Biomimetic Design as a Tool for Sustainable Architecture; A Theoretical Approach

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ABSTRACT

From 1970s energy crisis, population growth and climate change, topic of sustainability is one of the trends both in research and practice. Within this time many passive and active alternatives been proposed to be integrated to architectural design. One of the promising proposed approaches is biomimetic design. Natural world, with survival of decades through many changes, is the best source of inspiration for architecture. Biomimetic by understanding this facts, tries to learn from natural solutions imitate them and address human-caused problems.

Although, there is a considerable researches on this topic, but this thesis tries to review this terminology in literature with main aim of categorizing and presenting the biomimetic criteria which can be helpful for further researches and even practice of architecture.

Accordingly, author tries to present an in-depth literature review with content analysis method. For this purpose, the research of main scholars of the field gathered and studied and based on generated codes the biomimetic design criteria categories within four main groups. Beside the main criteria, the lessons from nature which criteria developed from and later the synthesis for architectural design been presented as well. After presenting the main outcome of the review, successful examples of biomimetic design studies and analysed based on biomimetic principles, biomimetic design criteria and the architectural synthesis from natural lessons in each case discussed as well.

In the end, this qualitative study with content analysis method, highlights the successful link between biomimetic design and sustainability, while, presenting the design criteria important to be considered for future designs. Lastly, the study argues that there is lack of development of biomimetic design in all criteria except the building physics since the majority of sample studies developed biomimetic on the envelope design or material design. Thus, in order to achieve the ultimate sustainability other biomimetic criteria should be more considered in design approach.

Keywords: sustainability, biomimetic design principles, biomimetic design criteria.

ÖZ

Sürdürülebilirlik 1970'li yıllardan itibaren enerji krizi, nüfus artışı ve iklim değişikliği göz önünde bulundurulduğunda hem araştırma hem de uygulamadaki eğilimlerden biridir. Bu süre içinde birçok mimari tasarıma entegre edilmek üzere pasif ve aktif alternatifler önerilmiştir. Bu önerilen alternatifler arasında umut verici yaklaşımlardan biri biyomimetik tasarımdır. Doğal yaşam onlarca yıl boyunca birçok değişiklikle hayatta kalması ile mimarlık için en iyi ilham kaynağıdır. Biyomimetik bu gerçekleri anlayarak, doğadan öğrenmeye çalışır, onları taklit eder ve insan kaynaklı sorunları ele alır.

Bu konuda önemli araştırmalar olmasına rağmen, bu tez amacı aynı terminolojiyi literatürde yeniden araştırıp, gelecekte daha ileri araştırmalar ve hatta uygulama alanında mimarlara yardımcı olabilecek biyomimetik kriterleri kategorize etmeyi amaçlamaktadır.

Buna göre yazar içerik analizi ile derinlemesine bir literatür taraması sunmaya çalışır. Bu amaçla, alanın önde gelen bilim adamlarının araştırmaları bir araya getirilmiş ve içinde biyomimetik tasarım kriterleri kategorileri incelenmiş ve oluşturulan kodlara dayalı olarak dört ana grup oluşturulmuştur. Temel kriterlerin yanında, doğadan alınan dersler hangi kriterlerin mimari tasarım için geliştirilip, sentezlenebileceği çalışmada sunulmuştur. İncelemenin ana sonucuna varıldıktan sonra, başarılı biyomimetik örnekleri tasarım çalışmaları, biyomimetik ilkeler, biyomimetik tasarım kriterleri temelinde analiz edilmesi ve her durumda doğadan çıkarılabilecek mimari çözümlerde sunulan tezde tartışılmıştır.

Sonuç olarak içerik analizi yöntemiyle yapılan bu nitel çalışma, biyomimetik tasarım ve sürdürülebilirlik arasında başarılı bir bağlantı sunarken, gelecekteki tasarımlar için dikkate alınması gereken önemli tasarım kriterlerini sunmaktadır. Son olarak çalışmada incelenen biyomimetik mimari örneklerinin daha çok bina kabuğu ve malzeme tasarımında gelişmiş olmasının yanı sıra yapı fiziği alanında bir gelişme gösteremediği değerlendirilmiştir. Böylece, nihai sürdürülebilirliği sağlamak için diğer tasarım yaklaşımında biyomimetik kriterler daha fazla dikkate alınmalıdır.

Anahtar Kelimeler: sürdürülebilirlik, biyomimetik tasarım ilkeleri, biyomimetik tasarım kriterleri.

Dedicated to my Father & Supervisor

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Chapter 1

INTRODUCTION

Sustainable development has been a critical subject in assessing and adopting potential challenges, production and consumption behaviors over the last 20 years. However, what constitutes critical sustainability knowledge for these disciplines is a widely subject of discussion.

The growing frequency and severity of social, ecological, and financial crises highlight the current global system's wide variety of challenges. Environmental depletion and climate change have cast doubt on industrial development models that rely on deforestation, nonrenewable resource extraction, and higher carbon emissions to drive growth. Water shortages, lack of livelihoods, and social and cultural disruption have been the shared platform for majority of societies. As a result of these pressures, policymakers, financial firms, and civil society players are continually focusing on sustainability (Williamson et al., 2003).

Human action is strongly related to environmental damage and current climate change. The previously multinational think-tank, the Club of Rome, openly challenged the economic blueprint for modern economies for the first time in 1968. Members of this team released the paper “The Limits to Growth” in 1972, arguing that economic prosperity and environmental conservation must be merged (Williamson et al., 2003). In 1987, the World Commission on Environment and Development, published a report which introduced the term sustainable development. This report was named as Brundtland Report (Sev, 2009);

> Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs… sustainable development is not a fixed state of harmony, but rather process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs (Sev, 2009).

Between 1968 and 1992, the idea of sustainability development and sustainability drew architects' interest in science, leading to the 1992 Rio Earth Summit. At the Rio Earth Summit, heads of state pledged to explore ways to achieve growth that meets current needs without jeopardizing future generations' capacity. Three values underpin the philosophy of sustainable development (Sassi, 2006);

- Consideration of whole cycle of materials
- Increased use of natural resources and renewable energies
- Reducing the usage of materials and energy

Sustainable development is focused on social programs that aim to balance ecological, economic, and social influences, in addition to environmental risk understanding. It ties up with the fundamental values of environmental law:

- Precaution
- Prevention
- Remedy at source
- Polluter pays
- Use of the best available technologies. (Sassi, 2006)

The Rio Declaration's values are linked to the creation of Agenda 21, a twenty-first-century development strategy. This proposes an integrated, innovative solution so as to achieve sustainability. Figure 1 illustrates the evolution of sustainable development awareness and its improvements over time.

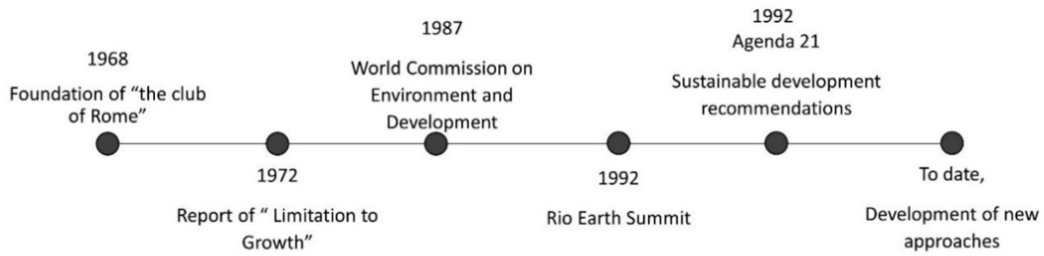


Figure 1: Development Timeline of Sustainable Development Concept (author, 2021)

While the need for environmentally sustainable architecture has been recognized for many years, widespread recognition of sustainable development dates only from the Rio Summit. During this time, a number of architectural alternatives appeared, including green buildings, high-tech, energy efficient, adaptive, biomimetic, and so on (Bauer et al., 2009).

Whereas sustainable architecture remains a common theme in architecture, current projects are ineffective; in other words, we see architectural designs that are less poor but yet fall short of the sustainability goal. "*We could have a world full of LEED platinum buildings and yet kill the planet*," said Bill Reed (2009), a visionary thinker in biomimetic architecture who co-chaired the creation of LEED standards from the beginning. He proposes that designs be "regenerative," suggesting that they can deal more with biodiversity problems. This is a solution that not only prevents the depletion of the earth's natural resources, but also allows for cooperation and development in a manner that benefits both life expression and versatility.

One of the key principles for achieving sustainable development, as discussed earlier at the Rio Summit, is to use the best available technology. Biomimetic architecture is one of the promising approaches for pursuing sustainable development that has become feasible in recent years thanks to technical advancement. Biomimicry provides a comprehensive and reliable approach to this issue (Skou, 2013).

For decades, nature has been one of the major inspiration source for human being. Throughout the history, utilization of natural elements for different purposes starting from ornamentation and appearance of it as art, to development of these elements and being part of architecture. Famous architects such as Wright, Pearce, Pawlyn or Calatrava introduced and developed architecture type which is known as biomimicry. The architecture type introduced with their works incorporated symbolism and much more informed comprehension beyond simplistic usage of these elements (Hu, Feng, and Dai, 2013). Engineers and researchers have recently begun to investigate and study the natural world in a more fundamental way to address societies challenges, and it is possible due to the advancement of technology in recent years.

Biomimicry is a relatively recent design concept in practice that explores strategies for sustainability for human-created obstacles by emulating principles evolved and developed by natural world (Hargroves and Smith, 2006).

In this research, it has been tried to have better understating over the concept of sustainability in architecture, and to follow, introduce the biomimetic approach. In this study biomimicry has been presented as one of the promising approaches for sustainable architectural design. In this manner, this study tried to have a systematic review over biomimetic design criteria and introducing the most suitable methods and approaches to be applied in architectural design.

1.1 Problem Statement

Architecture industry, buildings, throughout construction and after construction are using the most energy resources (48 percent) much more than transportation system (27 percent) and industrial field (25 percent) (Pérez-Lombard et al., 2008). As a result, buildings are critical components in ensuring overall sustainability in everyday life. This is one of the reasons that there is so much interest in finding sustainable architectural alternatives. Architectural science attempted to solve this everyday issue by incorporating various strategies and techniques for achieving architectural sustainability.

One of the promising solutions which introduced to the architecture field in last decades is "biomimetic design approach" over decades, with all impacts by human activity still natural ecosystem been sustainable and endured. As a result, this approach seeks to benefit from the natural environment in order to solve the question of architectural sustainability.

Within last years, there has been many researches done by scholars with research focus on biomimetic design in architecture. The researches, presented the principles of biomimetic, its application on architecture and the issues which still exist in this field.

In spite of all the participating researches working with biomimetic focus, this study tried to have comprehensive review over the criteria and classifications introduced by the main research scholars of this field. Within this investigation, it has been tried to gather all the information from literature and categorize them in a way which can be helpful for practitioners and researches for developing further successful solutions and designs based on biomimetic approach in order to achieve the main goal of sustainability in architecture. Such study can provide wider and clearer perspective towards most suitable biomimetic design criteria to be applied in building design.

1.2 Aim and Objectives

One of the promising approaches to achieve sustainability in architecture is biomimetic design approach. Thus, this study aims to present a review on researches done in biomimetic design field in order to gather the criteria and classifications introduced by researches and accordingly investigate and analysis the successful buildings designed by biomimetic approach as a sample study.

By presenting the gathered criteria this study aims to help designers to have more clear view towards biomimetic design definition, principles, criteria, and consequently hopping for seeing more successful building designs with biomimetic approach. With such result, the field of architecture can be one step closer to sustainability goal which now is vital if architects want to ensure that future generations enjoy a satisfactory quality of life.

Hence this study aims to;

- Present a study over the successful biomimetic designed buildings in order to highlight the approaches which can help sustainable architecture.

In order to achieve the main aim of this study, three objectives have been followed:

- Reviewing the meaning of sustainability in architecture, and its developments;

- Present and review the biomimetic design approach as a promising solution for sustainable development;
- Investigate biomimetic design approach criteria from the pioneers of this research field;
- Present a study over the successful biomimetic designed buildings in order to highlight the approaches which can help sustainable architecture

1.3 Research Questions

Throughout the literature review and samples study, this thesis tried to find answers for following question. The answers to this questions can smoothen the path for achieving the aim of the research

- What is the link between sustainable architecture and biomimetic design?
- What are the criteria and approaches for biomimetic design?
- What are the current successful cases and applied biomimetic criteria?

1.4 Research Methodology

This study is starting with descriptive methodology in order to carry out the theoretical part. In this manner, the literature review has been carried out based on the online source publications, books and article through the search engines such as google scholar, researchgate, Web of Science and etc. Hence with content analysis method this descriptive research aims to provide a systematic information related to main keywords of the study “sustainability” and “biomimetic design approach”.

Content analysis allows for a more objective assessment of a topic by summarizing any type of material by counting various components of the content. It also serves as a vital link between quantitative and qualitative research approaches. Although the approach has long been popular in the social sciences, it has recently piqued the curiosity of academics in a variety of sectors. This study's content analysis followed the established phases of this approach, which included first selecting the content to analyze, then generating a set of coding rules, coding the text according to the rules, and finally analyzing the findings. For this study the aim is to find out the biomimetic design criteria, thus, the content set as publications in the field by main scholars, the text been coded based on the biomimetic criteria and environmental sustainability and last result been presented as a table which includes the biomimetic criteria.

The content analysis method can be used in one of three ways: conventional, directed, or summative. To deduce meaning from text's content, all three methodologies are employed. For this study, a direct method to content analysis was used, the researcher constructs the initial coding scheme using current theory or a search before proceeding to examine the data in a directed content analysis, which is the same technique used in this study.

After gathering the literature review, the study continues as qualitative research for investigating the biomimetic design criteria from the pioneers of this field. Lastly, the chapter of samples study carries out within the comparative study, the gathered criteria will be studied through the successful constructed buildings based on biomimetic design approach. With this comparative study (criteria gathered from literature and successful examples in practice) it has been tried to give a wider view towards the current developments and condition of biomimetic design, and how this approach can be applied for future designs.

With the mentioned methodologies, this study has been formed within four chapter;

Chapter one is the introduction to the thesis. This chapter is giving the general introduction over the concept of sustainable development and selection of biomimetic design as the sustainable solution for this study. In this chapter the problem, scope, methodology and limitations of the research has been highlighted.

Follow to chapter one, chapter two of thesis is focusing on the literature review. Chapter two in overviewing the concept of sustainability in architecture, definition, design criteria, approaches and follow with focusing on biomimetic design approach for sustainable architecture. Thus, the definition, design approaches, solutions and design criteria of biomimetic design will be discussed. The main outcome of this chapter will be the systematic data gathering related to criteria for successful biomimetic design which will come from the pioneer scholars of this field.

Chapter three will have focus on sample study. In this chapter, 10 successful buildings design based on biomimetic principles chosen. Selected cases will be analyses based on the gathered criteria on chapter two. This analysis will give a wider perspective towards more suitable designs for achieving sustainable architecture goal.

Lastly, thesis will be finalized in chapter four by giving the last discussion, possible suggestions and hypothesis for further studies and conclusion.

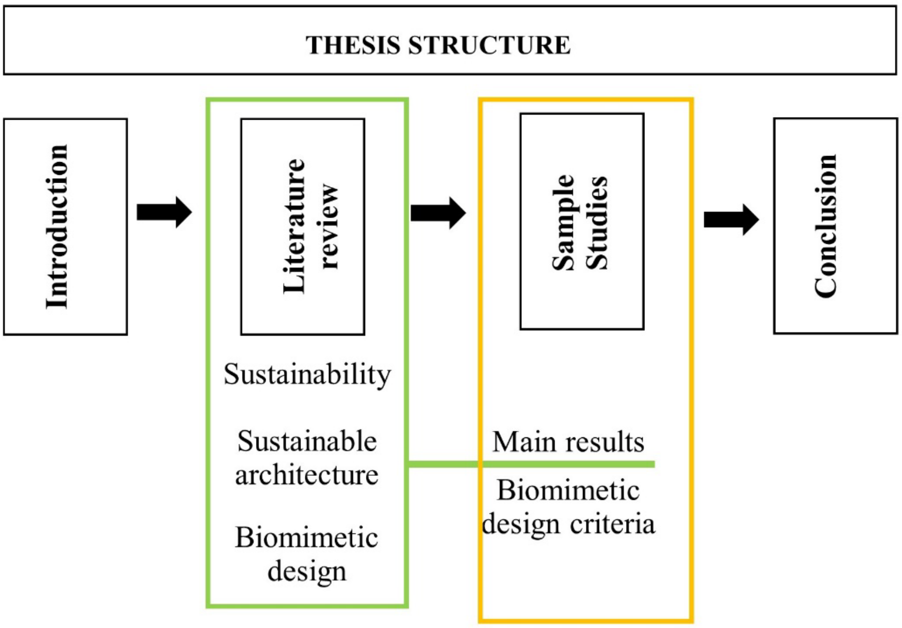


Figure 2: Thesis Structure (Author, 2021)

1.5 Limitation of Study

This study been developed under broad topic of sustainability, however sustainability is a very wide topic, thus, the study firstly been limited over approaches for achieving this goal. This study is focused on biomimetic design approach in the theoretical level. The theoretical aspect of this topic can cover many different branches, however, this study limited on presenting the principles and criteria of this approach in relation with sustainable architecture. In this manner, studies of pioneer researchers in this field gathered to present the link between sustainable architecture and biomimetic design approach. Thus, throughout this study, there is no intention for having quantitative study and proving the effectiveness of this approach over calculations. This data collection aims to give a perspective to architects to apply this concept in their designs if appropriate.

Although biomimetic design can effect on all pillars of sustainability (environment, social and economy), but in the second step this study has been limited on environmental sustainability, thus, the social and economic pillars of sustainability and their relation with biomimetic approach have fallen out of scope of this study.

In the last step, this study has been limited in the sample study by reviewing ten successful biomimetic design examples in architecture. Ten cases have been selected according to their different approaches towards application of biomimetic design and variety in locations which has been explained in detail in methodology of sample study chapter.

Chapter 2

LITERATURE REVIEW: BIOMIMETIC DESIGN APPROACH FOR ACHIVING SUSTAINABLE ARCHITECTURE

The term “sustainable” entered the consciousness of architects at the end of 20th century due to the energy crisis of 1970s and has since become an important concern in architectural discourse. In response to a spate of current worries about the implications of human activity, sustainable architecture is a new way of thinking about construction. In this light, the terms "green," "ecological," and "environmental" are labels that encapsulate the idea that architecture should fundamentally consider the relationship between buildings and their effect on the natural environment. The term "sustainable" is used to distinguish between architects who specifically refer to these problems and those who do not.

