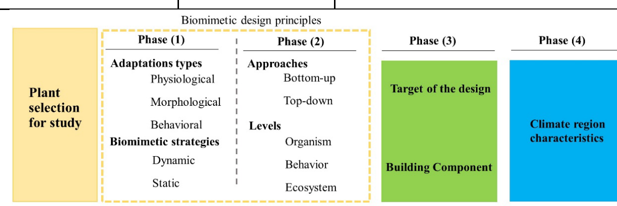

Figure 7 plant-inspired proposal development framework

The following section introduces two plant-inspired proposal development based on the explained framework. It investigates the application of the proposals on an existing building in the Mediterranean climate region to improve energy efficiency.

5. Case Study: Findings and Discussions

The case study of this research aims to propose biomimetic techniques for an existing building in the Mediterranean climate zone to improve the building's energy efficiency. Eastern Mediterranean University's new faculty of Education & Central Lecture Hall (Figure 8) in Cyprus has been selected for this study. The building designed by TASAR Design and Research Centre, Faculty of Architecture, EMU. For this project, Eastern Mediterranean University (EMU) and Erke Sustainable Building Design and Consultancy Ltd. signed a cooperation protocol regarding the LEED Green Building Certification (Platin).

The main aims of the projects were achieving sustainability for building by passive and active strategies, designing an environmentally friendly building, achieving the best interior and exterior spaces relationship, protecting the existing natural environment, increasing the quality of exterior spaces and easy accessibility both by vehicle and pedestrian.

Figure 8 New Central Lecture Halls and Education Faculty buildings (TASAR, 2018)

From the initial steps of the design, the maximum usage of the south direction was considered. In this case, the building got maximum benefits of solar energy and reduced the energy demand of the building for heating and daylighting. Usage of the PV panels by getting benefits of the south sun direction provides the hot water and is used for the building's floor heating system. Trombe wall as a passive solar technique designed for the west façade. This façade with an external layer of glass and the internal layer of high heat capacity was designed as a passive design decision. For the sunlight control on all the building facades except the eastern façade, shading elements were applied.

Although the architects' decisions helped the building achieve some level of sustainability, there is still a possibility to enhance the energy efficiency of this building to a higher level. In this manner, it has been tried to find plant-inspired solutions in the Mediterranean climate region and developing a proposal for higher energy efficiency of this building.

Perennial plants for this study epecifically Oxalis, belong to groups of plants that adapt themselves throughout the day and night due to exposure to sunlight. These groups of plants can close and open their leaves and flowers during night and day. This plant adaptation ability can translate to building envelope design and improve the building's energy efficiency by controlling the lighting exposure amount. Studying this plant in phase (1) shows the behavioural adaptation with dynamic strategy. Throughout phase (2), with a bottom-up approach, the plant adaptation ability can translate to architectural behaviour level and function sub-level. Learning from plant adaptation can be translated to folding shading intelligent systems for building envelopes with energy efficiency. This technique can be beneficial for the Mediterranean climate region, where buildings are exposed to sunlight for a long time. Following Figure 9 illustrate the proposal development from this plant.

