

AN ANALYSIS ON RESPONSIVE ARCHITECTURAL FACADES IN THE 21ST
CENTURY WITHIN THE CONTEXT OF BIOMIMICRY



by
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AN ANALYSIS ON RESPONSIVE ARCHITECTURAL FACADES IN THE 21ST
CENTURY WITHIN THE CONTEXT OF BIOMIMICRY

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ABSTRACT

AN ANALYSIS ON RESPONSIVE ARCHITECTURAL FACADES IN THE 21ST CENTURY WITHIN THE CONTEXT OF BIOMIMICRY

Throughout history, humankind has taken nature as an example in every field and has observed nature to seek solutions to problems. In this context, the concept of biomimicry came about and served as a bridge between nature and design. Biomimicry is a field that allows for organisms in nature to be examined, as well as integrate strategies developed by nature into design. Like the skins of organisms in nature, architectural facades create the border between buildings and nature, and fulfill an important role in meeting comfort needs of their users. Furthermore, building facades have a large impact on energy consumption, thus, contribute a significant portion of damage done to nature. In regards to that, it can be foreseen that facade designs that use biomimicry as a design method help increase the relationship between architecture and the environment, as well as benefit sustainability while meeting the comfort requirements of the users. With the help of 21st century technological advancements, responsive facade designs that can react to changes in environmental factors, and are sustainable, energy efficient, able to be adjusted based on user needs and wishes and are designed with smart materials, have gained importance.

This thesis focuses on 21st century responsive facades that used biomimicry as their design method. The following buildings fulfilling determined criteria have been analyzed within the scope of the thesis; Council House 2, Q1 Building, One Ocean Thematic Pavilion, Al Bahr Towers, Mokyeonri Wood Museum and Hive House. The facade design of these buildings have been inspected based on the organism they took inspiration from, their levels and approaches of biomimicry, their responsive facade systems and their impact on sustainability. The results on their inspection put forth that responsive facade designs that take advantage of biomimicry benefit nature and sustainability in thermal comfort, natural lighting and natural ventilation. With the advancements in material technologies, it is thought that the use of the organism and behavior levels of biomimicry will help transform responsive facade designs into facades that behave like organisms.

ÖZET

BİYOMİMİKİRİ BAĞLAMINDA 21. YÜZYILDA DUYARLI MİMARİ CEPHELER ÜZERİNE BİR ANALİZ

İnsanoğlu geçmişten bugüne her alanda doğayı örnek almış ve doğayı gözlemleyerek problemlere çözüm bulmaya çalışmıştır. Bu bağlamda biyomimikri kavramı ortaya çıkmış ve doğa ile tasarım arasındaki köprü görevini görmüştür. Biyomimikri, doğadaki organizmaları inceleyerek, doğanın geliştirdiği stratejileri tasarımlara aktarılmasını sağlayan bir alandır. Doğadaki organizmaların derileri gibi, mimari cepheler de binaların doğa ile arasındaki sınırı oluşturmakta ve kullanıcıların konfor şartlarının sağlanmasında önemli bir görev üstlenmektedir. Ayrıca bina cepheleri enerji tüketiminde büyük bir etkiye sahip olması nedeniyle doğaya verilen zararın da önemli bir kısmını oluşturmaktadır. Bu bağlamda bir tasarım yöntemi olarak biyomimikriyi kullanan cephe tasarımlarının mimarının çevre ile kurduğu ilişkinin artırılması ve kullanıcıların için konfor şartlarının sağlanması açısından sürdürülebilirliğe katkı sağlayacağı öngörülmektedir. 21. yy teknolojik gelişmelerin sayesinde değişen çevresel faktörlere yanıt veren, sürdürülebilir, enerji verimli, kullanıcıların ihtiyaç ve isteklerine göre uyarlanabilen, akıllı malzemeler ile tasarlanan duyarlı cephe tasarımları önem kazanmaya başlamıştır.

Bu tez 21. yy 'da yapılmış, bir tasarım yöntemi olarak biyomimikriye başvuran duyarlı cephelere odaklanmıştır. Tez kapsamında belirlenen kriterlere uyan; Council House 2, Q1 Building, One Ocean Thematic Pavilion, Al Bahr Towers, Mokyeonri Wood Museum ve Hive House binalarının analizi yapılmıştır. Bu binaların cephe tasarımlarının; hangi organizmadan ilham aldığı, biyomimikri seviye ve yaklaşımları, duyarlı cephe sistemleri ve sürdürülebilirliğe etkileri değerlendirilmiştir. Değerlendirmelerin sonucu biyomimikriye başvuran duyarlı cephe tasarımlarının, termal konfor, doğal aydınlatma, doğal havalandırma konularında doğaya ve sürdürülebilirliğe katkı sağladığı ortaya koyulmuştur. Malzeme alanındaki teknolojik yenilikler sayesinde biyomimikrinin organizma ve davranış seviyelerini kullanarak duyarlı cephe tasarımlarının bir organizma gibi davranan cephelere dönüşmesine katkı sağlanacağı düşünülmektedir.

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LIST OF SYMBOLS/ABBREVIATIONS

BMS	Building management system
ETFE	Ethylen TetraFluoroEthylen
GFRP	Glass fibre reinforced polymer
LED	Light emitting diode
PTFE	Polytetrafluoroethylene
UAE	United Arab Emirates



1. INTRODUCTION

Nature has the perfect ideal order, which is self sufficient, and it allows for all living and nonliving beings that exist within it to live among each other. Humankind is a part of this order and has looked to nature as an example since the beginning in providing for needs such as shelter and protection. Throughout history, a lot of issues were given solutions by using nature as a guide to the design process. In this context, the field of biomimicry was emerged, which reinforces the relationship between nature and design, and easily integrates to design the strategies developed by nature with an innovative approach. Biomimicry not only creates designs that is inspired by nature, but it also provides solutions to protect nature and to minimize the damage done to it.