A building that is appropriate for its environment was once a successful architectural picture. A structure that shields its users from adverse weather and environmental conditions. But, more recently, this viewpoint has shifted, and the natural environment is now seen as requiring care (Brown, 2005).

Construction is critical to long-term growth not just because of its economic value, but also because the construction industry has a substantial influence on living quality, comfort, and health. Buildings consume the bulk of nonrenewable energy and emit a large amount of pollution, accounting for half of all CO_2 emissions, Nowadays, the construction task is to create cost-effective structures that improve quality of life while minimizing social, economic, and environmental impacts (Kamar et al., 2012). The task of achieving sustainability in architectural design is becoming more prominent these days.

Anyone interested in architectural construction in recent years faced with the word sustainability in some forms. Many people are unfamiliar with the term, and although there are a few meanings available, they just hint at how to apply sustainability standards in practice. Furthermore, it is important to comprehend the meaning of sustainability (Brown, 2005). The following sections in this chapter try to give a clearer perspective towards concept of sustainability.

2.1 Sustainability Definition

In order for a subsequent conversation to proceed with a thorough grasp of its relevance and meaning, the term "sustainability" in the framework of architecture must be defined. Sustainability is more than simply an energy-saving approach; it is a method that also considers environmental challenges. To create a sustainable building, all of the sources in any scale that go into it must be considered for example: materials, energy usage, passive and active design, etc., and of course an awareness of the needs of the users. Although there are many concepts of sustainability, it seems sustainability is more of a method than a range of predetermined ideas (Moore et al., 2017).

Within many tries, the idea of sustainability has been defined. Sustainable development can be described in a variety of ways and from various perspectives. The goal of sustainable development is to ensure that everyone enjoys a good quality of life now and in the future. This necessitates achieving four main global goals at the same time: (Ding, 2008).

- Social change that takes into account everyone's needs;
- Environmental conservation in the effective level
- Responsible use of natural resources;
- Maintaining strong and steady economic growth and job rate.

The basic principle of sustainability is to concentrate on environmental circumstances in order to create a product with the most internal environmental features feasible while limiting the negative consequences of these structures. Architectural designs must react to the climate from the design stage onwards if they are to reduce their exposure to nature (Ding, 2008). Figure 3, is presenting the three main pillars of sustainability.

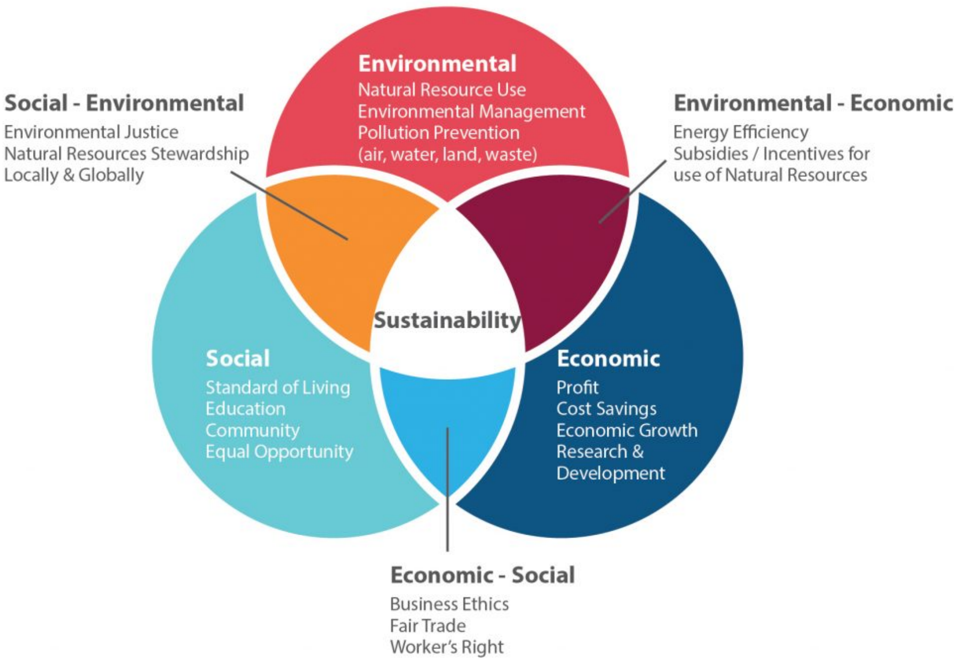


Figure 3: Three Main Pillars of Sustainability (Retrieve from: https://www.redalpi.com/web/sustainability/)

Within the literature review of sustainability concept, different definitions of this term has been introduced such as the definition developed in 1997 by Young as one of the first definitions for sustainability;

> Sustainability as a three-legged stool, with a leg each representing ecosystem, economy and society. Any leg missing from the 'sustainability stool' will cause instability because society, the economy and the ecosystem are intricately linked together.

Or conceptual definition presented by Johnston et al., 2007;

> the concept of sustainability to be used in the corporate community, developing the principle of triple bottom line. Triple bottom line refers to the three prongs of social, environmental and financial performance, which are directly tied to the concept and goal of sustainable development. They are highly interrelated and are of equal importance (Johnston et al., 2007)

However, the most used definition for sustainability, is the explanation given by Brundtland, et, al, in 1987;

"*sustainability is a development which meets the needs of the present without compromising the ability of future generations to meet their own needs*".

With same perspective as Brundtland, et, al, in 1987, American Institute of Architects, define sustainability for architecture as;

> In its broadest sense, sustainability refers to the ability of a society, ecosystem, or other ongoing system to continue functioning into the indefinite future, without being forced into decline through exhaustion or overloading of the key resources on which that system.

In some circumstances, the idea of sustainability can be achieved;

- the utilization of natural resources does not surpass their recovery rates;

- the rate of usage of nonrenewable capital does not surpass the rate of development of sustainable subtitue;

- The amount of pollution emissions should not surpass the environment's ability to absorb it. (Daly,1991)

2.2 Sustainable Architecture

There has been an increase in the amount of literature on sustainability in architecture in recent years. The basic principle underlying sustainability is to concentrate on environmental circumstances in order to create a product with the most internal environmental features feasible while limiting the negative consequences of these structures. If buildings are to limit their exposure to nature, they must respond to the climate from the design phase forward. The below are the goals of architecture sustainability: (Ding, 2008)

- Increasing human comfort
- A well-thought-out approach
- Designing for transition
- Reducing waste
- Reducing building costs
- Cutting down on building maintenance costs
- Preserving and enhancing natural qualities

In architecture, the term "sustainability" refers to the ability to envision future design and development. Sustainability encompasses not only human well-being, but also the preservation and conservation of the planet and its energy supplies. Sustainable architecture combines two goals: technological and human goals. The object of sustainable architecture was described by the International Council of Buildings (CIB) in 1994 as designing and inventing a safe artificial environment with an emphasis on ecological design and energy utilization. A sustainable building is one that has the least amount of incompatibility with the artificial and natural environments, which includes the building itself, the local ecosystem, the geographical environment, and the global environment (Zabihi & Habib, 2012).

In a broad sense, sustainable architecture reacts to and communicates with environmental and local situations, attempting to apply context ecological skills in order to create favorable environmental conditions; as a result, it is ecologically stable, indicating it causes the least impact of global harm while preserving flexibility and adaptability (Williams, 2007).

2.3 Types of Sustainable Architecture

Sustainable architecture that takes a holistic view and highlights current gaps. Taking into account that the term "architecture" has a broader definition that encompasses the building industry, government agencies, construction industry oversight, construction merchants, non-governmental organizations of architects, and so on. A dynamic relationship exists between architecture and three other disciplines: social, economic, and environmental. Following, the study examines the relationship between sustainable architecture and each of the sustainability pillars. Three forms of sustainable architecture are introduced through the various relationships: 1) Environmental sustainable architecture 2) Social sustainable architecture 3) Economic sustainable architecture (Asadi & Farrokhi, 2015).

2.3.1 Environmental Sustainable Architecture

On a global scale, architecture plays a significant role in climate change, resource scarcity, and waste. As a consequence, environmental preservation should be taken into account and given top priority. Environmental protection minimizes detrimental and irreversible consequences on the environment through making appropriate use of natural resources, supporting sustainable resources, and insulating the land, water, and air from pollution (Abidin & Pasquire, 2007). Natural resource mining is also a challenge for environmental preservation. Whereas architects have little influence over natural capital mining, they may assist to discourage it by mandating the use of less nonrenewable resources, more recycled goods, and energy (Roufechaei, et, al, 2014).

In order to be sustainable, building construction aspects must be taken into account. It is critical to attempt to humanize the urban environment by constructing buildings in harmony with their context and trying to communicate sense of location, based on an examination of basic functions and opportunities for versatility over time of buildings and their surroundings (Li, 2011).

Most architects lately believe that environmental design is an important part of their practice. However, not all of the projects that have been built have lived up to these expectations. On the other hand, few buildings lauded for environmental excellence have inspired architecturally, as carbon neutrality and usage control have often been favored over innovative architecture, living standards, and psycho-physiological wellbeing of occupants, reducing the architectural importance of the buildings made. A general absence of integrated technological expertise among architects has resulted in a discipline that is generally unprepared to tackle the significant paradigm shift involved in environmentally friendly architecture, with just a few exceptions. (Altomonte, 2009).

2.3.2 Social Sustainable Architecture

At a social level, sustainability has a significant impact, such as the potential to offer decent education, improve group consultation, and promote involvement in different fields. Major problems impacting the area, such as psychological distress, violence, and sociological exceptions, should be evaluated before implementing any effort to make an environment wealthier (Lombardi, 2001). Importantly, psychological quality of life takes both present and future users into account. This element is primarily concerned with human emotions such as protection, happiness, safety, and comfort. Architectural culture is a dynamic process that evolves over time as the thinking of each age shifts. For more socially sustainable projects and to prevent identity crises, designers should think about existing society, environmental elements, and design space. The first part of architecture is deciding what should be create (a cultural issue), and the second part is deciding how to build (a technological issue) (Parkin, 2000).

2.3.3 Economic Sustainable Architecture

From the standpoint of economic growth, sustainability concerns a broad variety of considerations at both the local and global levels.

Improved land efficiency and dependability as a consequence of lower maintenance and operating costs during the architecture's lifetime are the fundamental economic motivations for incorporating sustainability ideals. Integrating environmental values will also result in better living and working environments, as well as higher workforce satisfaction. Economic sustainability boosts profits by maximizing resource (human, material and financial) use (Zhou & Lowe, 2003).

In terms of economic viability, the building industry, on the other hand, must consider affordability, housing life cycle costs, renovation, market improvement, regulation enforcement, profitability, and risk control (Gloet, 2006).

As mentioned earlier in the “limitation of study” this study is focusing on the environmental sustainable architecture, thus the economic sustainability and social sustainability are out of the scope of this research. Although, some of the approaches and sample studies might meet the economic or social sustainability criteria as well, but they will not be discussed.

Following section tries to explore the main strategies of sustainable architecture, and briefly introduce the new approach towards sustainable architecture introduced to the field within last 50 years.

2.4 Sustainable Architecture Strategies and New Approach

In general, two major strategy groups have established sustainable architecture. “Passive strategies” and “active strategies” are two types of strategies, building solutions that are designed to respond to local climatic conditions in order to give the most comfortable inside atmosphere possible are referred to as Passive Architecture (PA) (Zaki et al., 2012). PA design strategies strive to keep the building cool by avoiding direct sunlight, promoting natural cross ventilation from the prevailing wind, and allowing plenty of natural light in. The passive solutions are focused on architecture approaches which should be addressed during the design process from the beginning. Active design strategies, on the other hand, rely on purchased resources (such as gas and electricity) to make buildings comfortable. These approaches make use of mechanical device elements such as air conditioning, heat pumps, radiant heating, heat recovery ventilators, and lighting systems. Electricity-generating technology such as solar panels (both electric and thermal), wind turbines, and other active solutions are also available (Ochoa & Capeluto, 2008). As a result, active strategies are focused on technologies and mechanics.

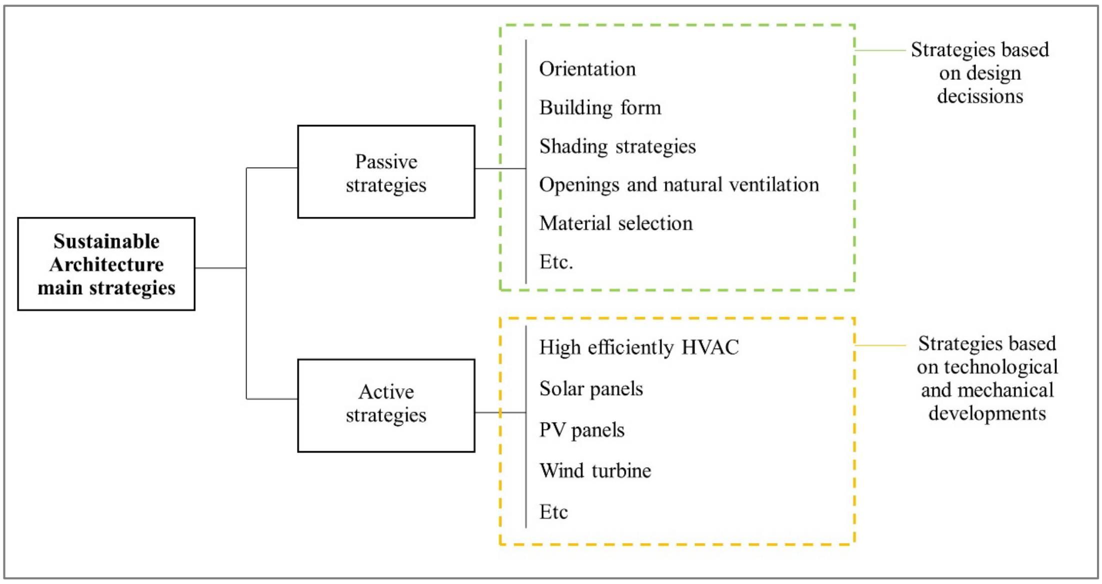


Figure 4: Sustainable Architecture Strategies (author, 2021)

Different terminologies of various approaches have been applied to the area of sustainable architecture within the framework and concepts of passive and active sustainable strategies, such as: “energy efficient design”, “responsive architecture”, “green design”, “eco-friendly” and etc.

Within the context of sustainable design, a new paradigm has emerged over the last 50 years. Whereas the essential notions of sustainable architecture remain the emphasis of this novel strategy, architecture has entered a new phase in which it has strived to exceed its specified bounds and has begun to think and operate alongside other fields. In this increasingly multidisciplinary age, it is vital to integrate several professions and subjects into the theoretical and practical realm of architecture. Mathematics, computer science, chemistry, social sciences, contemporary engineering issues, and other areas have had a permanent effect on architectural philosophy. Although many topics have an undeniable impact on architecture, biological science studies have gained the most traction, spurring on current study and experimentation in a variety of architectural subfields. Natural world and biology supplied a rigorous scientific and functional framework to planners and architects which confronted an essential need to adapt their techniques and refocus their aims in context of the continuous environmental degradation (Myers, 2012). With an emphasis on natural science and biology, this multidisciplinary period launched a new approach to achieving sustainable architecture. The "Biomimetic design approach," which is focused on perception, mimicking, and imitating natural processes, is a new approach.

Throughout this study, after highlighting the general understanding of sustainable architecture, its types and strategies, the focus will be on exploring biomimetic design approach as one of the newly developed and promising alternatives for achieving sustainability goal in architecture.

2.5 Biomimetic Design

The two words of bios and mimicry with meaning of life and imitate which come from Greek origin define the term biomimicry. Scientists such as Benyus in her researches defined this term as "conscious imitation of life's creativity." (Benyus, 1997). She and another prominent practicing architect, Michael Pawlyn, conclude that true ‘emulation' requires a thorough interpretation of the principle used by nature to accomplish that goal, rather than simply copying the natural form/shape.

Importantly, both have stressed the significance of such a possible best imitation, given that the world has developed in millions of years to develop the adaptations required to achieve the event (Singh and Nayyar, 2015) Nature is a never-ending great inspiration, with each organism unique and well-adapted to its surroundings. This modification has been passed down through the generations, passing the "survival of the fittest" test (El-Zeiny, 2012).

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."*

Biomimicry is a fairly recent field of applied science that looks to natural environments for guidance while developing new solutions to human problems. In the field of architecture, using nature as a "model" is widely accepted, particularly when it comes to conceptualizing new ways. The potential of biomimicry to have more sustainable and potentially even regenerative constructed environments is thoroughly examined.

Biomimetic design solutions can be generated within four steps in order to address human problems or needs.

- Adaptation type: what does nature do?
- Approaches: how is it carried out?
- Levels: what features are employed?
- Strategies: how can be employed in architecture? (Tabadkani & Roetzel, 2021)

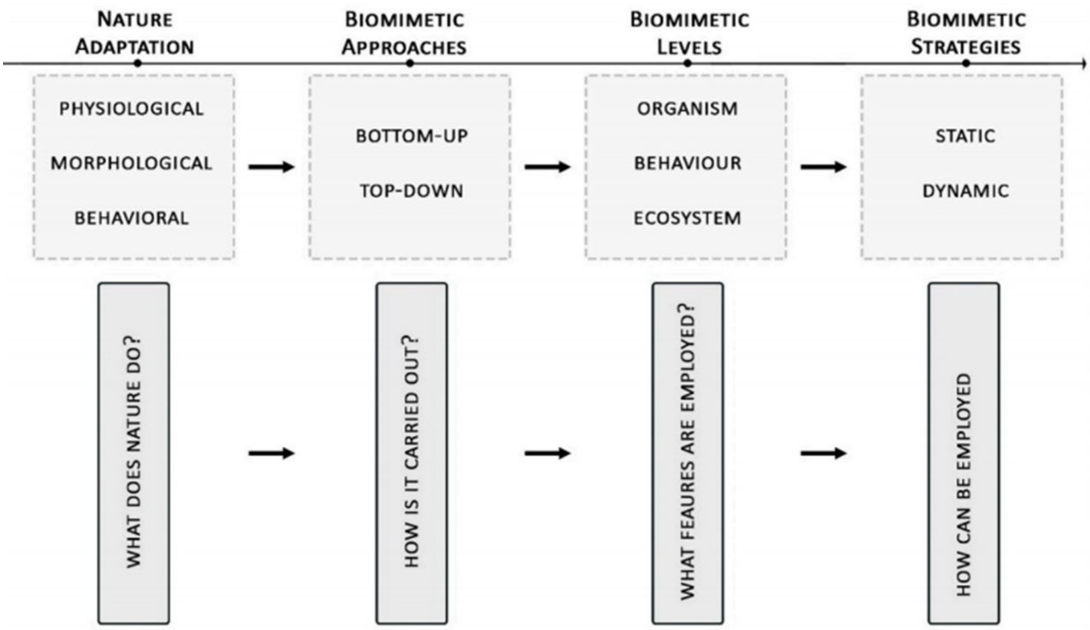


Figure 5: Development Steps of Biomimetic Design Solutions (Tabadkani & Roetzel, 2021)

In the following sections, after highlighting the definition of biomimetic design, the mentioned four steps will be explored in order to give a wider perspective towards solutions development for sustainable architecture by biomimetic approach.