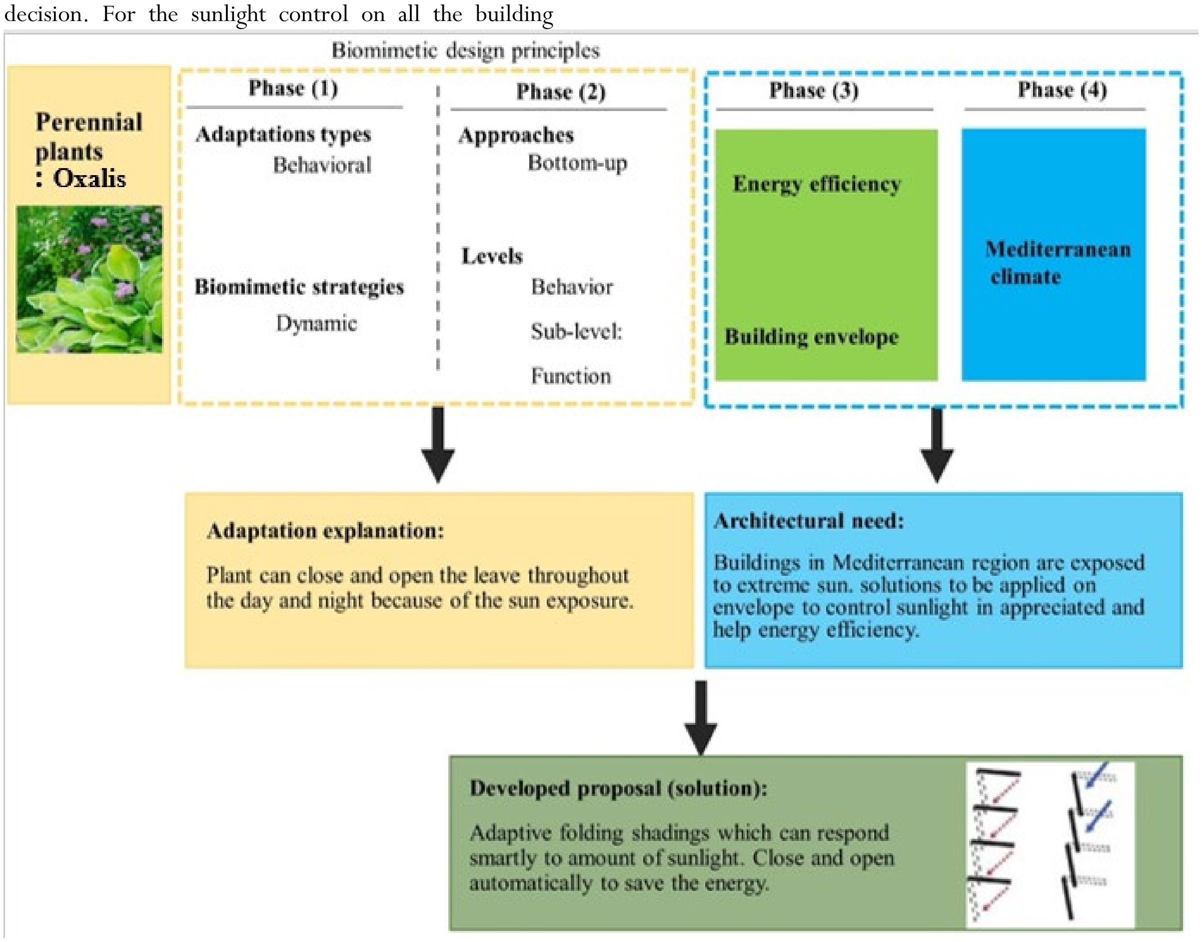

Figure 9 plant-inspired proposal for building enveloped based on Perennial plants adaptation.

The second proposal can be developed from Kalanchoe pumila leaves. This plant, with greyish-green leaves, developed a reflective surface on the leaves that allow them to survive under the sun for long hours. The same static approach can translate to architectural design, improving the energy saving for heating and cooling. By learning from the adaptation type of Kalanchoe Pumila leaves, it is possible to develop a proposal based on phase change material technique and apply a three-dimensional covering surface in material with unique properties to reflect the light. This proposal protects the building from excessive sunlight and temperature. Following Figure 10 illustrate the proposal development from this plant (López, et, al., 2017).