As a result of increased production and consumption in recent years, the risk of harming nature and of breaking the ecological order has heightened. In conjunction with this, harmful gases emitted by the built environment, unconscious industrialization, uncontrolled rise of population and other manmade matters have been causing global warming and climate change. These reasons show that today, there is a need for the natural environment to be protected and for sustainable solutions to be made. The field of architecture visually enhances the built environment, but it is also the field that interferes most with nature and depletes most natural resources. In this context, the primary responsibility of architecture toward nature is to design buildings that can adapt to changes in climate in order to avoid greenhouse gas emissions that are a result of this consumption of energy. Using nature as a guide and implementing knowledge gained by nature into the lives of the people, designing buildings with this approach can all be seen as solutions to the ecological issues mentioned above.

The reduction of the energy consumption of buildings greatly benefits creating a sustainable built environment and helps to avoid damage done to nature. New design strategies brought to the building facades, where the building first communicates with the environment, are one of the most effective solutions for energy efficiency in buildings. Building facades have an important role in temperature and light regulation and serve as an interface between the interior space and the outside environment. The concept of architectural facades have developed throughout history and it is no longer an element independent from the interior, it now has a holistic relationship with the building.

Technological advancements and the integration of the concept of sustainability to facade design in the 21st century has brought with it facade designs with different goals and construction techniques. Technological advancements of today facilitate the use of systems in architecture that can react to changing environmental factors and can adapt to user needs. This situation has created the responsive facade design, which is a representation of current developments in architecture. Responsive facade designs are a sustainable, energy-efficient, innovative design approach that provides users with a comfortable interior. It is predicted that the combination of responsive facade design and the concept of biomimicry can contribute to the creation of environmentally conscious and sustainable facade designs.

1.1. AIM OF THE THESIS

Today, one of the most effective approaches to increasing human awareness of protecting nature has been the concept of sustainability. The concept of sustainability is a holistic approach important to many areas, and it has increased awareness and consciousness toward nature. With this change in architecture, the creation of sustainable buildings has begun. The basic principle of sustainable architecture is to create buildings that use energy resources at a minimum, are nature-friendly, and meet the indoor comfort requirements of the users. Buildings designed with this approach are expected to maintain ecological balance and reduce adverse effects that cause climate change. At this point, it is thought of as beneficial to consider nature and to imitate the approach of nature that never completely consumes resources. Biomimicry is a field that aims to guide designers and architects in ensuring sustainability.

The opportunities of the 21st century allow every field to reach resources quicker, but that also means that those resources are being depleted that much faster. Despite the negative effects of humans, nature continues to meet the needs of living beings and ecosystems by trying to preserve its own cycle. The question of whether using the strategies that nature has developed in itself can contribute to sustainability in solving design problems has been subject to a number of scientific research.

In this context, one of the most effective solutions for sustainability in architectural designs today has been innovative, energy-efficient, responsive approaches introduced to facade designs. While building facades are the first visual part of the structure to appear from the

outside, they also serve as an interface indoors where users interact with environmental factors such as air, light and sound. Facade design is an area where design problems arise in matters of energy consumption, visual impact, thermal comfort and lighting. Therefore, the thesis aims to provide predictions and findings on the contribution of facade designs that use nature as a design method to the solution of design problems. In this context, research has been conducted to understand the impact of biomimicry based facade designs on sustainability. Just like organism skins or envelopes behave against any environmental effects, responsive facade designs have also been seen to be adaptable and movable facades that can react to environmental factors. Therefore, the base source of motivation of this thesis is to analyze the concepts of responsive facade design and biomimicry together. In this context, the research questions for the thesis are as follows:

- In 21st century responsive facade designs that use biomimicry as a design method, how are the strategies of nature taken advantage of in the design process, what are the effects of the levels of biomimicry on the design, and what solutions can be applied to the facade in conjunction with this?
- Can energy-efficient solutions be created in responsive facade designs inspired by organisms in nature?

According to the research questions mentioned above, 21st century responsive facade designs that use biomimicry as a design method have been focused on. Attention has been paid to the fact that the buildings examined in detail in the fourth chapter are facades that use the latest technologies, exhibit most effectively the impact of the movement of responsive facade designs, and are inspired by different organisms. In this context, it is believed that selecting the most recent examples contributes new and unique benefits to the work in this area.

1.2. SCOPE OF THE THESIS

In this thesis, the relationship between biomimicry and architectural design is primarily being examined. It is emphasized that biomimicry is not only a design approach that imitates the form of living and nonliving organisms in nature, but also a design approach that takes inspiration from the cycle in nature, the behavior of organisms, the ideal forms in

nature, and the ecosystems in nature. The books "Innovation Inspired by Nature" by Janine Benyus and "Biomimicry in Architecture" by Michael Pawlyn have served as the primary sources in the analysis of the concept of biomimicry. Research on the approaches and levels of biomimicry were mainly done through the definitions and examples conducted by Pedersen Zari and Michael J. Maglic.

Designs based on nature also existed before the concept of biomimicry emerged. Examples throughout the historical process show that people instinctively tend to recognize and imitate nature. When biomimicry became a field, this instinct was based on certain basic principles, enabling a design method to be created. Pioneering designs from other fields were also mentioned when analyzing the concept of biomimicry, rather than just giving examples of architectural design. This was done because it shows that sustainable and environmentally conscious designs can be created when biomimicry is used as a design method in all fields.