2.5.1 Biomimetic Adaptation Types (Nature Adaptation)

Biological models adapt in response to changes in their natural surroundings. Morphological, physiological, and behavioral adaptations are the three categories of adaptations.

Physiological adaptations refer to a chemical reaction, whereas morphological adaptations refer to a physical structure. In other words, physiological adaptation is an internal bodily system that controls and maintains an organism's ability to exist in its environment. Temperature control, poison release, and other applications are examples. Behavioral adaptations refer to an organism's kinetic response to stimuli, or the way it behaves to improve its survival (Kuru, et, al., 2018).

Adaptation stages, which correspond to these traits, are used to categorize the different forms of adaptations. Each biological pathway is classified as either dynamic or static. Static systems lead to functional nanoparticles and surface segmentation patterns, dynamic processes, on the other hand, react to the occurrence of a transition or acceleration.

The biological functions of the barrel cactus can be used to illustrate the various forms of nature adaptations that have been discussed. The shrink motion of the cortex is described as a complex mechanism that supports heat loss and maintains water at a constant pace by serving a high surface to volume ratio. At the stage of the cactus' structure, the cortex motion is a morphological adaptation. The ribs' external surface arrangement creates the required shape for cortical motion. The barrel cactus' famous form is due to its ribs, which are vertical stalk structures. Although the depth and width between the ribs change through fluctuation, their quantity remains constant. Areoles and spines are structures that sit on top of the ribs. Areoles are spine-bearing devices that can only be found in humans. As a static mechanism, areoles and spines work together to produce a textured morphology that regulates heat and light through self-shading. They also improve airflow near the branch surface, creating a microclimate. Plants on the skin surface of the stem have microscopic apertures that exchange air, heat, and light in a chemical reaction to meet photosynthetic demands. They're physiological changes that happen as a result of internal chemical processes (Kuru, et, al., 2018).

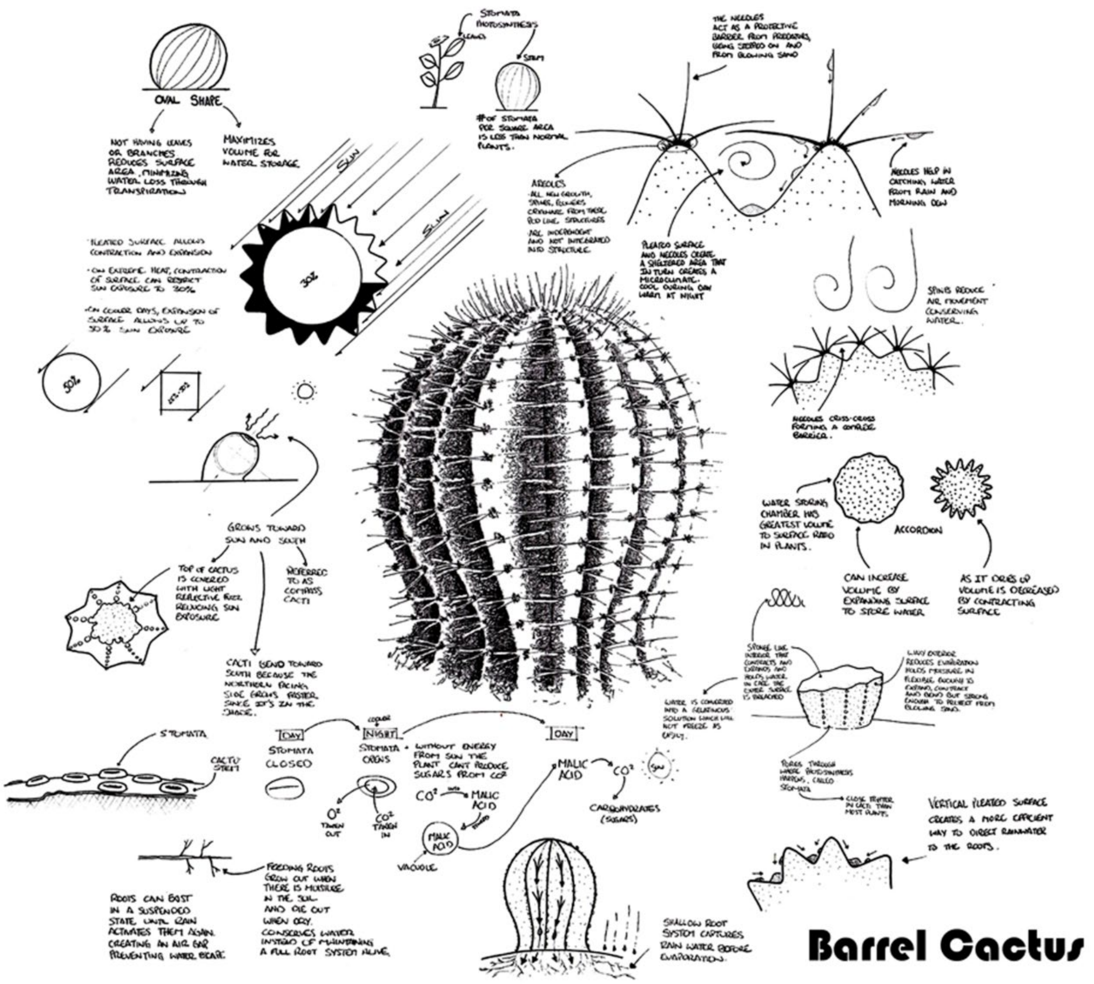


Figure 6: Barrel Cactus Natural Adaptation (retrieve from https://bouncingideas.wordpress.com/2011/12/14/learning-from-a-barrel-cactus/)

2.5.2 Biomimetic Approaches

Biomimetic design methods are divided into two groups: the first is referred to as "design looking to nature," and the second is referred to as "biology affecting design," and both approaches can be viewed as either a solution-based in other words top-down approach or a problem-based know as bottom–top approach, respectively (El-Zeiny 2012).

A shallow degree of translation occurs from design that is motivated by biology or follows a top-down approach (Zari 2010), as designers do not need in-depth science analysis experience, resulting in structures that imitate forms and only have a few mechanical features.

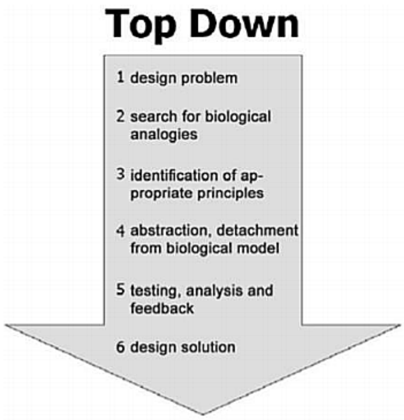


Figure 7: Top-Down Design Approach (Knippers, et al., 2012)

By replicating the aerodynamic and boxy form of the 'Ostracion meleagris,' the 'Bionic vehicle,' for example, is seeking to boost the volumetric capabilities of its prototype on a smaller wheel base. This method can be used as a turning stone to influence the building design in a sustainable manner, moving from "efficient" to "successful" over time (McDonough and Braungart, 2002). This shift from degenerative approaches to those that have regenerative flourishing potential in the ecosystem, according to regenerative architecture pioneers, cannot happen gradually, but rather by a grass-roots rethinking on how to do architectural design (Reed, 2007).

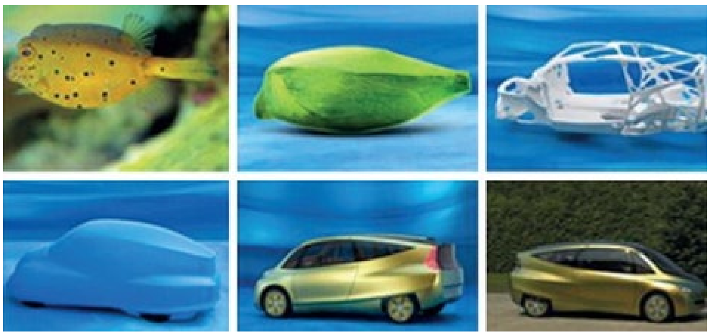


Figure 8: Bionic Car, Biomimetic Design with Top-Bottom Approach (Cuce, et, al., 2019)

Biology affecting architecture, also known as a bottom–top approach, entails a ‘biologist' counterpart at the very beginning of the process, as educated scientific science experience is to be used.

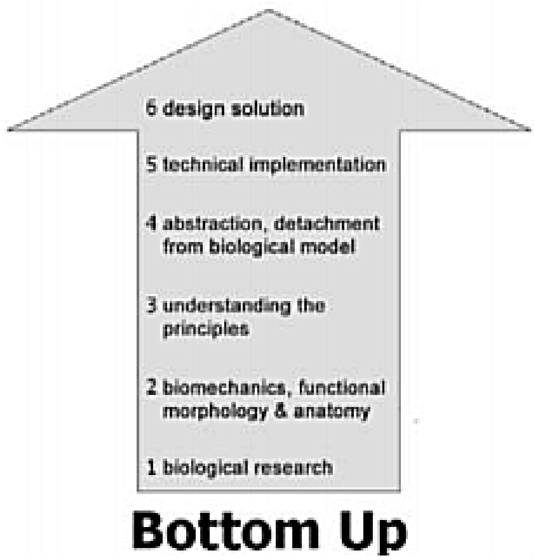


Figure 9: Bottom-Up Approach (Knippers, et al., 2012)

Multiple design ideas have resulted from the research of a 'lotus plant' and its outstanding self-cleaning characteristic, which allows it to emerge pristine in swamps, for example. The significance of this approach comes from the idea that evolution has the ability to affect humans in a variety of ways that extend beyond the limits of a single design challenge, resulting in previously unimaginable systems and alternatives. However, a significant model of the approach is rigorous applicable biological science and its novel adaptation to a design context. (Cuce, et al., 2019)

Figure 10: Lotus Plant Self-Cleansing Property, Biomimetic Design with Bottom-Top approach (Cuce, et al., 2019)

2.5.3 Biomimetic Levels

The organism itself, organism behaviors, and the ecosystem are three main categories of biomimetic levels. Structures are meant to imitate a single organism at the organism level. Continuing to study on this level without emulating how an organism communicates in a bigger context may not be enough to generate a structure that engages well with its settings. Buildings simulate how an organism reacts or interacts with its environment on a behavioral basis. In the other hand, buildings can imitate the natural form of the broader environment at the ecosystem level. Ecosystem principles state that ecosystems: (a) rely on sunlight; (b) maximize the structure apart from its elements; (c) are responsive to and forced to rely on local environments; (d) are diverse in modules, encounters, and information; (e) formulate long-term life conditions; and lastly (f) alter and evolve at multiple levels and velocity. To put it another way, an ecosystem is made up of a multitude of elements and processes that must operate together rather than against one another in order for the ecosystem to function properly. It is essential to obey the six concepts mentioned above in order for architecture to imitate nature on an ecosystem basis (El Ahmar, 2011). Following are few architectural examples within the principles of each mentioned biomimetic levels;

- In the level of organism, architecture is based on the organism's shape and/or functions, which are then applied to a structure. The Venus Flower Basket Sponge influenced Norman Foster's Gherkin Tower's hexagonal covering. This creature lives in an aquatic environment with strong water currents, and its lattice-like shell and circular shape help to disperse the stresses (Mesghali, 2010).

Figure 11: Example of Organism Level of Biomimetic in Architecture (Retrieve from https://www.researchgate.net/figure/Venus-Basket-sponge-left-Gherkin-tower)

- On a behavioral level, the structure mimics how well the organism interacts with its environment in order to build a structure that blends in without being seen. Mick Pearce collaborated with engineers from Arup Associates to create the Eastgate Centre, a huge office and retailing complex. To save money on managing the building's internal temperature, the project's architect studied African termite self-cooling mounds. The building lacks air conditioning or ventilation, depending instead on a passive cooling system influenced by African termite mounds. The structure, on the other hand, does not need to look like a structure of a termite mound to function as one, and instead draws influence from local Zimbabwean construction (Doan, 2012).

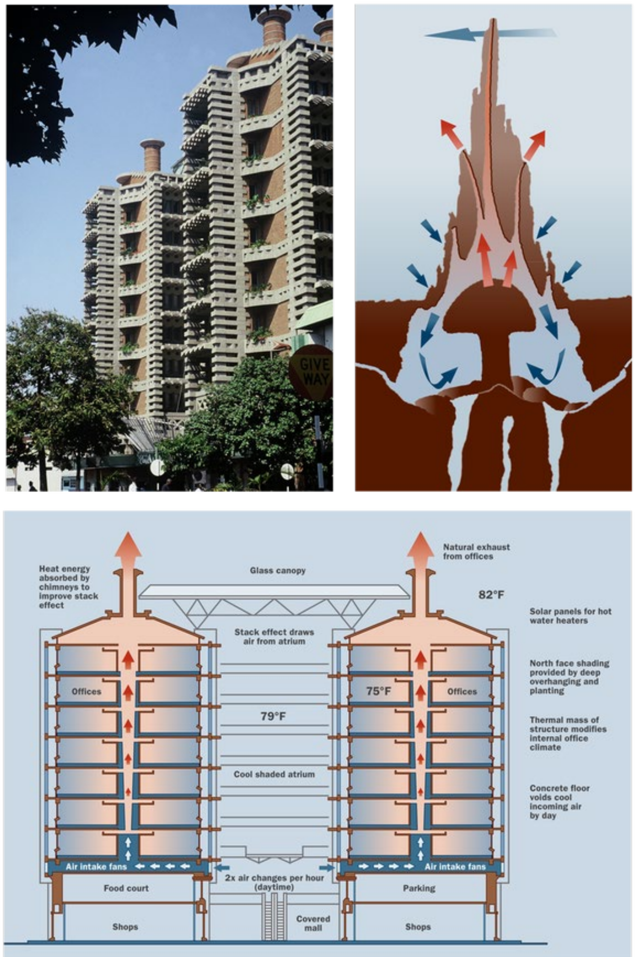


Figure 12: Example of Behavior Level of Biomimetic in Architecture (Retrieve from https://materialslab.wordpress.com/2015/11/26/learning-from-termites/)

- Building at the ecosystem level implies emulating how the environment's components interact, which is usually done on a bigger scale or as part of a larger initiative of various components rather than as a single structure. The Sahara Forest Project, planned by Exploration Architecture, is a greenhouse that seeks to act as a zero-waste system solely using solar energy.

Since the project's several elements function together in a cyclical environment, it is considered an ecosystem project. Exploration agreed to strike at the forest and desert borders to undo desertification after discovering that deserts used to be protected by forests. To fight climate change in an arid world, the project imitates the Namibian desert insect. It exploits the insect's ability to regulate its body heat by absorbing heat through the day and capturing water droplets that form on its wings at night. Evaporative cooling and humidity control are provided by the greenhouse structure using saltwater. During the night, the vaporized air compresses into fresh water, keeping the greenhouse warm. Because the excess water created by this process exceeds the demands of the inside plants, it is spat out for surrounding plants to rise. Solar power plants work on the principle that interactions are necessary in nature, allowing plants to survive in the shadow while gathering sunlight. The initiative is now in its pilot phase (Tabb, 2014).

Figure 13: Example of Ecosystem Level of Biomimetic in Architecture (Retrieve from http://www.solaripedia.com/13/370/5016/desalination_sahara_forest_project.html)

2.5.4 Biomimetic Strategies

Classification and arrangement of biophysical data is a difficult task, and a first method based on data collection is needed before applying natural solutions to architecture. The technique behind nature's adaptive response is one of the aspects and parameters. Dynamic mechanisms and static strategies are two types of strategies that may be classified. The macro and micro scales of these two basic methods are further split in these two categories.

Nature responds to environmental stimuli by motion (dynamic mechanism), known as tropisms or nasties, depending on whether the movement or reaction is based on the stimulus's position or direction. Static methods, on the other hand, emphasize multifunctional properties. Plants from dry and hot areas, for example, have varying adaptations to their habitat's harsh conditions. Plant interfaces may offer many solutions for different environmental factors, such as light reflecting or super hydrophilic surfaces (López, & Croxford, 2017).

2.5.5 Concept Generation

After a data collection to organize information from natural world and how they interact with their environment (based on all principles discussed earlier), a biomimetic design approach can be suggested. The approach leads to concept generation for biomimetic design. The suggested system for transferring biological data to architectural solutions and applications is depicted in Figure 14. Analysis, synthesis, evaluation, and implementation are the four steps of a biomimetic procedure from biology to architecture. The first three phases of this procedure can be performed as a basis for a future technology application. The framework is split into two major phases to explain how natural world concepts can be used to construct biomimetic design: the first is addressed to nature and how to define adaptation methods and processes in various environmental contexts. The second is about architecture and how to formulate and turn the chosen concepts into creative construction solutions. Stage of Nature is associated with more analytical and empirical ideas, and it is combined with a more deductive and imaginative stage in Architecture (Beesley, 2006).

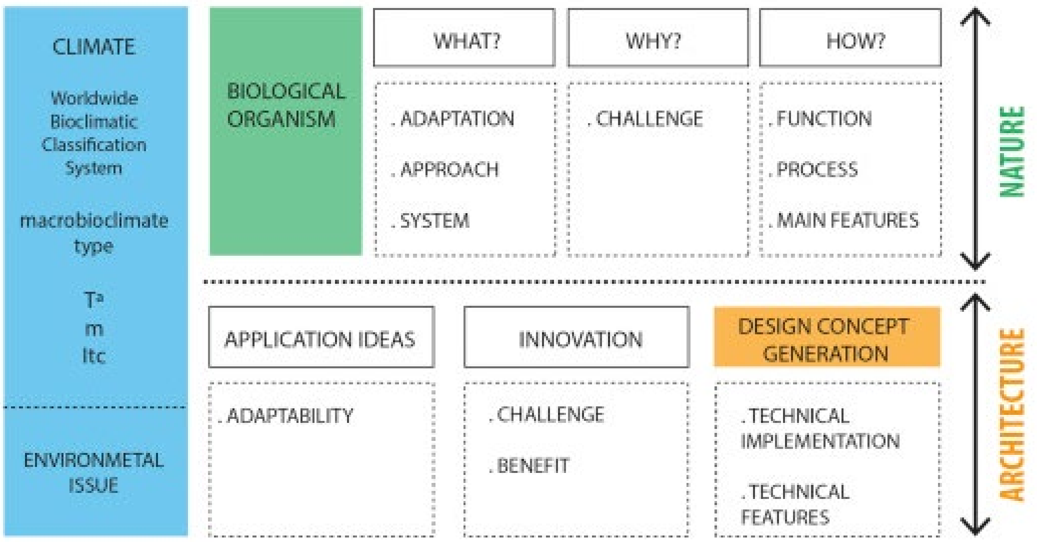


Figure 14: Framework for Concept Generation Based On Biomimetic Principles (López, & Croxford, 2017)

The first segment outlines research on distinct organisms and is organized around three main issues: what is nature's adaptation, why does nature have this adaptation, and how has nature evolved these specific capabilities.