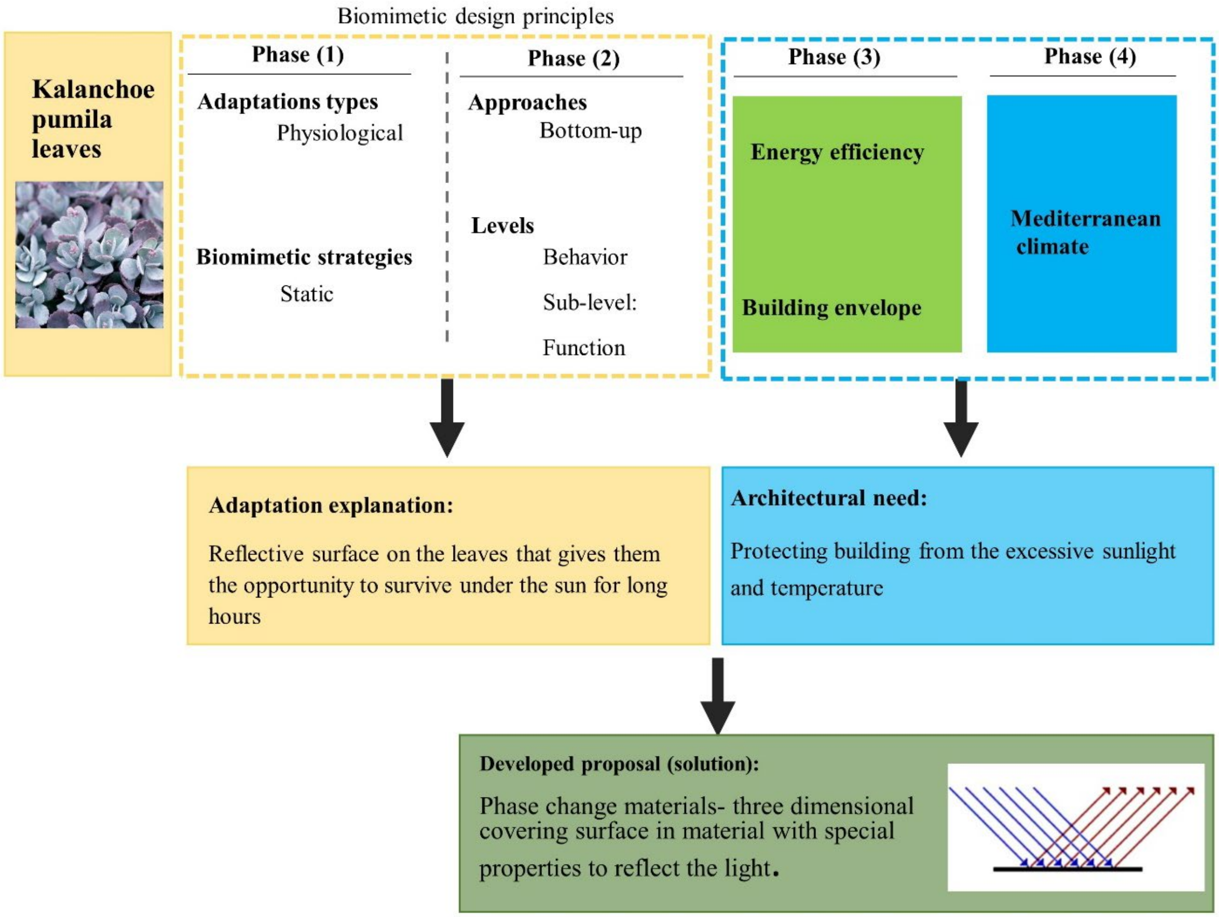

Figure 10 plant-inspired proposal for building enveloped based on Kalanchoe Pumila

Two developed proposals by the plant-inspired method can apply to New Central Lecture Halls and Education Faculty buildings envelope to enhance the building's energy efficiency (Figure 11). The intelligent folding shading devices inspired from adaptation in Perennial plants can be applied on the east oriented building envelope. In this case, the adaptive bio-inspired envelope will react to sunlight. This dynamic strategy will allow controlling the amount of sunlight entering the building. Thus, decrease the lighting load of the building. The second proposal can be applied to the southern envelope. The three-dimensional films acting as phase change materials can change the property of the southern envelope due to extreme sunlight exposure. This proposal decreases the cooling/heating load, and at the same time, the view outside to some level will be kept for lecture rooms and offices.

Figure 11 application of proposals on building envelope

Many more lessons can be learned from nature and, with the help of the proposal development framework, transfer them to architectural elements. However, it should be mention, variety of such proposals are still conceptual models, and the ones in practical use can be expensive alternatives. Thus, applying such ideas and approaches should be in proper context to achieve sustainability at all levels and not only from an energy efficiency point of view.

Moreover, in recent years there has been many invaluable studies on biomimetic appraoch for architectural design, but this study by proposing a conceptual framework tried to touch the practical point of this theory more. This study, firstly by giving a wide prespective towards the topic, increases genera ubdrestanding of researches and practitionares about the topic, and later by applying the theory and framewrok on the existing building presents the practicalty of this theory.

Application of the theory of plant-inspired adaptive envelope, not on a new designs, but on an existing building can highligh the opportunity of increasing the sustainability and energy effiiency of already existing building in environment.

Although, this study had a focus on mediterranean climate region, but same approach can be applied to find plant-inspired solutions for adaptive envelopes in variety of climate zones and by proposing the application of such solutions increase the energy efficiency of the existing building at same time as new constructions.

5. Conclusion

Achieving sustainability as an everyday goal is the main issue for architects and designers in recent decades. Building envelopes, as one of the most critical building components, plays an essential role in building sustainability, thus finding solutions and alternatives for envelope designs is one of the trends in architectural research. Adaptive envelopes seem promising alternative for improving the building's energy efficiency while providing high indoor environment quality. One of the approaches towards adaptive envelopes is biomimetic or bio-inspired envelopes.

This study has tried to review the 'biomimetic design' as a vital terminology in architecture. By understanding the principles of biomimetic, the concept of bio-inspired design has been investigated. After surviving millions of years, the natural world, due to the adaptability aspect, is the best source of inspiration. Learning from nature can apply the adaptation to the buildings, which can improve their sustainability drastically. Plants, due to their immobility, are the best source of inspiration for building envelope design. Plants, same as buildings, are static elements in nature which facing various environmental and climatic conditions. Here the contrast between plants and buildings in the adaptability. Over time plants learn to respond and adapt themselves towards critical climatic changes and survive; thus, the same approach can improve the buildings sustainability and survival without causing damage to the environment.

Furthermore, this study reviewed the plant-inspired design approach, and with the help of the literature review, introduced a framework for proposal development that works in four phases. The framework focuses on four aspects 1) lessons from nature- adaptations types and strategies 2) possible translation method- approaches and level 3) building physics and sustainability target 4)climate characteristics.

Two proposals have been developed throughout the study to be applied to an existing building in the Mediterranean climate region. Both proposal but upgrading the conventional building envelope to adaptive envelope improves the building energy efficiency. Two proposals with different adaptation types and strategies can decrease the building's lighting and heating/cooling load.

In today's world, with technological advancement development of ideas from the natural world is very appreciated. Although various studies are ongoing in concept developments or laboratories, some practical concepts are still available to be integrated into adaptive envelope design. However, the majority of the alternative is expensive applications and might not be suitable for all contexts. Further studies on biomimetic design and concept generation for the building envelope is still needed to reach the ultimate sustainability goal. As William Mc Donough said;

'A building should be like a tree; it should thrive on the Sun's energy while enhancing its surroundings.'

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