Biomimicry covers the groundwork of looking for solutions to architectural design problems and of creating innovative, sustainable and eco-friendly designs. The facade, which the building uses to communicate with its environment, and organism skins in nature have similarities. The strategies that nature has developed to create skin lead to looking at nature to solve design problems for facades. In this context, the secondary focus of the thesis was to look at the concept of architectural facades and building facades that were designed based on biomimicry. The concept of sustainability, which is an important criteria in architectural design, has been analyzed specifically for the architectural facades. The works of Christian Schittich and John Yowell were used as a reference in researching the sustainability of the architectural skin. In the analysis of biomimetic facade designs, research of Petra Gruber on the comparison of architectural facades and functions of organism skins, and designs are done on this subject by Ilaria Mazzoleni were used as sources.

In the 21st century, sustainability and technological advancements are reflected greatly on designs in the field of architecture. Research concluded that the two main subjects of the thesis, biomimicry and architectural facades, have evolved in the 21st century and continue to develop every day. As protecting nature gained importance, technological advancements in these times ended conventional architectural approaches and replaced them with innovative design. While architects created smarter and more well-equipped buildings with

these technological improvements, they began to research the nature compatibility of buildings and to design their buildings with this approach. This is why the thesis focuses on the 21st century as the time period.

When the development of 21st century architectural facades is analyzed, it is concluded that responsive facade designs interact the most with the environment and are the type of facade designs that integrates recent developments in technology. In this context, the thesis examines responsive facade designs. This research uses as a basis the work done by Negroponte, who founded the concept of responsive architecture, and Sterk, who is a pioneer in the development of responsive architecture. In addition, the thesis of Matin and Eydgahi is referenced to analyze the technologies used in responsive facade designs.

The case study of this thesis consists of 21st century responsive facade designs that use biomimicry as a design method. Buildings with biomimetic facades and responsive facades, which were built in the 21st century, were searched by literature review. While choosing these buildings, it has been important selection criteria that responsive facades respond to environmental stimuli with a dynamic system and use biomimicry as a design method. In this context, as a result of the research made, the buildings that do not meet the selection criteria are eliminated, it is considered appropriate to analyze 6 buildings that meet both criteria. The scope of this study chose the following buildings; the CH2 Building, the Q1 Building, the One Ocean Thematic Pavilion, the Al Bahr Towers, the Mokyeonri Wood Museum, and the Hive House. Buildings that were designed in the 21st century and use sustainable architecture approaches, but do not include responsive facades based on biomimicry and do not react to environmental effects were left out of the scope of the study. In addition, since the 21st century is still an ongoing process, newer examples are still under construction, and these examples can be increased for future research.

1.3. METHOD OF THE THESIS

The main goal of the thesis is to conduct research on the creation of architectural facade designs that use biomimicry as the design method. To do this, the main principles of the concept of biomimicry in the architectural design process have been examined. A conceptual introduction to biomimicry, its main ideology, its pioneering design examples throughout history, its principles, its goals, and its scale have all been defined, as well as

work done by scientists to serve as a guide to this design. The concept of biomimicry was examined with the help of many resources such as local and foreign sourced theses, articles, magazines, digital sources, speeches and many others. Through research, approaches and levels of biomimicry that guide the use of biomimicry in the architectural design process have been studied and these concepts are being analyzed through pioneering examples.

The concept of the architectural facade has been defined and its evolution throughout history has been analyzed chronologically with examples in order to study biomimicry specifically in the field of architectural facade design. In Biomimetic facade designs, examples of architectural facade design that use biomimicry to answer the questions of how inspiration was taken from which structure or organism in nature, and how these findings were integrated into the design. The concept of responsive facades, which, in current times, enables buildings to be energy efficient, sustainable and eco-friendly, has been examined and the technologies they use have been studied through examples.

Current examples of buildings were studied in order to hypostatize the data gathered from the analysis of the concepts of biomimicry and responsive facades. Two main criteria were used in choosing buildings. The first criteria is that the facade design must contain a biomimetic and responsive facade system, while the second criteria is that the building must be completed in the 21st century. As a result of a comprehensive scan of the literature 6 buildings were chosen for being current and for having sufficient data. The selected buildings were then analyzed within three parameters. These parameters were examined in regards to the following;

- **The effect of the concept of biomimicry on the facade:** What organism inspired the facade design, the level of biomimicry, biomimicry approach,
- **Responsive facade design:** What environmental factor is responded to, which technology is used, material used, technical solutions provided by the responsive facade design,
- **The effect of facade design on sustainability:** What are the benefits to sustainability of responsive facade design in the context of biomimicry.

The findings of these determined parameters were used to create a table on which each of the buildings were evaluated. This gathered data was used to provide results and suggestions in the conclusion chapter of the thesis.

The thesis uses a hybrid study method where both qualitative and quantitative research methods were used. While analyzing conceptual knowledge such as biomimicry and responsive architectural facade, literature review, that is, examining the theses and articles related to the subject, constitutes the quantitative method. The results, suggestions, and predictions for the future as a result of the analyzes made constitute the qualitative method. As a result, conceptual knowledge has been examined through buildings and supported by some tangible inferences.