The second phase is capable to abstract and translate the core concepts for environment adaptation into technological solutions and further applications for biomimetic architecture. Three key principles are used to address this stage: application ideas, innovation, and design concept creation. Adaptive facades (dynamic or static) are two examples of application concepts that indicate adaptability. Challenges derived from the environment's adaptations to their surroundings will boost creativity. As a result, innovative design concepts suggested which addressed some design challenges. Finally, because design model development is based on biological data, biological concepts must be translated into constructive concepts. Rather than being a straightforward translation, the resultant design description is motivated by study on the role, anatomy, and function of a given adaption. This exploratory phase will result in new ways (López, & Croxford, 2017).

2.6 Issues in Implementing Biomimetic in Architecture

Biomimicry is a current approach and evolving discipline of architecture that is being hampered by a number of problems. For example, biomimicry's advancement of engineering and technology is restricted to certain levels in order to move technical aspects from biology to architecture. Because of these drawbacks, the scope of research has been limited, reducing biomimicry's application to sustainable design. (Reap, et al., 2005). In a biomimetic perspective, nature has a variety of pathways and techniques that can be used. Obtaining a good biomimetic design, despite the fact that there are many varieties of biomimetic designs available, is extremely difficult in architecture. According to Lepora et al. 2013, the biggest disadvantage of biomimetic architecture is the lack of a consistent systemic approach; the lack of methodologies from the ecosystem's perspective restricts the supply of defined approaches and processes from the accepted frameworks. Current architectural styles that resemble nature are shape and morphology. However, such an advantage is rarely used to mimic natural structures, making it difficult to create a viable biomimetic design. According to Lepora et al. (2013), there are three barriers to biomimicry application in architecture:

- Study and selection of natural strategies

- Scaling problems when certain components run on specific scales Nano to Macro
- Conflict of integrated components of the architectural concept.

Royall, 2010 also stated several issues in implementing biomimicry, such as;

- It's difficult to separate the technique from simple problem solving and biomimicry, because it's always reduced to a linear process.
- The design method is largely reliant on computer software. The issue stems from the recognition disparity between machines and humans.
- Finding the best material for a system necessitates several of the physical examinations and geometric descriptions.
- The problem of determining the relationship between the elements,
- The management of ongoing assessment and feedback.

As a result, the key problem for implementing this technique in architecture is the practical application of biomimetic approaches.

2.7 Classifications and Criteria of Biomimetic in Architecture from Research Scholars Point of View

Architecture is a highly multidisciplinary fields that brought together a wide range of professions and disciplines at different dimensions and levels of complexity. Natural systems research has long been a source of design ideas. A biological approach is driving current research and innovation in a range of sectors, according to an examination of the intersections between biology and design. When utilizing biology's taxonomies to study the topic, various biomimetic methods in architectural projects are emphasized, and numerous scholars are currently involved with strategies to handle much more elements of this method (Gruber & Jeronimidis, 2012).

The previous sections of the thesis tried to give a general understanding over the principles of biomimetic approach, generating a concept for architecture based on those principles and also highlighted the issues which architecture field is facing in order to adapt and use biomimetic design. Beside the principles of biomimetic design (approaches, nature adaptation types, levels and etc.) the research scholars of this field introduced different classifications, criteria and characteristics for biomimetic design approach for sustainable architecture. This section of the thesis tries to gather the point of view of these scholars. Criteria discussed by main scholars of the field plus the general principles of biomimetic design can give a broader perspective over the concept of biomimetic and most suitable way to be applied in architecture.

2.7.1 Multi-Layered Characteristic of Nature

Prof. Dr. Peter Fratzl, as one of the leaders in the field of biological material science, has demonstrated via a number of papers that, a multi-layered is key aspect of natural systems. Precisely adjusted, and differentiated combination of fundamental components leads to structures with many interconnected functions (Dunlop and Fratzl 2010, Fratzl 2007). Such design ideas have seldom, if ever, been employed in architecture; if they have, it has only been in the most basic form. They can be classified as follows;

Heterogeneity: Natural structures are distinguished by the geometric distinction of their basic pieces. The use of digital design and manufacturing processes increases the geometric variation that can be accomplished in structures and makes natural topologies simpler to integrate into architecture. Natural structures are also distinguished by local modifications of physiochemical features.

Anisotropy: Fiber-reinforced materials have been used in variety of natural structures. Likewise, anisotropic fiber reinforcements are becoming more common in new high-performance materials.

Hierarchy: From the Nano- to the macro-scale, biological systems have a multi-level hierarchical system, with each degree composed of comparable chemical components but resulting in diverse and, to some degree, independent functional capabilities and adaptations. Building structures, on the other hand, demonstrate a totally different notion of hierarchy: they consist of a static system with components composed of various materials. In architecture, the natural idea of hierarchy is yet much investigated.

Multi-functionality: The change from mono-functional components to multifunctional material, for example the combination of sensors in adaptive structures, is the subject of current study. Architecture and technology have yet to discover systems that mimic natural aspects in terms of homogeneous texture and a diversity of purposes.

2.7.2 Categorization of Biomimetic Ideas to Be Applied in Architecture

Biomimicry affects architecture on several levels, similar to how biology inspires architecture. These levels may be divided into three categories: (1) form, (2) process, and (3) ecosystem. This technique is formalized by Zari (2007) for use in a design or architectural problem. The three levels stated above are reorganized and divided into sublevels, and how biomimicry is used to solve a design challenge is discussed. The study of Zari in 2007 became the foundation for many further studies.

Table 1: A framework for the application of biomimicry (Zari, 2007)

Level of Biomimicry		***Example - A building that mimics termites:***
Organism level (Mimicry of a specific organism)	*form*	The building looks like a termite.
	material	The building is made from the same material as a termite; a material that mimics termite exoskeleton / skin for example.
	construction	The building is made in the same way as a termite; it goes through various growth cycles for example.
	process	The building works in the same way as an individual termite; it produces hydrogen efficiently through meta-genomics for example.
	function	The building functions like a termite in a larger context; it recycles cellulose waste and creates soil for example.
Behaviour level (Mimicry of how an organism behaves or relates to its larger context)	*form*	The building looks like it was made by a termite; a replica of a termite mound for example.
	material	The building is made from the same materials that a termite builds with; using digested fine soil as the primary material for example.
	construction	The building is made in the same way that a termite would build in; piling earth in certain places at certain times for example.
	process	The building works in the same way as a termite mound would; by careful orientation, shape, materials selection and natural ventilation for example, or it mimics how termites work together.
	function	The building functions in the same way that it would if made by termites; internal conditions are regulated to be optimal and thermally stable for example (fig. 6). It may also function in the same way that a termite mound does in a larger context.
Ecosystem level (Mimicry of an ecosystem)	*form*	The building looks like an ecosystem (a termite would live in).
	material	The building is made from the same kind of materials that (a termite) ecosystem is made of; it uses naturally occurring common compounds, and water as the primary chemical medium for example.
	construction	The building is assembled in the same way as a (termite) ecosystem; principles of succession and increasing complexity over time are used for example.
	process	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and stores water for example.
	function	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilising the relationships between processes; it is able to participate in the hydrological, carbon, nitrogen cycles etc in a similar way to an ecosystem for example.

Later this category can be merged with other issues such as “Climate change studies”, “building physics”, “energy efficiency”, “Economic values” and so on. Reviewing the studies related to biomimetic with all the mentioned disciplines, can give a wider perspective towards criteria of biomimetic design.

2.7.3 Biomimetic Design Criteria in Respond to Climate and Ecological Design

Biomimicry provides criteria and solutions that experts in the built environment may use to adapt buildings to climate change, as Pedersen Zari addressed in her 2010 study "*Biomimetic design for climate change adaptation and mitigation*." Either the first or most frequent is to plan for severe climate change consequences on the physical environment. The second is a system-wide approach to modifying the physical environment to make it more adaptable and resilient.

- *Responding to the direct impacts of climate change*

There are numerous creatures in environment that effectively deal with the same challenges that the built environment will face as climate change advances. While climate change has a variety of affects that vary depending on where you live, there is a wide array of animals and ecosystems that successfully manage comparable difficulties. Overheating, high winds, for example, are all efficiently managed by species and ecosystems.

There are benefits and drawbacks to adjusting to the rapid impact of climate change. A delaying response to climate change consequences is desirable, particularly if the economic means necessary to investigate, develop, and test technologies are available. Yet, it necessitates specific data of the effects of climate change on a specific place, which is impossible to anticipate in many circumstances. One advantage of this technique is that technological and architectural solutions to direct effects may be transferable to other places with similar problems.

- *Systemic improvement of the built environment*

Ecosystems are often robust, and many can withstand infrequent rapid changes whilst allowing species to thrive. Nature 's adaptability to fast changes brought on by climate change, on the other hand, is difficult to anticipate (Walther et al., 2002) beside this, imitating nature can provide knowledge to understand how the architectural buildings can act rather like a system than collection of irrelevant entity, and as result making it more adaptable to change. The reality that nature are composed of species and systems in intimate connections is one feature that allows them to make successfully adapt to ongoing change. Enhanced power of resilience and the capacity of the entire system to respond to change are often associated with high variety in terms of these interactions between species.

- *Mimicking the process strategies of ecosystems*

Architects have an effective model for the future in terms of determining how systems in buildings or wider perspective, urban settings should be placed and operated by replicating natural process methodologies. Pedersen Zari and Storey undertook a comparative examination of information in the fields of ecology, biology, and biomimicry in 2007 to establish a collection of natural process approaches in order to exploit a border perspective of how nature operate. Despite the fact that many ecological aspects are ideal for architects to consider in the construction of regenerative built environments, natural traits that allow them to adapt are valuable in the face of climate change crisis.

- *Mimicking the functions of ecosystems*

Ecosystem functions, as defined by some ecologists, are the products and services provided by ecosystems that humans use. Human survival is dependent on ecological functioning. Whilst people may not be likely to substitute the now unrestricted natural ecosystems that have been utilized, Constanza et al. calculated in 1997 that if they were to be paid for in monetary terms, the cost would potentially be roughly twice the whole global national income potential. If a structure is to engage with existing ecosystems and promote health rather than degrade it by copying natural processes, designers can determine what the quantifiable ecological aims should be for that structure in a given region and climate. The architecture is well established to have a significant detrimental impact on key ecological functions (Graham, 2003). As the urban setting increases and the climate keeps changing, one method to mitigate this is to create constructed settings that replicate natural services, hence reducing strain on ecosystems. This is distinct from design methods or even process-level ecosystem biomimicry in that it goes above emulating nature as a representation, which might also easily be misinterpreted. Biomimicry at the function level, like process-level ecosystem aim creator for the development, with particular approaches to reach these objectives pulled from a variety of design methodologies. At the function level, ecosystem biomimicry establishes criteria to verify that the innovations or processes to be included in a growth are suitable in terms of total environmental effect.

The impacts of climate change that the building design is accountable for would be minimized, and the architecture would become more adaptive to climate change if these regenerated nodes established part of the built environment and began to fulfill even modest elements of ecosystem services. Following Table 2, is presenting the challenges of climate change in ecosystem process and the criteria of biomimetic design in order to respond to this issue.

Table 2: Biomimetic criteria to be consider in order to respond to climate change (author, 2021)

Challenge	**Level**	**Lessons from nature**	**Biomimetic criteria**	**Design proposals and techniques**
Climate change	**Process**	Usage of renewable energies	Renewable sources	Active and passive solar design
		Optimizing the system rather than component	Effectively transform energy. Materials should serve a variety of purposes.	Design for reduction and reuse
		Dependent on local conditions	Utilization of local materials	More robust local communities
		Diverse in components and relationship	Increase diversity to increase the resilience	Participatory design Ecological design
		Favorable to sustainable life	Production and functioning should	Life cycle analysis

		be environmentally being	
	Adaptation	Plan to allow constant change	Flexible design method
Functions	Proving service	Development should provide raw materials for futures	Green roofs, Vertical farms, Reuse
	Regulating service	Development should regulate climate where possible	Storage of Carbone in building structure, Living mechanism
	Supporting service	Development should contribute to renewal	Water recycling, cradle-to-cradle design, reuse techniques

2.7.4 Biomimetic Design Criteria in Respond to Building Component Design-Building Physics

- **Materials**

According to a 2005 research by John et al. titled "sustainable building solutions: a review of lessons from the natural world," biomimetic is at the crossroads of three disciplines and hence need knowledge from biologists, biophysicists, and material scientists.

Building materials must perform their intended purpose not just when they are first placed, but also for a reasonable amount of time beyond that. Their life span may be as long as the structure or for example paint only a few years before they need to be replaced. However, because a material's endurance or useable life is always related to the unique mix of components of the environment under which it is exposed, resilience should therefore be related to the unique circumstances. Most building materials have intricate physicochemical properties.

Since they do not grasp the ramifications, the chemical composition of materials is rarely significant to the material consumer or preprocessor. Nevertheless, a material's reactivity towards other materials and some components of the surrounding is determined by its chemical makeup. Some materials, for example, release chemical compounds, which have an impact on indoor air quality. To recognize the fundamental differences in the classifications and kinds of materials, the designer requires a basic understanding of chemistry. It's particularly notable because little modifications in content can have a huge impact on the qualities that arise.

It's customary to conceive of a material in terms of the actual unit in the overall structure, even if that component is a beam or a column, while designing structural systems. The engineering features are stated in the form of the base material, which is considered to be homogenous on a scale appropriate for the design. This way of thinking about a substance prevents comprehension of its behavior since the elements that govern the substance's reaction cannot be grasped at this size. It would be like attempting to predict the behavior of a steel bridge to a particular weight rather than being able to assess the tension in any individual member (Crawford, 1978).

It is required to consider about a material on a micro scale in order to comprehend its physico - mechanical behavior. An examination of fundamental biological materials, on the other hand, reveals the chemical components that organisms utilize to give the qualities required for specific mechanical activities. It's worth noting that they're quite few, significantly less than what's accessible to architects. They don't have any distinguishing properties, and neither of them have especially large Young's modulus, impact resistance, or durability when comparing to numerous technical materials. Although having substantially lower intensities than most, they cannot be classified as "high-performance materials." They are effective not really because they are result of how they are joined to function.

The University of Illinois has developed a synthetic material that can self-heal after being cracked, based on biological mechanisms in which injury stimulates an automatic healing process. This method has the potential to prolong the life of materials by two or three times. Smallest cracks on materials can cause both mechanical and electrical damage on polymer composite circuit boards, as a result, their ability to self-heal and restore structural stability may aid in their longevity. (An, et al., 2021).

In the industrial sector, re-materialization refers to recycling process that increases the value of materials by allowing them to be used more than once in high-quality products. This method provides a design approach for maximizing the favorable benefits of materials while also contributing to the Earth's rich material flow cycle.

It is an unavoidable reality that practically all load-bearing materials in nature are fiber combinations of some sort. The utilization of fibers in materials provides a lot of design freedom and flexibility, but it also comes with a few drawbacks. Fibers are most efficient when carrying pure tensile stresses, either as structures in their own right or as reinforcement in composite materials utilized as biaxial tension membrane structures. Both man-made and biological materials suffer from this issue. In Nature, there are four solutions available: Incorporate high-modulus mineral elements that are closely associated to the fibers to aid in the transmission of compression; change the flexural strength so that tensile stress does not impact along the fibers, and substantially cross-link the network infrastructure to increase lateral stability;

(Jeronimidis, 2000) Fibrous systems have more potential for better functioning since there is no obvious boundary among materials and structures.

Long-term experience with conventional materials allows for the estimation of the same material's behavior under comparable situations. Such tests have revealed how materials react the way they do. When novel materials are being created or conventional materials are being utilized in an untested environment, the capacity to anticipate is severely constrained unless the 'why' of previous experience, and hence the basic variables involved, is known.

Table 3: Biomimetic design criteria in material scale (author, 2021)

Component	**Properties**	**scales**	**criteria of Biomimetic material**
Materials	Chemical	Micro-scale	Durability
			Phase change
			Recycle
	Physical	Macro-scale	Flexibility
			Self-repair
			Shape-memory

- **Envelope**

Bio-inspired: Loonen in his work "bio-inspired adaptive building skin" in 2015 introducing some criteria and characteristic for biomimetic design, introduces the concept of bio-inspired design and tried to answer "how do living organism capture, concert, store and process energy, water and sunlight? With the aim to answer this question, he in explains three main criteria of biomimetic design in order to achieve sustainability goal by focusing on the building envelopes: “adaptability, multi ability, evolvability”.

Adaptability, as described by Fergison et al. in 2007, is a system's ability to offer intended functionality while taking into account many criteria under changing conditions, with design variables altering their physical value over time. The occurrence of non-simultaneous quality requirements gives rise to multi-ability. It contrasts from adaptability in that numerous criteria are met sequentially rather than simultaneously. Unlike traditional systems, which are built to meet a single set of requirements, it gives opportunities for the viewing variety of independently customized states Multi-ability encourages more effective utilization of resources. While adaptability is mostly concerned with short amount of time adjustments, evolvability is related to flexibility of the system. It considers the adjustments of the system in longer period. Evolvability, on the other hand, is viewed as a good side effect rather than a primary design goal; the ability to leave choices open maintains possibilities to respond to the changes as they occur in the future.

In the resent review study of Tabadkani et al. in 2021, the principles of bio-inspired or biomimetic envelopes studied in the practice, and some criteria and classifications added based on the performance of the system. In this study the motion of the envelop categories into two typologies. 1) basic movements 2) folding movements.

The first adaptable envelope typology is a multi-unit device, in which the envelope contains various shading units, each of which may be altered using one or more fundamental motion classifications. As a result, the design of a biomimetic envelope begins with a clear awareness of adaptable parts' movements. The most common kind of adaptability is rotational movement.

- Sliding motion that indicates a bi-dimensional form alteration
- A rotational motion that relates to a three-dimensional form alteration such as revolving, or swinging.
- Combination of both motions to produce more complex movements such as folding or rolling (Moloney, 2011).

Foldable structures to apply three-dimensional changes over the envelope, notably to counteract solar radiation, sunshine, and look out, are the second novel option for developing new generations of biomimetic envelopes. Bending methods may be used to create sophisticated adaptive geometries as well as reverse deformations. As a result, there are two methods for using folding structures as shading devices: origami and curved-line folding are two types of origami (Tachi & Epps, 2011).

Table 4: Biomimetic criteria for adaptive envelope (author, 2021)

Component	**Biomimetic criteria from nature**	**Biomimetic design suggestion**	**Element**	**Motion typologies**	**Types**
Envelope	Adaptability	Biomimetic adaptive envelope	Shading devices	Basic movements	Translational
					Rotational
	Multi-ability				Combined
				Folding movement	rigid origamis
	Evolvability				curved-line folding

- **Form**

Biomorphi: At every level, there is a clear and significant contrast between biomorphism and biomimicry when architecture is considered (Pawlyn, 2010). Some notable designers, such as Eero Saarinen, Antonio Gaudi, and others, have been experimenting with alternative methods to architectural design based on form seeking for centuries. Following the Industrial Revolution, natural sciences such as physics, chemistry, and particularly biology dominated both the practical and theoretical worlds. As a result, these significant breakthroughs, revolutions in the universe of thinking, were certain to influence architects. Several of them drew ideas for new metaphorical and unorthodox shapes from nature.

Surrealist and Art Nouveau works have influenced biomorphic design. Grefory Grigson, created the word "Biomorphism" in 1936, and it has existed as a style since then, using the power of computing to accomplish or imitate the free-forms observed in nature. It is also linked to scientific advancements, particularly in arithmetic, because fractal geometry can now describe natural geometry that cannot be described by Euclidian geometry. We can use this information to find forms since we can unroll nature's process of making envelope, and volumes. However, this sort of form-finding process overlooks one of the most important design engagement requirements: the intended outcome. A shape that seems like a living thing, but the function isn't compatible with this manner. As a result, it's important to consider if the outcome provides the answers that are necessary. Biomorphic design is a style that may be seen in many locations and at various erasGaudi built the famed La Sagrada Familia in Spain to replicate the natural world on an organism, quite like Frank Lloyd Wright spoke discussion of harmony amongst human objects and the natural environment.

Today, this mindset has moved to one that is more scientific and sophisticated in nature (Arslan, 2014).

- **Sensors**

In year 2000, Ivanov talked about the role of sensors in architecture and attaining sustainability. According to this research, the natural world is the ideal model for building sensors. Digital systems may now be found in a wide range of industries, due to the advancement of microprocessor electronics. Computational biology, artificial intelligence, and combinational chemical manufacture are just a few of the multidisciplinary disciplines that have sprung out as a result of new computer-assisted methods. Digital systems have largely supplanted analogue devices due to their high signal to noise ratio and low error coefficient. Those systems, however, lack the data capability of genuine biological sensors, which are completely analog. Biological sensors consistent efforts amounts of data in real time as they operate at the complex nature–animal interface. Biological sensors also have an unique capacity to perform several functions. The sensors in our fingers' tips aren't just touch sensors; they're also pressure and shape memory devices and understanding temperature.

Currently, building sensors are basic and far from multi-functionality. The combination of many sensors creates new opportunities for reducing bridge among sensors. By merging current technologies such as micro-electro-mechanical systems (MEMS) with thin-film technologies, sophisticated sensors for multi-functional applications may be built. Industry, on the other hand, may make use of such technology to create effective, long-term alternatives. If architects and developers want to modify their strategy for sustainability, the monitoring sensors in the Building Management System (BMS) may need to be raised to a quality equivalent to those.

Following table 5 is summarizing the architectural sensors according to biomimetic criteria.

Table 5: Architectural sensors based on biomimetic criteria (author, 2021)

Component	Natural example	Biomimetic criteria	Biomimetic architectural solution
Sensors	Biological sensors	Multi-functionality	chemical sensors
			adjacent sensors
			Advanced sensors

2.7.5 Biomimetic Design Criteria in Respond to Energy Efficiency

The three major characteristics of biomimicry, as stated by Benyus, have pushed the aims of attaining sustainability are: nature as mentor, nature as measure, and nature as model. Public buildings make for over a third of global energy usage, according to the International Energy Agency. As a result, lowering building energy usage is critical. thus, energy consumption has been dubbed "the most critical environmental issue." Energy-consuming systems can benefit from technological advancements that improve their energy efficiency. (Herring and Roy, 2007). Biomimicry has been recognized as a new architectural method for increasing energy efficiency in the same environment (Lurie-Luke, 2014)

Minimizing embodied energy (EE) and operational energy (OE) are the two basic techniques to lowering overall building energy usage. Nature appears to utilize low-energy processes, implying that there are various instances of biological species that may be investigated as a source of novel methods for lowering OE. In their work published in 2020, Imani and Vale emphasized a full list of universal thermal adaption techniques used by all sorts of plants and animals. This study's thermo-bio-architectural approach is a bio-inspired design tool for connecting thermal issues in buildings to applicable thermoregulatory answers in nature. It was created after a thorough assessment of the literature on natural species thermoregulation techniques. The goal was to obtain optimal categorization of biological thermoregulatory methods in order to find appropriate thermal adaption methods in a systematic manner, which may subsequently inspire prospective creative design techniques. Table 6 is highlighting the general biomimetic criteria related to energy efficiency.

Table 6: General biomimetic criteria and solutions for energy efficiency (thermal adaptive) (author, 2021)

Challenge	**General biomimetic solution**	**goal**	**Biomimetic criteria (actions from nature)**	**Some natural solutions**
Energy efficiency	Biological thermoregulatory solution	heating	Heat generation	Nesting
			Increasing heat gain	Shuttling, Light channeling, Orientation
			Decreasing heat loss	Hunching, Preening, Insulation
			Avoiding heat loss	Burrowing, Extracellular freezing
		cooling	Decreasing heat gain	Orientation, Compact forms, Reflective
			Avoiding heat gain	Shading,
			Increasing heat loss	Climbing, Thermal hyperpnea

2.7.6 Biomimetic Design Criteria in Respond to Economic Values

In 2002, William McDonough and Michael Braungart established a new technique based on biomimetic concepts for determining the effects of architecture on the nature while considering economic values. The goal of this technique is to move the focus away from the only pursuit of financial gain and toward identifying the worth of the environment and achieving equal results for humanity.

The triple bottom line has been and continues to be an effective instrument for incorporating sustainability to the corporate content. It has developed a novel metric of company performance by combining traditional economic aims with environmental and social issues. Nevertheless, a business strategy that is primarily concentrated on the bottom line might conceal potential for innovation and value creation in the development process. Improved sustainable design techniques can redirect research and development from a process oriented at reducing end-of-pipe liabilities to one targeted at developing safe, high-quality goods from the outset.

This novel design point of view results in triple top line growth: items that benefit nature and culture while also generating profit. The triple top line's design follows the rules of nature to provide industry with the resources it needs to create systems that produce wealth securely. Materials become nourishment for the land to industry in these new living societies. Value and quality are expressed in goods, methods, and facilities that are so ecologically smartly built that they leave footprints to savor rather than regret. When environmentally intelligent design ideas are widely used, both nature and commerce may thrive and expand (McDonough & Braungart, 2002).

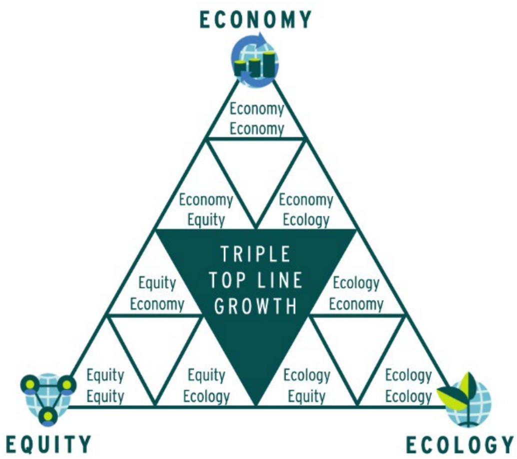


Figure 15: Triple Top Line Growth (retrieved from https://munichvp.com/introducing-the-triple-top-line/)

In order to find out the biomimetic criteria which can address the challenges in field of architecture, a study with the content analysis methodology carried out. Qualitative content analysis is one of numerous research methods used to analyze text data. Among three different approaches of contact analysis method “conventional, directed, or summative”, content analysis method with directed approach found most suitable (Downe-Wamboldt, 1992). With a directed approach, analysis of this study started with a theory and relevant research findings related to biomimetic approach as guidance for initial codes. After studying the biomimetic design approach in a wide context and understanding its definition, principles and purposes, the initial coding has been identifying in order to find out the biomimetic criteria and characteristics. In this manner, the researches done by main scholars of the field has been studied, the table 6 presents the main sources and their focus of study which used as the coding later. The main issues discussed by these scholars identified the main challenges and the criteria of biomimetic design to address them.

Table 7: Analysis of relevant research finding and initial codes

Studies of main scholars					
Researcher	year	Publication	Focus of study	Main codes	Biomimetic criteria
Graham Peter	2003	Building Ecology – First Principles for a Sustainable Built Environment	Climate Ecological factors Environmental impacts	• Climate • Environment • Ecosystem	Table 2
Pedersen Zari, M. and Storey, J.B.,	2007	An ecosystem based biomimetic theory for a regenerative built environment	Climate Environmental impacts		
Pedersen Zari	2010	Biomimetic design for climate change adaptation and mitigation	Climate change		
John, et al	2005	sustainable building solutions: a review of lessons from the natural world	Materials science	• Materials • Adaptability • Chemical properties • Physical changes • Behavior analysis	Table 3
Fergison et al	2007	Flexible and reconfigurable systems	Building Envelope	• Adaptability	Table 4
Loonen	2015	bio-inspired adaptive building skin	Building Envelope	• Envelope • Adaptability • Multi- ability • Evolvability • Shading • Bio-inspired	
Tabadkani et al	2021	Design approaches and typologies of adaptive facades: A review	Building Envelope	• Envelope • Shading • Biomimetic façade • Motion	
Pawlyn	2010	Biomimicry In Architecture	Building form	• Biomorphi • Whole building structure	
Ivanov	2000	Advanced sensors for multifunctional applications	Building sensors	• Advanced sensors	Table 5
Herring and Roy	2007	Technological innovation, energy efficient design and the rebound effect	Energy efficiency	• technological advancement • operational energy	Table 6
Imani and Vale	2020	A framework for finding inspiration in nature: Biomimetic	Energy efficiency	• Energy consumption • thermal adaptation • thermoregulation	

		energy efficient building design		
William McDonough and Michael Braungart	2002	Applying the Principles of Green Engineering to Cradle-to-cradle Design	Economy	• triple line top method

After analyzing the text from the main scholars of the files and based on their main research focus, the codes have been highlighter. Figure 16 is illustrating the steps of the content analysis with directed approach. From the main keyword of sustainability to all the codes which presenting the biomimetic criteria and characteristics.

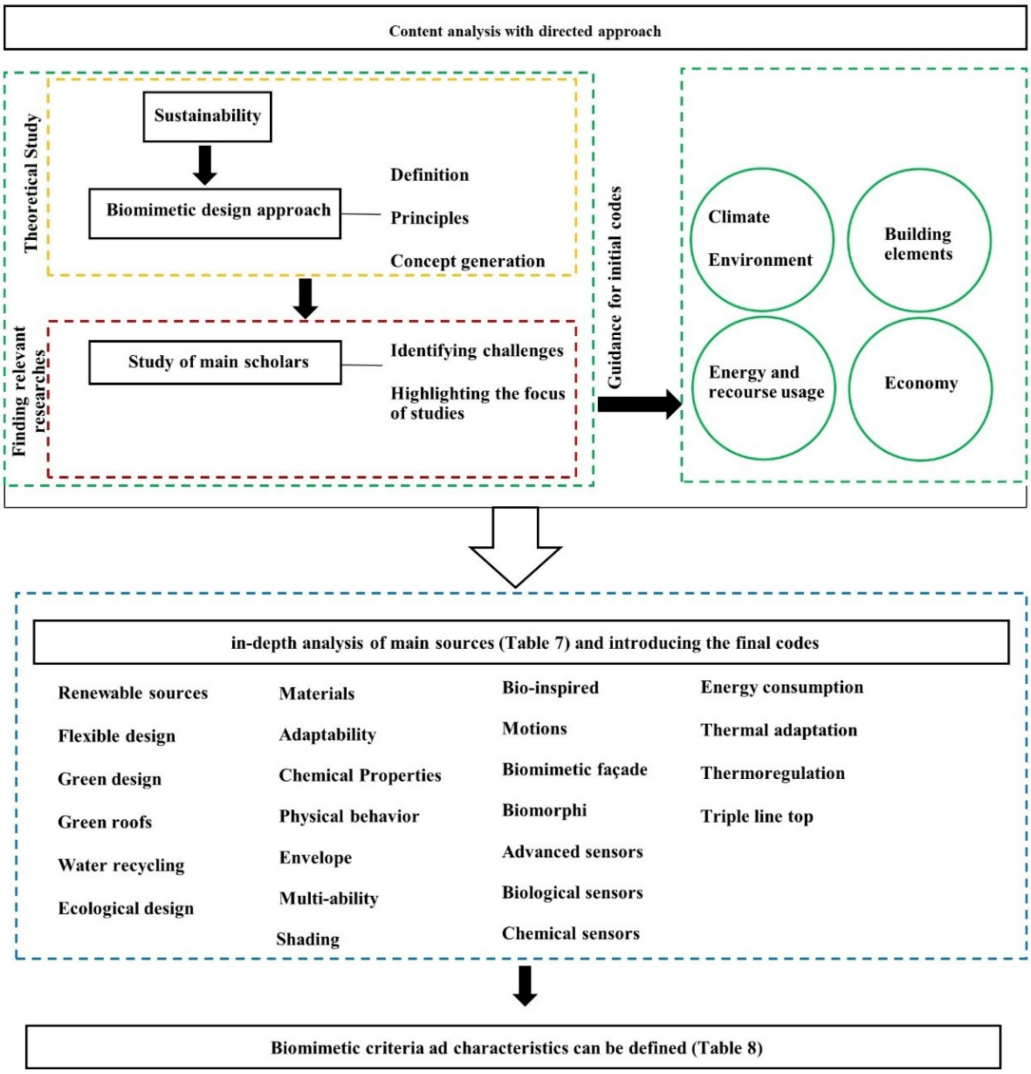


Figure 16: Description of Content Analysis with Directed Approach (Author, 2021)

As presented in figure 16 and table 7, based on the main scholars' researches the initial codes, and later the main codes been defined. This process helped the data gathering related to criteria and characteristics of biomimetic design approach in order to respond the problems in architecture. Table 8, presents the summary of all analysis and can be used as a guideline for designing successful buildings based on biomimetic design criteria and answer the main goal of sustainability in architecture.

Table 8 : Biomimetic criteria for architectural challenge (author, 2021)

General biomimetic characteristics

Level of Biomimicry		Example - A building that mimics termites:
Organism level (Mimicry of a specific organism)	*form*	The building looks like a termite.
	material	The building is made from the same material as a termite; a material that mimics termite exoskeleton / skin for example.
	construction	The building is made in the same way as a termite; it goes through various growth cycles for example.
	process	The building works in the same way as an individual termite; it produces hydrogen efficiently through meta-genomics for example.
	function	The building functions like a termite in a larger context; it recycles cellulose waste and creates soil for example.
Behaviour level (Mimicry of how an organism behaves or relates to its larger context)	*form*	The building looks like it was made by a termite; a replica of a termite mound for example.
	material	The building is made from the same materials that a termite builds with; using digested fine soil as the primary material for example.
	construction	The building is made in the same way that a termite would build in; piling earth in certain places at certain times for example.
	process	The building works in the same way as a termite mound would; by careful orientation, shape, materials selection and natural ventilation for example, or it mimics how termites work together.
	function	The building functions in the same way that it would if made by termites; internal conditions are regulated to be optimal and thermally stable for example (fig. 6). It may also function in the same way that a termite mound does in a larger context.
Ecosystem level (Mimicry of an ecosystem)	*form*	The building looks like an ecosystem (a termite would live in).
	material	The building is made from the same kind of materials that (a termite) ecosystem is made of; it uses naturally occurring common compounds, and water as the primary chemical medium for example.
	construction	The building is assembled in the same way as a (termite) ecosystem; principles of succession and increasing complexity over time are used for example.
	process	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and stores water for example.
	function	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilising the relationships between processes; it is able to participate in the hydrological, carbon, nitrogen cycles etc in a similar way to an ecosystem for example.

multi-layered characteristic of nature	
Characteristic	Explanation
Heterogeneity	natural constructions are characterized by a geometric differentiation of their elements
Anisotropy	fibre-reinforced composite materials
Hierarchy	multi-level hierarchical structure from nano- to macro-scale
Multi-functionality	multifunctional material systems

Biomimetic criteria for architecture in order to respond to sustainability challenges

Challenge: Building Physics

Component	Properties	scales	criteria of Biomimetic material
Materials	Chemical	Micro-scale	Durability
			Phase change
			Recycle
	Physical	Macro-scale	Flexibility
			Self-repair
			Shape-memory

Component	Biomimetic criteria from nature	Biomimetic design suggestion	Element	Motion typologies	Types
Envelope	Adaptability	Biomimetic adaptive envelope	Shading devices	Basic movements	Translational
					Rotational
	Multi-ability				Combined
				Folding movement	rigid origamis
	Evolvability				curved-line

Component	Biomimetic criteria	Lessons from nature
Form	Form finding method-**Biomorphi**	nature's way of creating edges, surfaces and volumes

Component	Natural example	Biomimetic criteria	Biomimetic architectural solution
Sensors	Biological sensors	Multi-functionality	chemical sensors
			adjacent sensors
			Advanced sensors

Challenge: economic value

New methodology	explanation
triple top line growth	products that enhance the well being of nature and culture while generating economic value

Challenge: climate change

Level	Lessons from nature	Biomimetic criteria	Design proposals and techniques
Process	Usage of renewable energies	Renewable sources	Active and passive solar design
	Optimizing the system rather than component	Transform energy effectively. Materials should have multiple functions	Design for reduction and reuse
	Dependent on local conditions	Use materials locally	More robust local communities
	Diverse in components and relationship	Increase diversity to increase the resilience	Participatory design Ecological design
	Favorable to sustainable life	Production and functioning should be environmentally benign	Life cycle analysis
	Adaptation	Plan to allow constant change	Flexible design method
Functions	Proving service	Development should provide raw materials for futures	Green roofs, Vertical farms, Reuse
	Regulating service	Development should regulate climate where possible	Storage of Carbone in building structure, Living mechanism
	Supporting service	Development should contribute to renewal	Water recycling, cradle-to-cradle design, reuse techniques

Challenge: energy efficiency

General biomimetic solution	Goal	Biomimetic criteria (actions from nature)	Some natural solutions
Biological thermoregulatory solution	heating	Heat generation	Nesting
		Increasing heat gain	Shuttling, Light channeling, Orientation
		Decreasing heat loss	Hunching, Preening, Insulation
		Avoiding heat loss	Burrowing, Extracellular freezing
	cooling	Decreasing heat gain	Orientation, Compact forms, Reflective
		Avoiding heat gain	Shading,
		Increasing heat loss	Climbing, Thermal hyperpnea

Chapter 3

BIOMIMETIC DESIGN SAMPLE STUDIES

For many years, environment has indeed been connected with architecture and has provided as a source of inspiration. Have also paved the way for the growth of many design movements and concepts. Biomimicry is an example of a concept that has inspired and led to the physical surroundings in the context of structures, ideas, and designs. Biomimetic is a strategy of overcoming human difficulties by studying and copying natural techniques, as detailed in depth in the preceding chapter. Environment is held up as examples, and a guide. Rather than replicating the structure exactly, biomimicry is widely used in architecture to create sustainable solutions by implementing the basic governing the design. It contains a wide scope of architectural issues, such as materials, structure, and design, among others.