The thesis consists of five chapters, including the introduction and conclusion chapters. The introduction chapter of the thesis has explained the aim, scope, and method of the thesis. The second chapter focuses on the concept of biomimicry, which is one of the main subjects of the thesis. Approaches and levels of biomimicry are examined through examples and their use in architecture is studied. The third chapter of the thesis analyzes the concept of facades, which is the other main subject of the thesis, through the frame of sustainability. This chapter focuses on responsive facade designs. By using the information gathered in the second and third chapters, the fourth chapter of the thesis chooses pioneering 21st century responsive facade designs that use biomimicry as a design method and evaluates them. The fifth chapter of the thesis is the conclusion chapter, sharing the results of the rest of the chapters of the thesis.

2. THE RELATION BETWEEN BIOMIMICRY AND ARCHITECTURAL DESIGN

Nature has been the guide to the solutions of the problems faced by mankind from the past to the present. Design solutions that can meet all of our daily needs, such as the need for shelter, needs to live and the need for protection, are all hidden in nature itself. And this led mankind to understanding, analyzing and researching nature. It is very important to understand the concept of biomimicry and adopt its principles to create designs inspired by nature. Therefore, in the second chapter of the thesis, a conceptual introduction to biomimicry is conducted and certain biomimicry-based design methods are examined.

In chapter 2.1 of the thesis, a general definition of biomimicry is made and its origins are mentioned. It aims to understand the main idea of biomimicry by taking a look at the views of researchers and scientists who are pioneers in the field of biomimicry. In addition, some examples of design inspired by nature throughout history are mentioned, which emphasizes that biomimicry is an approach that has existed in our lives for a long time. After that, the goals and basic dimensions of biomimicry are analyzed. Biomimicry life principles, the measures of inspiration taken from nature and the detailed analysis of the biomimicry design spiral are the necessary stages in accurately transferring the principles of biomimicry to designs. These are the steps required to inspect nature in order to use biomimicry in design, and to help identify the data to take inspiration from.

In the subtopics 2.2 and 2.3 of the thesis, the approaches and the levels of biomimicry are defined. The fundamental approaches of biomimicry in architectural design, design inspired by biology and design influenced by biology, and some design examples of these approaches are analyzed. Analysis of approaches of biomimicry contributes to the study of the organism level of biomimicry, behaviors and ecosystems. Analysing levels of biomimicry can show how different natural organisms and ecosystems inspire designs, and examples of this can be seen in the architecture industry, as well as other industries. Lastly, chapter 2.4 examines the integration of biomimicry in the field of architecture. This chapter analyzes some noteworthy examples of buildings throughout history that use biomimicry as a design method in architecture. These examples help architects designing in the field of architecture, explore how to simulate nature and provide solutions to problems. Architects who use biomimicry in their architectural designs for materials,

structures, facades, and aesthetic reasons contribute to the emergence of more sustainable and eco-friendly designs. In this context, the topics analyzed in the second chapter of the thesis are aimed at understanding biomimicry through its basic stages and help further the research for analysis of areas biomimicry is used in architecture.

2.1. THE CONCEPT OF BIOMIMICRY

Nature inspires the design process with its own processes and its own solutions to its problems. Observing living and nonliving things in nature and learning about the design strategies of nature, mimicking nature or taking inspiration from nature, these all provide designers new ways to design. The synthesis of the context of nature and design has created the concept of biomimicry. Biomimicry is a concept that transfers the strategies offered by nature to designs.

Biomimicry consists of the Greek words "bios", meaning life, and "mimesis", which means to mimic. Biomimicry is a new science that aims to mimic, or take inspiration from, the accumulated data of the models of nature, natural systems, the stages of formation in nature and elements of nature in order to solve problems [1].

The term biomimicry began to take place in scientific literature in 1962, but it became common in 1980 [2]. Biologist and founder of biomimicry Janine Benyus taught the public about the concept of biomimicry with her 1997 book *Innovation Inspired by Nature*. According Janine M. Benyus, biomimicry is "the conscious mimicking of nature's genius" [1].

Design inspired by biology has been called different names throughout history such as biodesign, bionics, biomimesis, bio-inspiration, biophilic, but all these names meant the same. Academic studies done by scientists such as Biology Professor Steven Vogel, Biomimetics Professor Julian Vincent and Biology Sciences Author Janine Benyus helped research done in these fields to grow. Vincent defined biomimicry as "abstraction of a good design in nature", while Pawlyn defined it as "the mimicking of the functional basis of biological forms, systems and processes in order to produce sustainable solutions" [3].

When looking at the definitions of biomimicry made by researchers who study the concept of biomimicry from a scientific perspective, it is found that most answers to design

problems can be found in many living species in nature, and that by using biomimicry, solutions to these problems can also be found.

There are also writers and scientists with some negative arguments for biomimicry. Steven Vogels, an American academic, has shared such views in his book *Cats' Paws and Catapults*. In his book, the author called this "Naïve Biomimicry". He described scientists and inventors who took the same systems found in nature and turned them into human-scale products, without making changes, as "naive" [4]. He argued that most of the designs that used these criteria were unsuccessful. In his book, he not only discusses certain failed biomimicry designs, but also some successful designs that were a result of the correct application of biomimicry criteria.

Although the concept of biomimicry has gained scientific awareness just recently, its foundations date back to much earlier. Leonardo da Vinci is viewed as the first artist and scientist that integrated biomimicry in the design process. Leonardo da Vinci expressed his admiration for nature as follows "Human craftsmanship will never devise an invention more beautiful, more simple or more direct than does nature. Because the inventions of nature are never lacking, and never superfluous" [5].