This chapter of thesis, aims to analyze successful building examples which designed according to biomimetic approach principles. Throughout this analysis, number of cases will be introduced and investigate based on criteria and characteristics presented in chapter two, Table 8. It has been tried by studying the biomimetic criteria on the existing building samples, present a clearer view over the biomimetic design in practice of architecture which also might help practitioners designs in future based on biomimetic approach.

Selected buildings, are successful examples around the world with different functions. The biomimetic approach can be applied on different components and in different scale. The main focus of the study will be on the building physics and biomimetic criteria of chosen samples.

3.1 Sample Studies Methodology

After a wide research, for carrying the sample study for this thesis, ten successful biomimetic design cases have been selected. in order to address a wider perspective towards current development in this field, it has been tried to select cases which they have different approaches on application of biomimetic design in architecture. Cases utilizing biomimetic approach within different scales, from materials, to façade, envelope, form and the whole structure. In the other attempt, it has been tried to select cases within different climatic regions in order to present successful approaches for different climate characteristic. In this manner, this sample study can help architects to find suitable examples according to architectural and climatic challenges which they face.

In order to carry this sample study, each building has been reviewed related to the biomimetic principles applied in their design and later they have been analyzed according to the biomimetic characteristic and criteria which formulated in the previous chapter. In the end of the analysis of each case, it has been highlighted how the lesson from nature been synthesis to architectural approach. All the analysis has been gathered in a table as main result of this section.

3.2 Sample Studies

- **Council House 2, Melbourne**

Hansen Yuncken's Council House 2 (CH2) was Australia's first building to receive a six-star green design rating. Ever since completion in 2006, CH2 has influenced the local landscape and influenced architects all around the world.

Every component of the structure has been studied and revised from the ground up, resulting in new ideals based on the aim to be as loyal to the underlying "rules of nature" as practicable. The design concept focuses on creating suitable architectural solutions that are a clear and honest depiction of the dynamics interactions that nature employs in her own creations. This has ramifications for the building's architectural design as well as all of its very advanced engineering. The structure of this building has been subjected to a thorough reconsideration in order to make it more in tune with natural phenomena.

The building's exterior responds to external conditions by animating itself. This is the pinnacle of biomimicry: the structure moves and comes to life in reaction to its surroundings. Figure 17 depicts the adaptability of the building façade to changing environmental circumstances (Kennedy,2016).

Figure 17: CH2 Adaptive Envelope Design Based On Biomimetic Approach
(Retrieved from https://www.mickpearce.com/CH2.html)

CH2 is cooled by a precise control of the temperature differential between night and day air, similar to the concepts utilized in the design of Eastgate (inspiration from termites). In this scenario, motorized shutters made of repurposed wood are used to open up an entire side of the structure to direct airflow. This "night flush" removes heated air from the office and retail areas, allowing the concrete block above to cool down. Warm air rises to ceiling apertures, passes through empty floors to a vertical shaft, and finally reaches roof vents. For a portion of the day, this passive treatment is sufficient to keep the areas pleasant. Throughout the day, cool fresh air rises via floor registers (French and Ahmed, 2010).

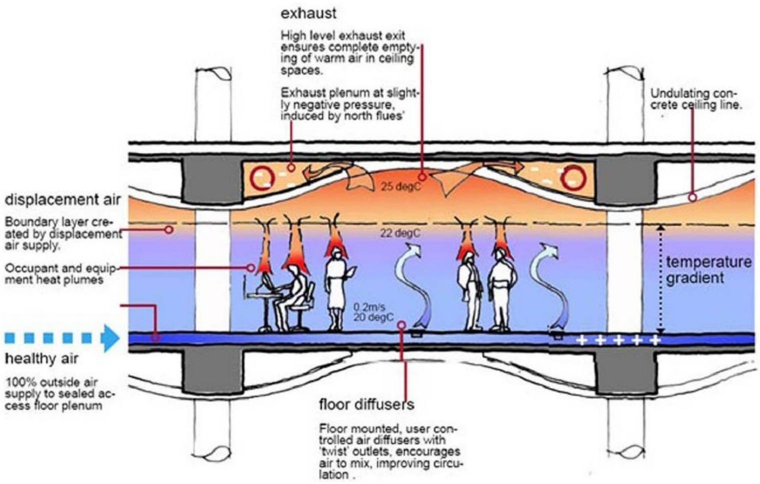


Figure 18: Cooling and Air Flow in The Building (Retrieved from https://www.mickpearce.com/CH2.html)

To condition the air in the structure, CH2 employs another temperature change of a fluid, water. Water is first "mined" from the city's sewage system, filtered, and then used to flush toilets, water plants, and condition the air. The AC water is piped down the exterior of the building through five 15-meter "shower towers", which produce evaporative cooled air for induction into the lower commercial rooms. The residual water is routed into basement storage and chilled using a phase change equipment before being distributed as needed. The phase change device is designed by 10,000 stainless steel spheres holding high-freezing-point (15 degrees C) salts that are frozen at nighttime and then utilized to cool water for circulation daytime, similar to how ice cubes chill your drink when they melt. The freshly cooled water is piped from the basement to cooled beams throughout the structure. When the impacts of the night scour have worn off, these beams are strung copper pipes that drip cold air down later in the day (French and Ahmed, 2010).

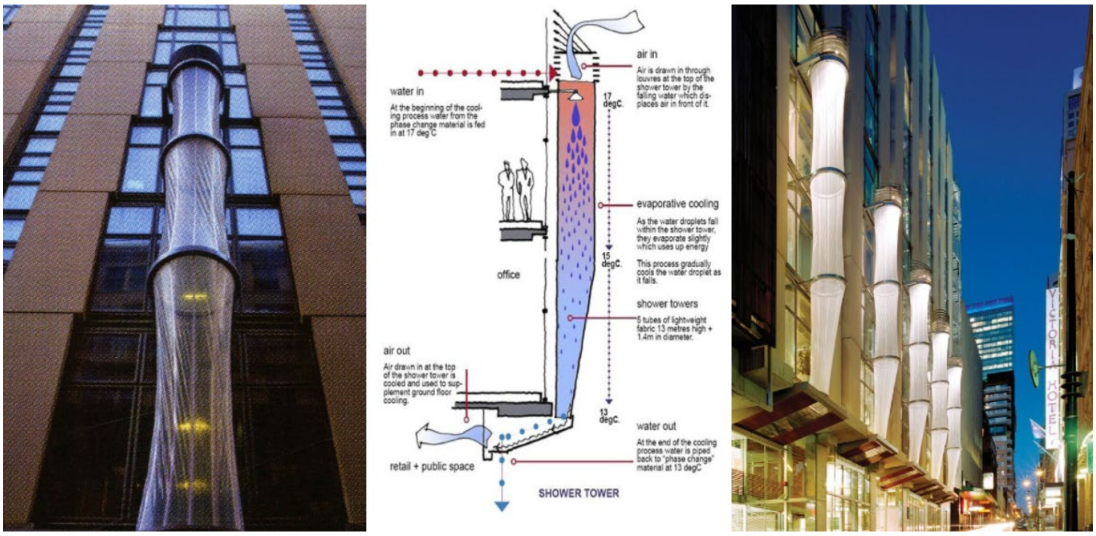


Figure 19: CH2 Water Re-Use System (Retrieved from https://www.mickpearce.com/CH2.html)

Analyzing the CH2 based on the biomimetic criteria shows that this building addressing biomimetic design approach within different levels;

- In ecological and environmental level building is using renewable resource technique by recycling water and use for different purposes,
- As an envelope design, by having an adaptive façade shading design controls the lighting load of the building,
- Usage of phase change materials for recycling process,

- By idea of termite's natural ventilation and heating/cooling system it controls the energy consumption of the building. usage of concrete as thermal mass helps this process as well.

Following Table 9 is presenting biomimetic criteria and characteristics applied in CH2.

Table 9: Summary of biomimetic criteria and applied solutions in CH2 (author, 2021)

Building name	Challenges	Lessons/ responds of nature	Biomimetic criteria	Solution in building
Council House 2	Climate and ecological design	Supporting service	Development should contribute to renewal	Water recycling
	Building components-materials	Adaptability	Adaptability Flexibility	Phase change materials to help water recycling
	Building components-envelope	Adaptability	Biomimetic envelope	Shading with basic movements
	Energy efficiency	Renewable courses	Thermoregulatory solutions	Thermal mass Natural ventilation

- **Milwaukee, Art Museum**

Calatrava's first structure in the United States is the Quadracci Pavilion. Its goal wasn't just to expand the Milwaukee Art Institution's area; it was also to give the museum a different style, with an incredibly modern white building that looks like a ship's prow sticking out into the sea. The white steel and concrete shape, designed as a standalone entity, is suggestive of a ship and contrasts the current assemblage in both shape and materials. A stunning dynamic structure, a brise-soleil with vents that open and close such as the wings of a giant bird, is featured in the pavilion. When the form is opened, it will become a symbol against the backdrop of the lake, announcing the opening of new exhibitions. The axis of a linear mast, inclined at 47 degrees and parallel to the neighboring bridge mast, serves as the pivot line for the slats. The Milwaukee Art Museum's architecture provides for possible upgrades on the opposite end of the Kahler building, offset yet symmetrical to the display facilities (Yetkin,2020).

Figure 20: Movement of Bird Wing Like Roof Structure- Form to Function (retrieved from https://inhabitat.com/amazing-calatrava-shade-pavilion-for-the-milwaukee-art-museum/)

This building is the great example of form to function in biomimetic design approach. The moveable, wing-like sunscreen that rests on top of the museum's Hall, opens and closes throughout the day like the wings of a bird.

Bio- inspired (Bird wings) ------ form to function ------ adaptive form ----- shading

Table10: summary of biomimetic criteria and applied solutions in Milwaukee Art Museum (author, 2021)

Building name	Challenges	Lessons/ responds of nature	Biomimetic criteria	Solution in building
Milwaukee, Art Museum	Building components- Form	Adaptability	Biomorphi: bird wing like roof structure	Shading with basic movements

- **Institute Du Monde Arab**

The Arab World Institute is amongst the most prominent Parisian landmarks due to its architectural excellence and the beauty of its interiors. Its construction started in 1980, with the Arab States and France working together to fund it.

Figure 21: Institute du monde Arab (Retrieved from http://www.archipicture.eu/Architekten/Frankreich/Nouvel%20Jean/Nouvel%20Jean%20-%20Institut%20Du%20Monde%20Arabe%201.html)

With its 240 mashrabiyas, the South façade has traditional Arab geometric motifs. Mashrabiyas are as precise as clockwork and as complex as a mosaic. They are both utilitarian and decorative, more of a screen than a wall. Natural light may be controlled using photoelectric cells and moveable apertures dependent on the amount of sunlight. The structure's adaptable façade is designed to seem like an eye's iris. The structure's exterior functions as an automated eye that dilates and closes in response to changing circumstances throughout the day, while the dynamic façade on the south preserves thermal exposure. This helps to regulate the amount of light that enters interior rooms while also maintaining thermal comfort (Öztoprak, 2018).

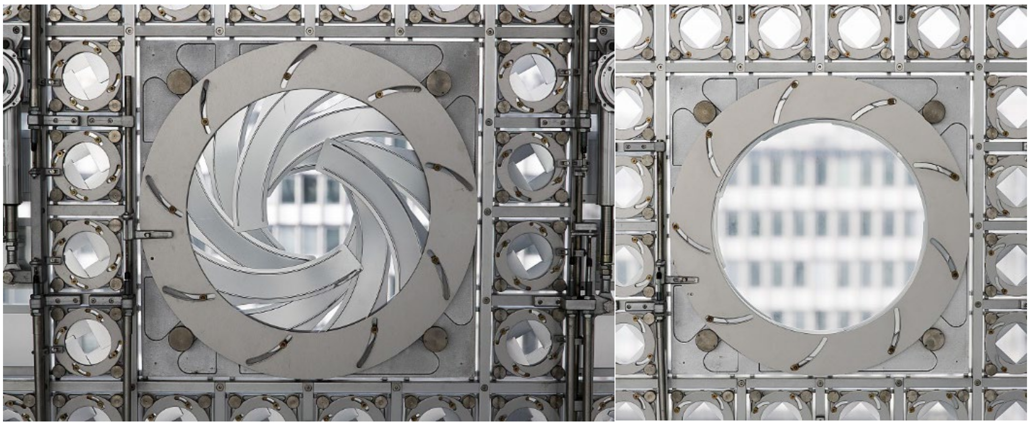


Figure 22: working mechanism of building envelope inspired from iris of the eye (Retrieved from https://www.imarabe.org/en/architecture)

Thus, the biomimetic criteria used in this building has been applied on the building component- envelope design. this building with the bio-inspired designed envelopes tried to manage the lighting load of the building and create a comfortable indoor environment for users.

The movements of iris of the eye sensitive to the light has been the inspiration for this design. this inspiration has been applied to the level of function and applied as shading techniques on the façade.

Bio-inspired (iris of the eye) ------- Adaptive envelope ------- Shading design

Table11: Summary of biomimetic criteria and applied solutions in Institute du monde Arab (author, 2021)

Building name	Challenges	Lessons/ responds of nature	Biomimetic criteria	Solution in building
Institute du monde Arab	Building components-envelope	Adaptability	Bio-inspired envelope	Kinetic façade-shading based on iris of the eye

- **Gherkin Tower**

The Gherkin, also known as 30 St Mary Axe, is a commercial high rise building situated in London, England. The famed architect Norman Foster designed it, and it was finished in 2003. It stands 180 meters tall with 41 storeys. Swiss Re, a reinsurance firm located in Switzerland, commissioned to create it. Because of its clearly identifiable pickle-like curving shape, the structure was named "The Gherkin." As it rises from the ground, the structure grows slightly outward before narrowing to a curved tip. This form maximizes public space at the building's bottom while minimizing wind swirl. The lenses at the peak of the panoramic dome is the sole curved piece of glass in the building, regardless of the fact that the whole structure is curved.

The Venus' flower basket sponge, a sort of glass sponge, served as inspiration for The Gherkin's construction. The sponge's lattice-like skeleton and spherical form offer rigidity and distribute stresses from powerful currents, allowing it to live at vast depths. A mesh of silica spicules provides structural stability to its body, which may flex at crossing places to absorb stress The sponge's empty "basket" is made up of this silica structure, which filters sea water for minerals. Flagella guide water upwards as it travels through the lattice. The Gherkin imitates the sponge's form and lattice structure in order to perform the same functions in air as it does in water. The building's circular form decreases wind deformations and generates exterior pressure differentials that power the natural ventilation system. In comparison to the geometric form of a standard office tower, air may flow more freely around the structure. The façade is surrounded by a lattice-like, diagonally supported framework that allows for an open floor layout without inside columns. The openness also allows for a lot of natural light to enter (Alberti et al., 2003).

Figure 23: Venus Flower Sponge as Inspiration of Gherkin Structure and Envelope (Retrieved from https://en.wikipedia.org/wiki/30_St_Mary_Axe)

The main construction of the building is an aluminum cast steel diagrid framework, which was influenced by the hexagonal skin of the Venus flower sponge. WSP Cantor Seinuk describes Yoram Eilon, vice president of The Diagrid structure as "a succession of triangles that merge gravity and lateral support into one, resulting in a stronger, more efficient, and lighter building than a normal high-rise." The Diagrid creates a vertical cantilever by dividing the tower height into a number of modules. The Gherkin was built with natural ventilation and the ability to "breathe" like a lung for long-term sustainability. Gaps in the flooring enable natural ventilation by cycling air between floors. On each floor, there are six of these atria, which span numerous floors at once and are built in a diagonal lattice pattern. On the sixth storey, there are just a few interruptions as a firebreak. The air trapped between an additional layer of glass in the double-skin façade creates a double glazing impression, secures the office space through passive heating and cooling, and gives the appearance of double glazing. Because to the building's natural ventilation and insulation, it uses half the energy that a similar-sized skyscraper would (Bengani, 2015).

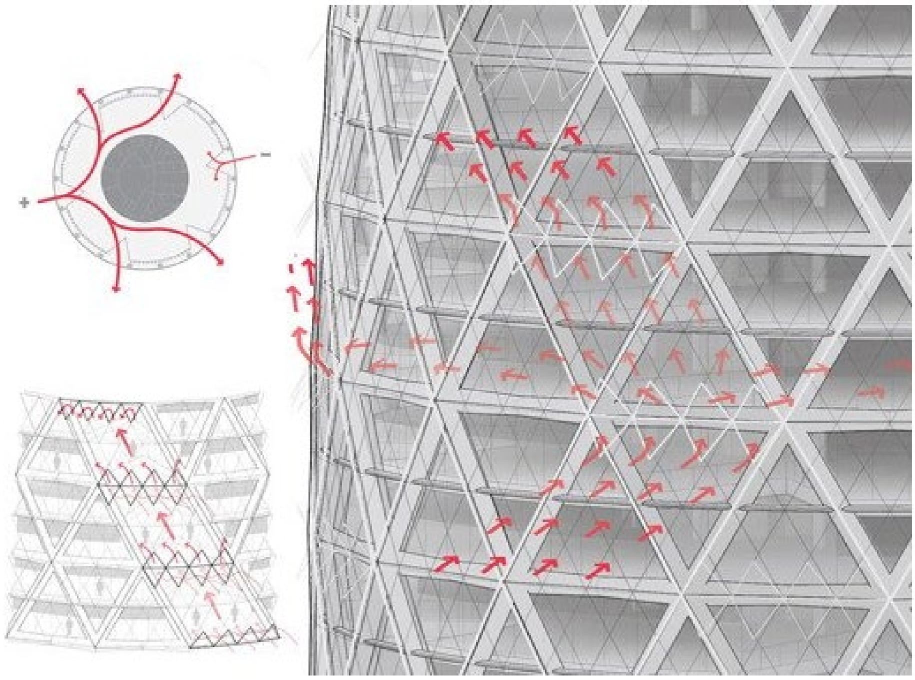


Figure 24: Air Flow and Natural Ventilation (Retrieved from https://www.fosterandpartners.com/projects/30-st-mary-axe/#drawings)

Thus, to sum up this building in the organism level of biomimetic, got inspired from the structure of Venus flower sponge and used the same technique in order to be resistance to wind pressure. This bio-inspired designed applied on the structure and envelope of the building, makes this design one of the successful sustainable design examples.