Leonardo da Vinci using his observations of nature as a model for most of his designs proves how forward thinking he was. Davinci designed a machine in the 1500s called the ornithopter that was a man powered flight machine inspired by how birds flap their wings to fly. The machine had 10 meter wide wings made of a lightweight and durable pine frame covered in pure silk. The pilot would turn the pedals with their hands and feet to power the motion of the machine [6]. These drawings were not realized in the time they were drawn. But later they inspired the first ever produced plane in 1903 by the Wright Brothers, in their designs they combined observations of movements of pigeons and Da Vinci's drawings [7].

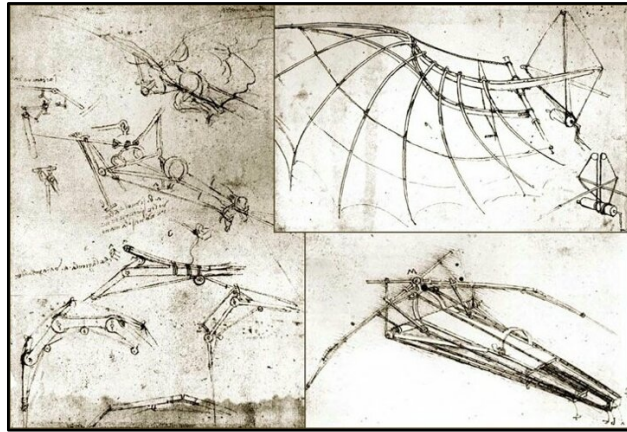


Figure 2.1. Leonardo da Vinci's flying machine sketch [8].

French entomologist Réne-Antoine Réaumur provided a substitution for paper production with his 1719 research in the paper pulp made by wild bees using wood. In 1809, Sir George Cayley succeeded in reducing the friction coefficients of ships' vessel bodies after getting inspired by the aerodynamic forms of dolphins and trout [3].

A more recent biomimicry concept was the Velcro, designed by Swiss engineer George de Mestral in 1948. As shown in the image below, the spiky seeds of the burdock stuck on the dog's collar were observed and Velcro was designed by using the curvy tips of the spikes as inspiration [3].



Figure 2.2. Burdock seed and Velcro [9].

As awareness of biomimicry increases, designers, especially those in the 21st century, have not been shy with integrating biomimicry into their design processes. Industrial designer Ross Lovegrove takes inspiration from nature when designing objects for day-to-day use. Lovegrove argues that observing natural processes in nature helps with gaining new perspectives on design. The image below showcases one of his designs that follow the process, a staircase that he calls DNA, or design, nature and art. The design of the staircase mimics the spiral form of DNA [10].

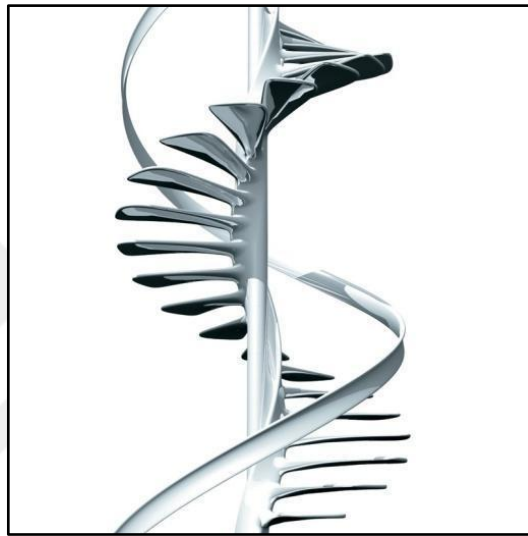


Figure 2.3. Staircase designed by Ross Lovegrove by using DNA as inspiration [11].

Before the concept of biomimicry was defined in science, many designs were made after certain observations of organisms found in nature inspired them. After Janine M. Benyus helped make biomimicry a field of science, it was embraced by designers and scientists and consciously used by them in their design processes. Observing nature gave designers a new perspective while also making their process faster and more efficient. Thus, biomimicry has become a design method that is applied in many different areas of work with positive results.

For nearly 3,8 billion years, the world has been improving the lives of living beings through trial and error. Therefore, it is important to look to nature for inspiration when designing. Biomimicry is not just an approach for complex designs, but a versatile concept that addresses the problems faced in the daily lives of people. It is possible to find more efficient solutions for problems using human inventions by looking at nature. The goal of biomimicry is to establish products, processes and principles that provide innovative

developments for human life. It aims to contribute to the design processes in the following topics [12]:

- Sustainability,
- Increasing Performance,
- Reserving Energy,
- Reduce Cost,
- Eliminating the concept of waste, and redefining it.

The definition of sustainability is making a product from a source while benefiting from and making use of the source and making sure not to deplete or damage the source [13]. The generally accepted meaning of the concept of sustainability is the definition made by the Brundtland Commission in 1987 "Sustainability is to meet our needs today without risking the ability of future generations to meet their own needs, and without damaging the lives of future generations" [14]. Many institutions, councils and agencies have done research on the concept of sustainability. The United States Environmental Protection Agency has established the concept of sustainability on a simple basis and they argue that the provision of conditions that can sustain human life depends on the nature that surrounds us. They also believe that these conditions should be met alongside the social and economic needs of present and future generations. In recent years, designers and architects have responded to this by designing products based on the concept of sustainability, in order to protect nature and the future generations.

The concept of biomimicry follows principles such as; simple to complex development, efficient energy use, utilisation of eco-friendly materials, ensuring that the products and design processes created are environmentally friendly. For example, an organism that has been damaged by impact on its body begins to repair the damaged area by entering a self-healing process. The structure of the bone also detects the damage and responds in order to repair. This information, which was derived from research, has inspired the design of a synthetic material, the development of self-healing polymers for use as building materials. When the material is damaged, the tiny capsules are released containing the repair agents that repair the cracks [15]. This helps reduce maintenance and renewal costs and it

increases the durability of the material. Self-repairing materials inspired by organisms and systems found in nature are an important example of sustainability in terms of biomimicry.

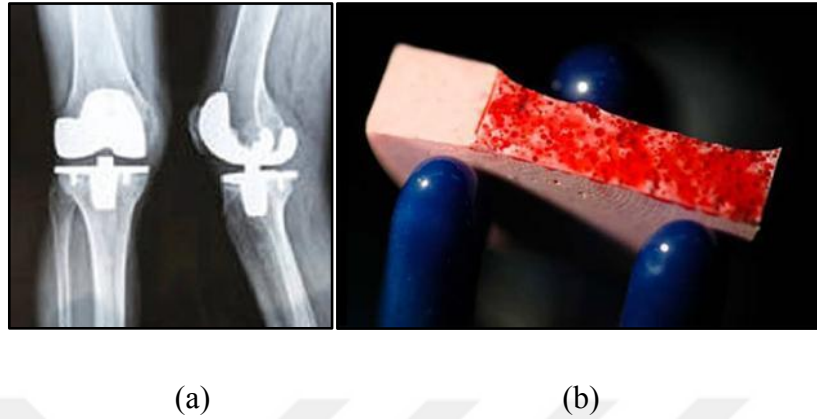


Figure 2.4. (a) Bone structure, (b) self-repairing polymer material, inspired by bone structure [15].

Nature continues to exist by testing design strategies in all conditions and eliminating those that are not favorable. And biomimicry helps designers learn the strategies of nature and use them to develop our designs. Some examples of performance improvement provided by biomimicry are designs inspired by the foot shape of a gecko. As seen in the image below, the hair under the gecko's feet allows it to adhere to a surface when it applies pressure with its feet, while allowing it to easily lift its feet at will. The properties of the gecko feet were used in Nike's mountain shoes, the fabric industry at large and it also allows robots to move on smooth surfaces [12].

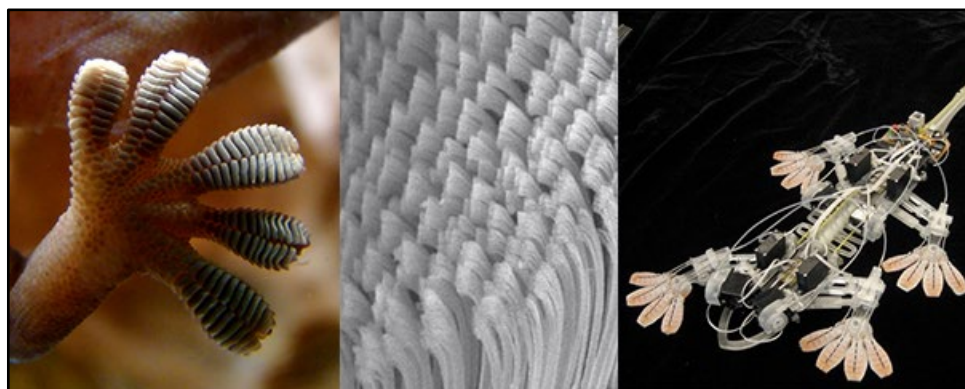


Figure 2.5. Fabric and robot designs inspired by the structure of Gecko [12].

The use of energy in nature is much less costly than the world created by mankind. Plants in nature provide their energy needs from sunlight, while animals eat plants or hunt other animals for the energy that they need. Nature develops incredible strategies in order to store and use this hard to get energy. The principle of reserving energy helps to optimize energy use by mimicking the strategies found in nature and in developing technologies that helps with using energy more efficiently.

One design that was inspired by how nature reserves energy was the bioWAVE, a wave energy system that is a product placed on the seabed. This system was inspired by the oscillation movements of seaweed, it transmits wave movements from the depths of the ocean into hydraulic pressure, allowing the turbines to rotate. This process transforms the motion of the waves into electrical energy, thus providing energy efficiency [16].

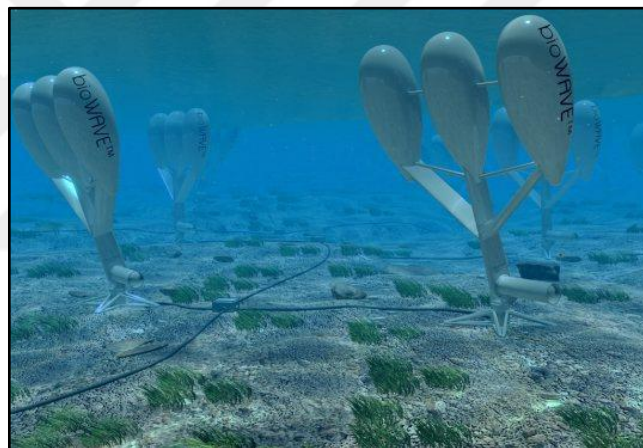


Figure 2.6. bioWAVE [16].

The strategy that nature follows on material use is using what is available. This strategy learned from nature allowed designers to use less raw materials, therefore reducing costs [12]. An example of cost reduction, one of the principles of biomimicry, would be photovoltaic systems created by simulating how a leaf uses energy. There is ongoing research in this context for solar cells inspired by the methods of nature. These cells result in a more flexible and cost-effective solar cell by adding chlorophyll to water gel-based carbon materials [15].