Table 12: Summary of biomimetic criteria and applied solutions on The Gherkin (author, 2021)

Building name	Challenges	Lessons/ responds of nature	Biomimetic criteria	Solution in building
The Gherkin	Building structure and envelope Heating/ cooling	Flexibility and durability Organism form	Bio-inspired structure Bio-philic	The structure inspired by Venus flower sponge use the same durability in front of strong wind flow Natural ventilation

- **The Eden Project**

The Eden Project is a tourist destination in Cornwall, England, in the United Kingdom. The facility is characterized by two massive shelters, each of which resembles a natural biome and is made up of interconnecting domes that host thousands of plant varieties. Geodesic tubular steel domes support hundreds of ethylene Tetrafluoroethylene (ETFE) blown hexagonal and pentagonal cells in the biomes. The first biome is modeled like a rainforest (and is the world's largest indoor rainforest), whereas the second biome is modeled after a Mediterranean climate. The property also features an outdoor botanical garden with numerous indigenous plants and species to Cornwall and the United Kingdom in general, as well as other plants with interesting backstories, such as those with a long history (Pawlyn, 2019).


Figure 25: The Eden Project (retrieved from https://www.edenproject.com/eden-story/behind-the-scenes/architecture-at-eden)

The air pushed into the ETFE layers enhances the insulation level without reducing the light's quality as passing via the material. The quantity of air seen trapped amongst layers may be adjusted; for example, in the winter, the pillows are filled with more air to boost insulation, and in the summer, they are slightly compressed to allow for more cooling in the room. The pillows are designed to simply remove from the steel frame, allowing them to be exchanged whenever a more suitable material becomes available. The geodesic dome form has the benefit of easily adapting to most ground surfaces. Other advantages of using inflated ETFE, a light and sturdy material (one percent of the weight of double glazing), include a lighter steel frame, greater sunshine and it expenses 1/3 less than the typical glass option. The completed construction is lighter than the air it holds (Pawlyn, 2019).

Figure 26: ETFE Pillows (retrieved from https://www.edenproject.com/eden-story/behind-the-scenes/architecture-at-eden)

To sum up Eden project in the level of eco-system is applying biomimetic criteria to architecture. This project by using advanced martial (ETFE) imitating a biomes structure with inspiration from bubbles which can allow more light inside the building while keep the structure light. With this method artificial environments have been created which allows different plant kinds grow in UK.

Table 13: Summary of biomimetic criteria and applied solutions on Eden project

Building name	**Challenges**	**Lessons/ responds of nature**	**Biomimetic criteria**	**Solution in building**
Eden project	Building structure	Eco system working mechanism	Bio-inspired structure Advanced materials	Usage of ETFE and geodesic dome which allow the light weight structure plus the extensive amount of light

- **BIQ House**

The BIQ House was built in 2013 in Hamburg, Germany, which has a cool European climate. The building has 15 apartments on four levels and a rooftop level, ranging in size from 50 to 120 square meters with a gross floor area of 1600 square meters (Buildiup, 2015). In a low-energy residential structure, integrated photo-bioreactors in 120 panels installed on the envelope create algal biomass and heat as renewable sources of energy. The algal façade panel system offers a thermally regulated microclimate, noise reduction, and dynamic shading around the building (Arup, 2016).

Figure 27: BIQ House (retrieved from https://www.bagarquitectura.com/biomimicry-architecture-examples/)

Fresh water algae are used in the windows of this home. When the light shines through the windows, the algae create biomass, which turns into Biogas, which is then delivered to a fuel cell. The BIQ is the first residential building to fully achieve algae power enthusiasts' hopes. Glass-plated containers of suspended algae cover the building's two sun-facing faces. To avoid the organisms from settling on the glass and decomposing, pressurized air is fed into the system, providing them carbon dioxide and nutrients while moving them around—creating the lava lamp effect. Scrubbers remove any stuck biomass, allowing the remaining algae to complete photosynthesis with more sunlight. Algae is harvested, mashed into biofuel, and burnt in a local generator to generate electricity on a regular basis. Excess can be traded for food supplements, used to generate methane for external power sources, or saved for later use. As a consequence, the structure is shaded from summer heat by algal flora, insulated from street noise, and has the ability to generate enough energy to support itself. As a consequence, the structure is shielded from summer heat by algal vegetation, insulated from street noise, and has the ability to self-generate enough energy to power its own excavators, heat, and electricity (Elrayies, 2018).

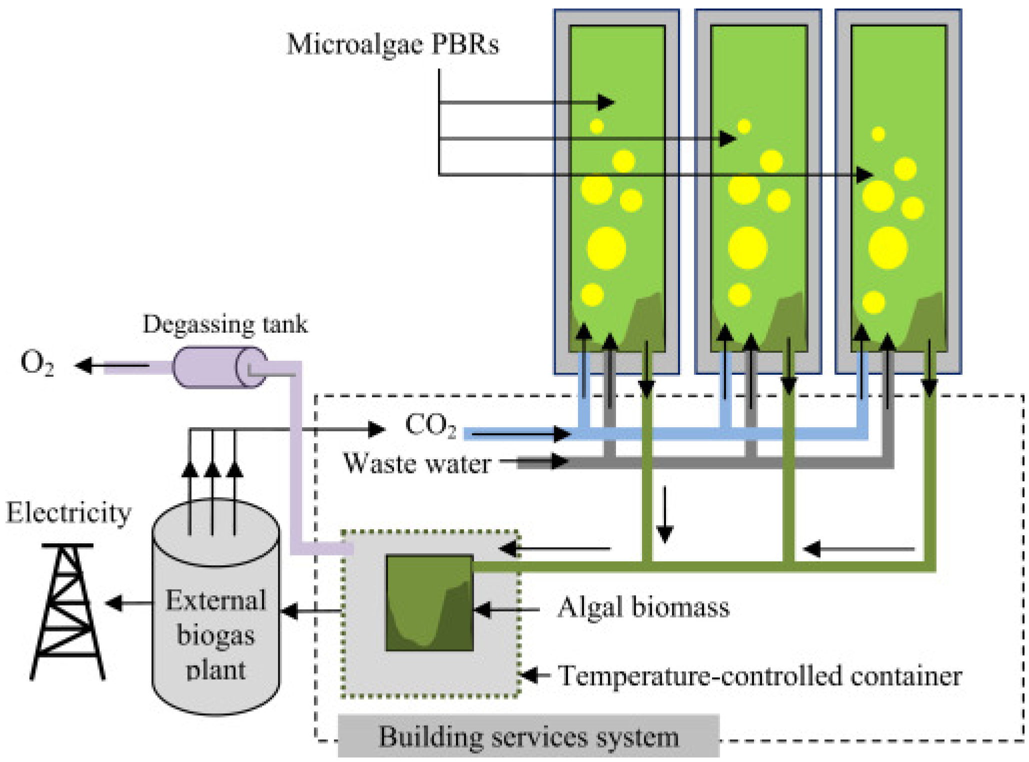


Figure 28: Working Process of Algae Power Produce (Elrayies, 2018)

Thus, this building by having different approach responding to sustainability with biomimetic approach. In this building the working mechanism of the façade designed by integrating nature (algae working mechanism). With this approach, designer learned from natural world solution toward energy efficiency, but not only imitate the idea but used the natural element in their design. so, in this design the algae located in the tank on the façade, help energy production for the building and can be used as shading devices.

Table 14: Summary of biomimetic criteria and applied solutions on BIQ House (author, 2021)

Building name	Challenges	Lessons/ responds of nature	Biomimetic criteria	Solution in building
BIQ House	Energy efficiency	Algae working mechanism	Energy production, heating	Use of algae in façade which reacts to sun direction and produce energy+ shading

- **Thematic Pavilion Expo 2012**

This structure, which won first place in an open international competition in 2009, is adding life to a new boardwalk within a former industrial waterfront. It's most famous for its fish-like appearance, which is the result of a cutting-edge envelope technology constructed of glass fiber reinforced polymers (GFRP) that can be molded into a variety of dynamic designs a research study at the ITKE University Stuttgart investigates how biological movement mechanisms might be implemented at an architectural scale prompted the integration of moving lamellas into the building's surface. It was created in collaboration with Knippers Helbig Advanced Engineering in order to provide forward-thinking ideas to the general audience (Lienhard et al., 2010).

Figure 29: Thematic Pavilion Expo 2012 (Knippers et al.,2012)

A novel sort of dynamic façade system inspired by flexible deformation principles inherent in plant motions is featured in this building. The project serves as a paradigm for enhanced biomimetic research and design, as well as a unique use of glass fiber reinforced polymers (GFRP) for deployable structures. The use of GFRP permits for massive and repeatable elastic deformations, allowing us to consider changeable structures in a whole new light.

The envelope is 140 meters long and 3 to 13 meters high. It is made up of 108 kinetic GFRP vents that are held in place at the top and bottom by permanent supports on one edge and extensible operators on the other. These operators press the top and lower edges together, causing the GFRP piece to bend and rotate to the side (Schinegger, et al., 2011).

The movable louvers provide a climatic purpose and can be operated in a variety of ways specific to the needs of the user. The louvers are separately operated and make an animated behaviors pattern along the façade within the control strategy. The choreography that could be used varies from subtle local motion to large-scale waves that affect the entire length of the façade (Knippers et al.,2012)

Figure 30: Movement of Louvers on Façade (Knippers et al.,2012)

Table 15: Summary of biomimetic criteria and applied solutions on Thematic Pavilion Expo 2012 (author, 2021)

Building name	Challenges	Lessons/ responds of nature	Biomimetic criteria	Solution in building
Thematic Pavilion Expo 2012	Building physic and energy efficiency	flexible deformation principles found in plant movements	material usage adaptability	of glass fiber reinforced polymers (GFRP) for deployable structures kinetic movable louvers

- **Esplanade Theater**

The building is a performing arts center in Singapore's Downtown Core, near the Singapore River's mouth. It comprises of a music hall that seats around 1,600 people and a performing arts theatre that seats around 2,000 people. It is named after the surrounding Esplanade Park. Construction of the building which cost 600 million SGD, completed in 2001 and opened to public in 2002.

Figure 31: Esplanade Theater (Retrieved from: https://www.modlar.com/photos/9746/esplanade-theatres-on-the-bay/)

The building was built in collaboration by two architects: DP Architects (DPA) of Singapore and Michael Wilford & Partners (MWP) of London, however the latter departed the project in May 1995. Two circular space frames with triangulated glass pieces and sunshades combine exterior vistas with shading devices in this design.

Host a skin that is based from the Durian plant. The exterior shade system is likewise dynamic, since the triangular louvers adapt to the sun's direction and position during the day.

Figure 32: Building Skin Inspired by the Durian Plant (retrieved from: https://parametrichouse.com/biomimicry-architecture-3/)

With folded shading devices that progressively change shape and position, a supplementary sun shading lattice is utilized. This world-class performing arts venue's distinctly Singaporean essence comes from the ensuing dynamic and ever-changing mesh of dappled sunshine and shadows.

A coating structure comprises of lightweight, curving steel space frames with triangular aluminum sun shields was created in the style of the durian fruit, which has a formidable thorn-covered husk to protect the seeds within. The design and depth of the sunshade louvers were chosen by an exhaustive study of the local sun path, which revealed that it is almost perfectly east-west. The shields were then calibrated using complex geometry analysis and computer modeling to alter form and orientation depending on the angle the sun hits them during the day (HomeKlonding, 2017).

Figure 33: Building's Shading Devices (retrieved from: https://parametrichouse.com/biomimicry-architecture-3/)

Table 16: Summary of biomimetic criteria and applied solutions on Esplanade Theater (author, 2021)

Building name	**Challenges**	**Lessons/ responds of nature**	**Biomimetic criteria**	**Solution in building**
Esplanade Theater	Building physic	Principles of Durian plant skin for protecting the seed inside	Shading devices adaptability	responsive shading devices

- **Eastgate Center**

The Eastgate Centre in Harare, Zimbabwe, exemplifies the finest in green architecture and environmentally responsible design. The incorporation of biomimicry concepts in the design of the country's largest office and shopping complex is an architectural marvel. The designed by architect Mick Pearce in partnership with Arup engineers, has no conventional air-conditioning or heating, but uses design principles influenced by native Zimbabwean masonry and African termite self-cooling mounds to stay controlled year-round with radically lower energy consumption.

The Eastgate Centre consumes less than 10% of the energy that a comparable structure of its size would. These cost-cutting measures have resulted in a $3.5 million savings for Eastgate's proprietors due to the elimination of an air-conditioning system that did not need to be installed. Apart from being eco-friendlier and healthier for the environment, these benefits are passed on to occupants, whose rentals are 20% lower than those in the adjacent buildings (INHABIT, 2012).

Figure 34: Eastgate Center (Retrieved from:
https://earthbound.report/2020/05/15/building-of-the-week-eastgate-zimbabwe/)

In Zimbabwe, termites construct massive mounds within which they cultivate a fungus that is their main food supply and must be kept at a certain temperature. during the day, termites open and close a number of heating and cooling vents throughout the mound, achieving incredible temperature control. Air is drawn in at the lowest portion of the mound, down through enclosures with muddy walls, and up via a channel to the apex of the termite mound using a system of precisely controlled convection currents. In order to adjust the temperature, the hardworking termites dig new vents and fill up existing ones on a regular basis. Same principles have been applied in design of Eeastgate center which decrease energy consumption of the building drastically (INHABIT, 2012).

Figure 35: Eastgate Ventilation Mechanism Based on Termites Mounds (Retrieved from: https://blogs.archea.in/biomimicry-nature-inspired-architecture-biomimicry-architecture/)

Table 17: Summary of biomimetic criteria and applied solutions on Eastgate center (author,2021)

Building name	**Challenges**	**Lessons/ responds of nature**	**Biomimetic criteria**	**Solution in building**
Eastgate center	Building physic and energy efficiency	Termites natural ventilation system	Biomorphy- learning from the formal performance	Natural ventilation system

- The National Aquatics Center

The National Aquatics Center, or 'Water Cube,' was built for the 2008 Beijing Olympic Games and was one of the greatest spectacular and thrilling athletic arenas ever built. Five swimming pools are enclosed within the bubble walls, as well as a restaurant, seats, and amenities for 17,000 spectators.

Figure 36: The National Aquatics Center, Beijing (Retrieved from: https://yeswebim.wordpress.com/2015/04/13/bim-and-scripting-beijing-national-aquatics-center/)

The shape of the structure is based on the natural development of soap bubbles. Arup's structural engineers and designers realized that a form based on this unique geometry would be extremely repeatable and buildable while seeming organic and unpredictable.

For the façade, ethyl Tetrofluoroethylene (ETFE) was selected. This material is less than 1% the weight of glass and provides higher thermal insulation. Solar energy is captured and utilized for heating to the tune of 20%. The daylight that enters the cube reduces the amount of energy needed to illuminate the pool area by up to 55 percent.

Figure 37: Usage of ETFE for Façade (Retrieved from: https://inhabitat.com/the-watercube-wins-australias-highest-architecture-award/)

Several energy conversion devices, including such heat recovery from warm exhaust air for warming up the chilly outside air, have been added into the design to more minimize the center's energy usage (fresh air supply).

Water conservation was also important to Arup's design philosophy because Beijing has a water constraint. The business suggested that 80 percent of the water collected from roof, and pool backwash systems be reused and recycled. By releasing directly to the sewage system, these attempt to lessen demands on local collecting waterways and the local water supply system (Zhang, et al, 2012).

Table 18: Summary of biomimetic criteria and applied solutions on The National Aquatics Center (author, 2021)

Building name	Challenges	Lessons/ responds of nature	Biomimetic criteria	Solution in building
The National Aquatics Center	Building physic and energy efficiency	Bubbles structure	Advanced materials Biomorphy: Light-weight structure of bubbles	ETFE material Advanced structure

3.3 Result and Discussion

In previous section of this chapter, it has been tried to review some of the successful architectural design examples from different countries which approached to their design process with biomimetic principles. Following table is summarizing all the sample studies. The table can highlight that biomimetic design approach has been applied on architecture within different levels of organism, behavioral and eco-system. Different natural inspiration could turn to solutions for architectural design which can solve variety of problems for structure, envelope, materials and so on. biomimetic approaches have been developed as dynamic or static solutions through the advanced materials, dynamic shading devices, mechanical system and all successfully addressing the ultimate goal of sustainability in architecture.

The sample study shows the most developments of biomimetic design approach is within building physics criteria. majority of solutions offered for building envelope by introducing the adaptability to the building façade. In this manner, solutions such as kinetic façade or bio inspired facades can be seen. Following the shading device design development for building envelope, in the second place, most attention has been given in material design. although, in the field of material design still majority of studies is in conceptual phase but still some examples of advanced materials can be seen in practice.

This study shows, the examples of biomimetic designs are mostly being in developed countries due to expensive application of advanced technologies and materials. The least attention has given to economic values. Although, designing with biomimetic criteria can improve the economic pillar of sustainability from some perspectives (reducing the heating/cooling or lighting load), however, still none of the projects started with enhancing economic values from the first place.