It is important to use the processes of nature for the transformation of substances and nutrients in design in order to use resources more efficiently and avoid unnecessary waste. For instance, spider webs in nature have a structure that requires ten times the energy to destroy compared to any other weblike structures found in biodiversity. Another thing about the webs made by spiders is that they're recyclable. They do this by eating the damaged webs that they had made in order to create more webs. These systems found in nature inspire the designs of many different textile machines.

All of these principles show that biomimicry is a useful way to translate the extraordinary strategies of nature into design. Learning the goals of biomimicry and progressing design processes in line with these concepts is one of the objectives of this thesis. This aims to ensure that the new products are sustainable and energy-optimized, while minimizing waste generation and reducing the cost.

Nature has all sorts of different information due to its biodiversity, therefore the problems and solutions gathered from nature that are applied to design must be determined carefully. Therefore, it's a very important step for designers to get to know the problem they have and accurately identify where to look for a solution. Although designers who use biomimicry as a design method might not know about biology, one of the objectives of this thesis is to teach biomimicry principles in order to help solve problems with ideas from nature. This chapter describes the systematic way to find solutions for problems with ideas from nature, alongside some examples of these methods being implemented.

Biomimicry has 3 basic dimensions in its general approach to nature [1]:

- The Nine Principles of Life
- Nature as a Model, Measure and Mentor
- Biomimicry Design Spiral

These approaches that biomimicry has towards nature must be analysed to determine what design processes can be inspired by nature and to find the solutions to the problems that surface. The three basic dimensions were determined by doing scientific research for this research topic. Biomimicry Life's Principles refers to the properties of nature that can inspire design. These principles are an important guide to understanding how nature

sustains its own creations. Nature as a model, measure and mentor also gives designers certain criteria about which properties to take a look at when taking inspiration from organisms and systems in nature. This is about finding which of the inspirations from the properties of nature should be implemented into design, and about what nature teaches us. The design spiral created by scientists who study and work in the field of biomimicry determines the problems that are faced in the design process and this helps in finding out what steps need to be taken in order to solve them. Examining these processes helps with analyzing the criteria in the fourth chapter of this thesis, as well as it is aimed that the output of this research would open a new window to the biomimicry-based designs of the future.

2.1.1. Biomimicry Life's Principles

Benyus' questions for determining if biomimicry is a good model for design are explained as the nine principles of life. These principles reflect the properties an ecosystem has in its nature and they underline the statement that by using these principles, ecologically sustainable products can be made. According to Benyus, the nine principles of life are as follows [1]:

- "Nature runs on sunlight."
- "Nature uses only the energy it needs."
- "Nature fits form to function."
- "Nature recycles everything."
- "Nature rewards cooperation."
- "Nature banks on diversity."
- "Nature demands local expertise."
- "Nature curbs excesses from within."
- "Nature taps the power of limits" [1].

Yeang argues that for living beings to survive, the properties of their ecosystems must be understood, he also makes a similar classification to the rules of nature from Benyus' nine principles of life. They are as follows:

- "Energy resources must be renewable,"
- "Resources must be recyclable,"
- "Form follows function,"
- "There must be systematic control,"
- "There must be an abundance of structural diversity,"
- "There must be an information network and communication between species" [17].

Nature is a manufacturer that runs a vast factory on a regular basis. It continues to produce with minimum cost and maximum gain by avoiding energy waste and producing designs that are suitable for their purposes. It recycles and reuses anything that remains unused. All of these factors show that nature is a system that must be mimicked and taken inspiration from. Designs made with these criteria in mind tend to easily integrate into nature and they help create an environment that is sustainable.

2.1.2. Nature as a Model, Measure, and Mentor

In order for nature to be used as an example in the design process, rules found in nature must be analyzed and its principles of operation must be understood. Benyus interprets the relationship between nature and design in three different ways, model, measure and mentor [1]:

- **Nature as a Model:**

This reinforces the idea that biomimicry is a field of science that aims to help people find solutions to their own problems by taking how nature deals with its own problems as the inspiration or muse for the design process. The goal here is to manufacture as the living beings in nature do; using the sun and simple compounds to create fibers, ceramics, plastics and chemicals that are biodegradable.

- **Nature as a Measure:**

The measure in which biomimicry evaluates innovation is by its effectiveness of problem solving and the feasibility of its ecological standard in regards with sustainability. Since its conception nature has been everchanging, nature also knows how each of its systems work, how strongly each of them operate and nature has done this up until this day. All reasons show that nature is the most favorable measure when it comes to design.

- **Nature as a Mentor:**

Biomimicry is a new way to observe, interpret and get to know nature. It is a concept that teaches to learn from nature, instead of trying to absorb from nature.

As a result of observations conducted to understand nature, Benyus and Dr. Maibritt Pedersen Zari have done research to find out how applicable biomimicry is and they both put out the same conclusions about levels of biomimicry. These levels determined by these two researchers are separated into three levels; organism, behavior and ecosystem. Benyus' organism level refers to the transferring of simple properties of the source that was taken inspiration from, such as its form, into design. The behavior level refers to the transfer of its behavioral qualities, instead of its appearance. While the ecosystem level is the transfer of the source into design by taking into consideration all facets of the environment the source is in [18]. Chapter 2.3 of this thesis goes into more detail on the charts that resulted from Zari's research and Benyus' levels of biomimicry.

This chapter classifies on what level the data taken as inspiration from nature is used when integrating biomimicry into design. The use of nature as a model, measure or mentor in design can be an example of what biomimicry has to offer to designers.