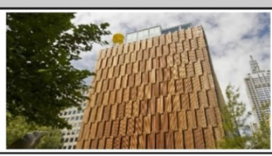
Table 19: Summary of sample studies (Author, 2021)

Building	Biomimetic principles										Biomimetic criteria						Concept
	Approach		Adaptive type			levels			strategies		Building Physic				Energy efficiency		Lesson from nature
	Top down	Bottom up	Morph.	Phys.	Beh.	Org.	Beh.	Eco-sys.	dynamic	static	material	envelope	form	sensors	Heating	cooling	
Council House 2, Melbourne		X		X	X		X		X	X	X	X	-	-	X	X	- Supporting service - Adaptability - Renewable courses

Macro	Micro	Shading
-	X	

Materials criteria: Chemical- Micro scale- Phase change
Envelope criteria: Biomimetic envelope- Adaptability- Flexibility

Thermoregulatory solutions

Building description	Environment, climate challenges				Economic value	Architectural synthesis
Architect: Hansen Yuncken Location: Melbourne, Australia Year: 2006 	Process	-	Functions	X	Triple top line growth	-Water recycling -Phase change materials -Shading with basic movements -Thermal mass Natural ventilation
	Development should contribute to renewal				-	

Building	Biomimetic principles										Biomimetic criteria						Concept
	Approach		Adaptive type			levels			strategies		Building Physic				Energy efficiency		Lesson from nature
	Top down	Bottom up	Morph.	Phys.	Beh.	Org.	Beh.	Eco-sys.	dynamic	static	material	envelope	form	sensors	Heating	cooling	
Milwauke, Art Museum	X				X		X		X		-	X	X	-	-	-	Adaptability

Macro	Micro	shading
-	-	

Form criteria: Biomorphi: bird wing like roof structure
Envelope: Roof- Shading

-

Building description	Environment, climate challenges				Economic value	Architectural synthesis
Architect: Calatrava's Location: USA Year: 1997 	Process	-	Functions	-	Triple top line growth	Shading with basic movements
	-				-	

Building	Biomimetic principles										Biomimetic criteria						Concept
	Approach		Adaptive type			levels			strategies		Building Physic				Energy efficiency		Lesson from nature
	Top down	Bottom up	Morph.	Phys.	Beh.	Org.	Beh.	Eco-sys.	dynamic	static	material	envelope	form	sensors	Heating	cooling	
Institute du monde Arab	X				X		X		X			X	-	-	-	-	- Adaptability

Macro	Micro	Shading
X	-	

Envelope criteria: bio-inspired envelope- Adaptability- Flexibility

-

Building description	Environment, climate challenges				Economic value	Architectural synthesis
Architect: Jean Nouvel, Gilbert Lèzenes, Jean-François Bonne Location: Paric, France Year:1987 	Process	-	Functions	-	Triple top line growth	Kinetic façade- shading based on iris of the eye
					-	

Building	Biomimetic principles										Biomimetic criteria						Concept
	Approach		Adaptive type			levels			strategies		Building Physic				Energy efficiency		Lesson from nature
	Top down	Bottom up	Morph.	Phys.	Beh.	Org.	Beh.	Eco-sys.	dynamic	static	material	envelope	form	sensors	Heating	cooling	
Gherkin Tower	X		X			X				X		X	X	-	X	X	Flexibility durability Organism form

Macro	Micro	Shading
-	-	

Envelope criteria: bio-inspired structure- bio-philic

Air flow and natural ventilation

Building description	Environment, climate challenges				Economic value	Architectural synthesis
Architect: Norman Foster Location: London, UK Year:2003 	Process	-	Functions	-	Triple top line growth	The structure inspired by Venus flower sponge use the same durability in front of strong wind flow Natural ventilation
					-	

Building	Biomimetic principles										Biomimetic criteria						Concept
	Approach		Adaptive type			levels			strategies		Building Physic				Energy efficiency		Lesson from nature
	Top down	Bottom up	Morph.	Phys.	Beh.	Org.	Beh.	Eco-sys.	dynamic	static	material	envelope	form	sensors	Heating	cooling	Eco system working mechanism
The Eden Project		X	X					X		X	X	X	X	-	-	-	
											Macro: - / Micro: X						
											Material criteria: Advanced materials **Envelope criteria**: bio- inspired structure (form and envelope)				-		
	Building description										Environment, climate challenges				Economic value		Architectural synthesis
	Architect: Nicholas Grimshaw Location: Cornwall, England, UK Year: 2001 										Process: -		Functions: -		Triple top line growth -		Usage of ETFE and geodesic dome which allow the light weight structure plus the extensive amount of light

Building	Biomimetic principles										Biomimetic criteria						Concept
	Approach		Adaptive type			levels			strategies		Building Physic				Energy efficiency		Lesson from nature
	Top down	Bottom up	Morph.	Phys.	Beh.	Org.	Beh.	Eco-sys.	dynamic	static	material	envelope	form	sensors	Heating	cooling	Algae working mechanism Diverse in components and relationship
BIQ House	X				X		X		X		X	X	-	-	X	X	
											Macro: X / Micro: -	shading					
											Material criteria: bio-inspired materials. Advanced materials				Producing energy, Heating purposes		
	Building description										Environment, climate challenges				Economic value		Architectural synthesis
	Architect: Splitterwerk Architects Location: Hamburg, Germany Year: 2013 										Process: X		Functions: -		Triple top line growth -		Use of algae in façade which reacts to sun direction and produce energy+ shading Ecological design
											Increase diversity to increase the resilience						

Building	Biomimetic principles										Biomimetic criteria						Concept
	Approach		Adaptive type			levels			strategies		Building Physic				Energy efficiency		Lesson from nature
	Top down	Bottom up	Morph.	Phys.	Beh.	Org.	Beh.	Eco-sys.	dynamic	static	material	envelope	form	sensors	Heating	cooling	flexible deformation principles found in plant movements
Thematic Pavilion Expo 2012		X			X		X		X		X	X	-	-	X	X	
											Macro: X / Micro: -	shading					
											Material criteria: Advanced materials **Building envelope:** Adaptability, movable shadings						
	Building description										Environment, climate challenges				Economic value		Architectural synthesis
	Architect: Soma Location: Yeosu, South Korea Year: competition in 2009. constructed 2012 										Process: -		Functions: -		Triple top line growth -		Glass fiber reinforced polymers (GFRP) for deployable structures kinetic movable louvers

Building	Biomimetic principles										Biomimetic criteria						Concept
	Approach		Adaptive type			levels			strategies		Building Physic				Energy efficiency		Lesson from nature
	Top down	Bottom up	Morph.	Phys.	Beh.	Org.	Beh.	Eco-sys.	dynamic	static	material	envelope	form	sensors	Heating	cooling	Natural adaptability of Durian plant skin for protecting the seed inside
Esplanade Theater	X		X			X			X		-	X	-	-	X	X	
											Macro: - / Micro: -	shading					
											Material criteria:- **Building envelope:** Adaptability, movable shadings						
	Building description										Environment, climate challenges				Economic value		Architectural synthesis
	Architect: DP Architects (DPA) of Singapore and Michael Wilford & Partners (MWP) Location: Singapore Year: 2001 										Process: -		Functions: -		Triple top line growth -		Responsive building skin Adaptive shading devices

Building	Biomimetic principles										Biomimetic criteria						Concept
	Approach		Adaptive type			levels			strategies		Building Physic				Energy efficiency		Lesson from nature
	Top down	Bottom up	Morph.	Phys.	Beh.	Org.	Beh.	Eco-sys.	dynamic	static	material	envelope	form	sensors	Heating	cooling	Termites natural ventilation system
Eastgate centre	X				X		X			X	-	X	X	-	X	X	
											Macro: - / Micro: -						
											Envelope criteria: bio-inspired structure- bio-philic				Air flow and natural ventilation		
	Building description										Environment, climate challenges				Economic value		Architectural synthesis
	Architect: Mick Pearce in partnership with Arup engineers Location: Zimbabwe Year: 1996										Process	-	Functions	-	Triple top line growth		Natural ventilation
															-		

Building	Biomimetic principles										Biomimetic criteria						Concept
	Approach		Adaptive type			levels			strategies		Building Physic				Energy efficiency		Lesson from nature
	Top down	Bottom up	Morph.	Phys.	Beh.	Org.	Beh.	Eco-sys.	dynamic	static	material	envelope	form	sensors	Heating	cooling	Bubbles light weight structure
The National Aquatics Center	X		X			X				X	X	X	X	-	X	X	
											Macro: - / Micro: X						
											Envelope criteria: Advanced materials bio-inspired structure- bio-philic				Heating load		
	Building description										Environment, climate challenges				Economic value		Architectural synthesis
	Architect: Arup's structural engineers and designers Location: Beijing Year: 2008										Process	-	Functions	-	Triple top line growth		Usage of ETFE and bubble inspired structure which allow the light weight structure plus the extensive amount of light
															-		

This sample study even presenting a very successful examples in architecture which by using biomimetic design going one step forward towards sustainability as the main goal, but also highlights the need for more development of this approach within different criteria and not only in building physics.

If the biomimetic design wants to achieve ultimate sustainability goal it needs to address all pillar of sustainability and in this case one of the main issues is economic criteria. Ways should be found to make the biomimetic design approach more economically accessible. The approaches should have more view towards the ecosystem and climate as well. In the end one of the main targets of sustainability is to be responsive towards ecosystem and climate change, thus criteria in design of biomimetic which can address this goal must be more integrated to the design solutions.

Chapter 4

CONCLUSION

Sustainability is one of the most pressing challenges in today's globe, due to population expansion, energy crises, and climate change on a different scale. In all fields, which architecture is not exceptional, the major goal is to reduce the negative effects of human activities on the natural world while also attempting to improve living quality. Thus, since 1970s and energy crisis, finding solutions and methods to address this concern is a trend in architecture.

One of the promising solutions which got more attention in recent years is biomimetic design. the main concept of biomimetic design is coming from natural world. What we see around us, is an environment which survived during centuries by adapting and evolving itself towards variety of environmental changes. This fact, makes the nature the best source of survival examples and sustainability solutions which can help architecture. Biomimetic design approach tries to address the ultimate goal of sustainability in architecture by imitating the natural solution for human-based problems in this field.

Therefore, this study by selecting biomimetic design approach as one of the successful solutions for sustainable architecture tries to review this concept. First of all, after understanding the link between sustainability and biomimetic design, the study reviews the literature of biomimetic design in order to find out all principles of this terminology. After understanding the definition of biomimetic and principles of biomimetic design, it has been tried to find out the criteria of biomimetic design approach.

In order to categories and gather the biomimetic design criteria, a content analysis method has been carried out. With help of this method, the main sources from main scholars of this field has been gathered and the initial codes been generated. After the coding and studying the main sources the biomimetic criteria has be categories within four main groups of; a) ecological and climate change b) building physics c) energy efficiency and d) economic values. Each of the main groups studied more in detail, so as results the main criteria of biomimetic design presented in the second chapter of the study.

In the next step, some of the successful architectural examples with biomimetic design approach been analyzed. For this section of the study, ten successful examples from different locations selected. the selection of samples shows the appearance of biomimetic design as early as 1987 in Paris. Thus, this approach although got extra attentions in recent years but it is not necessarily a new approach as it can be seen throughout the architectural history.

Analysis of selected cases highlights, the majority of architectural examples with biomimetic design approach located in developed countries which it is due to the fact of economic status of the countries. Biomimetic design approaches are usually expensive solutions with advanced technologies and materials which might not be the best solution for many countries. A building can not a sustainable example unless it meets economy pillar of sustainability as well, thus, biomimetic design will not be a sustainable approach for many countries and many projects.

Analysis of biomimetic principles on the cases highlights the majority of samples developed with top-bottom approach. Cases have been developed mainly with behavioral adaptation type and in behavioral level. Lastly, majority of studied cases designed with the dynamic biomimetic strategy. Following figure 38, illustrate the biomimetic design principles presented for selected samples.

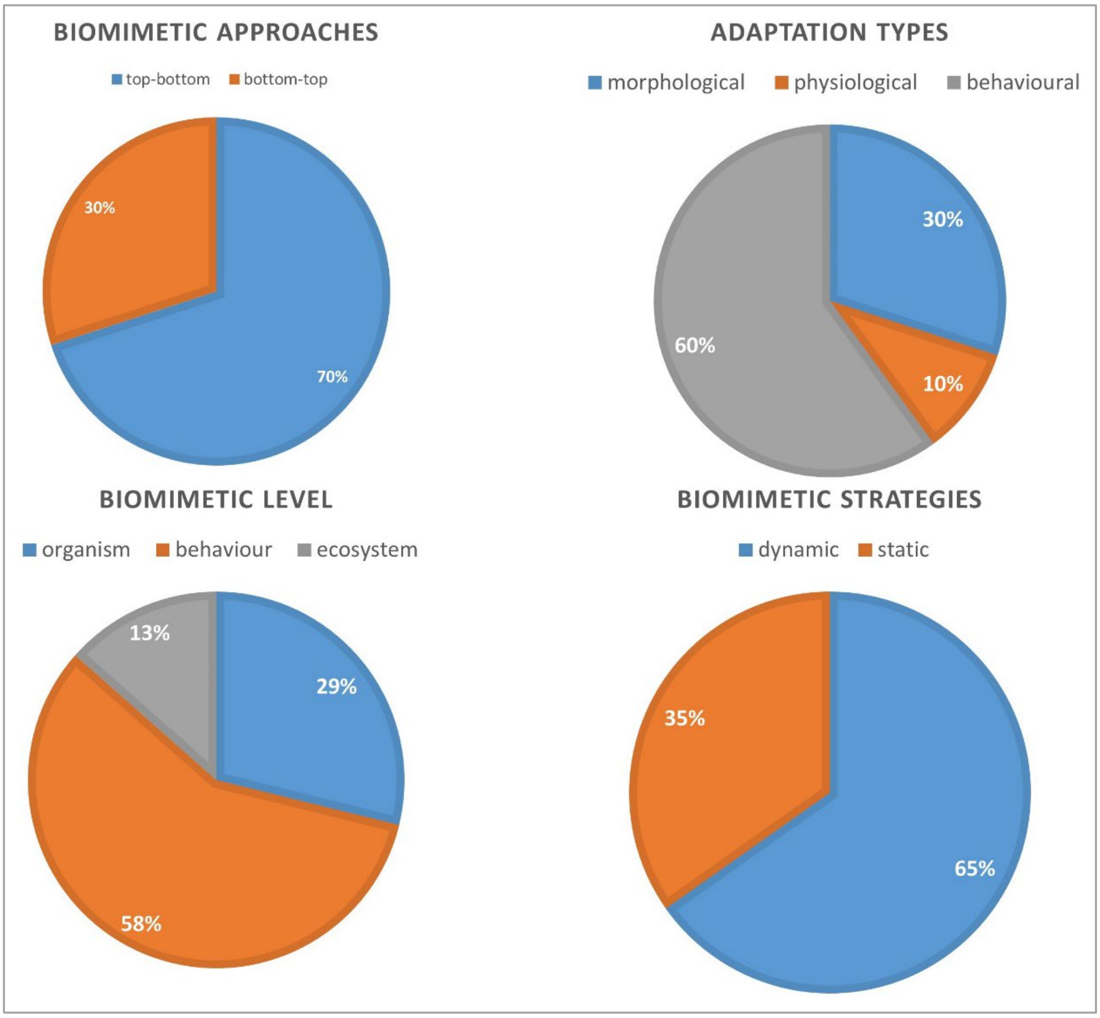


Figure 38: Illustration of Samples Biomimetic Approaches Analysis

Analysis of samples highlights that the biomimetic design criteria in architecture is more developed related to building physics. In this manner, adaptive façade with adaptive shading devices, or advanced materials with adaptability in macro or micro scale can be seen the most. Analysis of cases highlights none of the examples been developed based on economic value criteria of biomimetic design from the initial steps of design. Among studied cases only two cases have addressed the climate challenges in their design, BIQ house in process level and Council House 2 in function level.

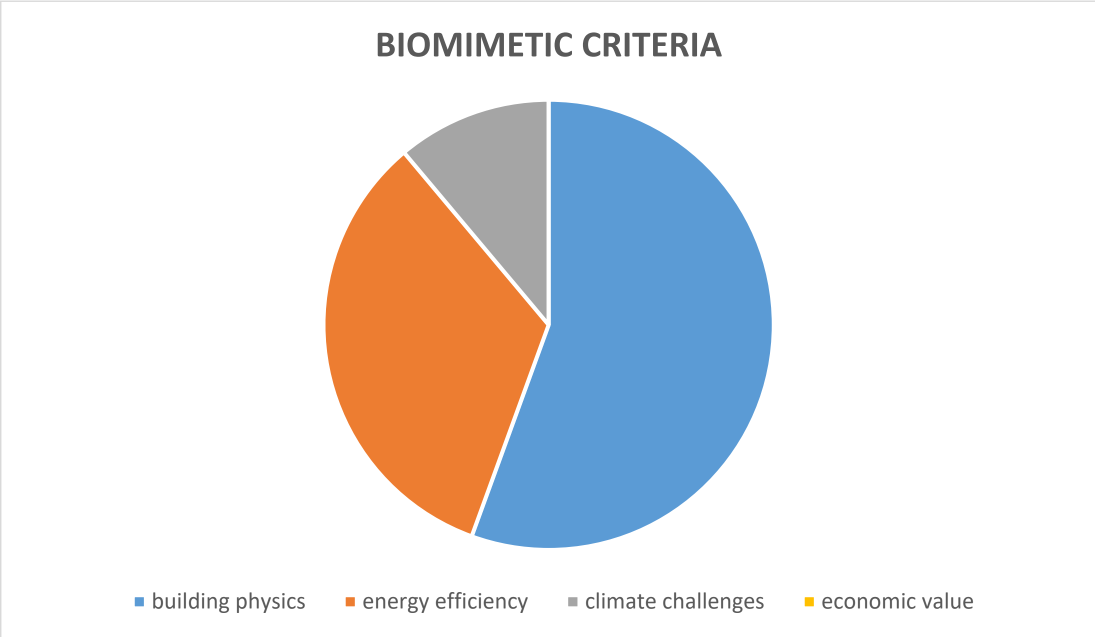


Figure 39: Illustration of Samples Biomimetic Criteria Analysis

Within developments on building physics, majority of attention given to envelope design. biomimetic design has been applied on envelope level on all selected cases. The application of biomimetic design on envelope can be seen mostly on shading devices design. however, in all cases there is no only one approach and combination of criteria can be seen. In most of cases, biomimetic criteria applied in different scales in a project. However, there is no example for utilization of sensors. This fact can present the extra need for stepping forward in research of sensors and bringing them in practice of architecture.

Majority of cases seven out of ten have been successful on addressing the energy efficiency from heating and cooling point of view which can highlights that biomimetic approach and be a game changing approach for energy efficiency and consequently sustainability.

To sum up, this study started with a proposition that biomimetic design can be an approach which address the sustainability goal. After studying the terminology and categorizing the criteria with content analysis method and later based on that analyzing the architectural example, it can be highlighted that biomimetic design approach can be one of the promising approaches for sustainable architecture. Although, it still needs more developments on three other criteria than building physics specially for the economical values.

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