2.1.3. Biomimicry Design Sprial

The design spiral is a diagram created by Carl Hastrich, an industrial designer, in 2005 for the Biomimicry institute in order to transform the strategies of nature into innovative and sustainable design solutions. After adding the principles of biomimicry to a classic design process, Hastrich mimicked one of the models of nature and then made this whole process into a spiral structure. In the design spiral shown in the diagram below, designers are able

to create their designs by passing their products through the following stages, distill, translate, discover, emulate, and evaluate. If the results do not resolve the issue, the cycle is restarted [19].

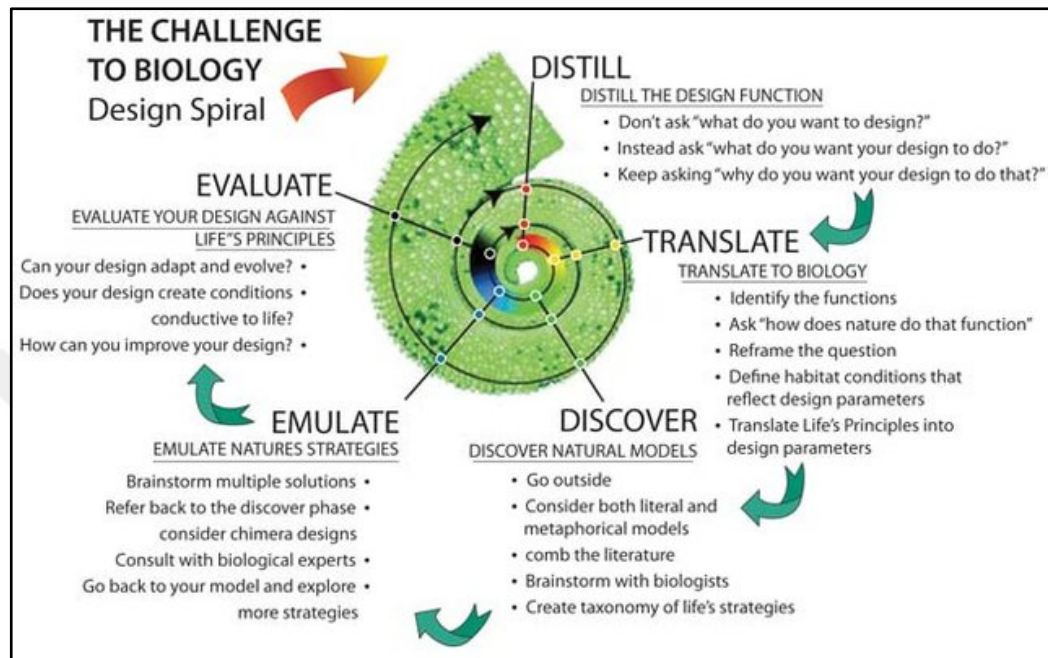


Figure 2.7. Biomimicry design spiral [20].

Carl Hasrtrich explained the design spiral with 5 main steps [21]. During the distill step, design criteria are made that define human needs. One of the first steps of this spiral is the conception of a model that defines the design problem. Later on, this model must be separated into parts in order to determine the design criteria and the cause of the problem. Instead of asking what to design in this step, the question why must be asked until the root of the problem is found, in order to find the function that is the goal of the design process. Lastly, in order to specify the properties of the problem, the target audience and location must also be found, meaning where and to whom the solution is to be provided to [22]. This allows the design function to be determined.

In the Translation step of the design spiral, the problem is re-examined with biological terms in mind and a nature-centric approach is taken towards the problem. The design function is compared to its corresponding solution in nature. The question of what kind of approach nature took to solve, or fail at solving the problem that is similar to the problem in the design [21]. Then the problem is reimagined while using different terms in order to

get a new perspective. The properties of the living space are analysed by determining factors such as climate, food, as well as social factors and variable factors [22].

The Discovery step on the other hand analyzes natural models that have the same function or context as the design problem [21]. The most effective solutions nature has to offer are determined as a result of this analysis. Then, the biological strategies that support the survivability and success of the organisms and ecosystems that found the best solution is determined. Further detail is given about the different approaches taken by the organism that inspiration was taken from. Biologists are consulted in order to ensure that this data is implemented correctly into design, and the design problem is solved by observing the furthest points of the habitat with their help.

Another step of the biomimicry design spiral is the emulating step [21]. Models and processes of biostrategies that have been successful in nature are analyzed. Strategies and classification are made as a result of the analysis. Organisms that use the most successful method to solve the design problem are identified and the selected organisms' work principles are abstracted. These studies help develop ideas and solutions based on nature models; these ideas and solutions are then transferred to the design by using the methods of mimicking form, mimicking function and mimicking the ecosystem [22].

The evaluation step compares the design to the successful principles found within nature. This helps find new ways to improve the design while also asking questions about manufacturing, additional products or materials to use [22].

The spiral shape of the biomimicry design diagram gives designers the ability to do a quick round around the spiral in the beginning of the design process in order to inspire creative ideas, while also allowing designers to identify certain outcomes before a solution can be determined. This approach minimizes the time required to find a sustainable design.

The order of the steps on the spiral and the being able to retrace these steps during the process allows for more innovative and effective design answers to be found. Based on the necessities of the design, the process can be started on any of the steps on the spiral to answer the questions that help with those necessities. If the concept of biomimicry is used to find a solution to the design process' problems, the process begins with the distill step. In order to explore models of nature to find an organism to take inspiration from, the process begins with the discovery step. To evaluate the sustainability of an existing design

and to improve it, the process begins with the evaluate step and completes the design spiral [19]. By doing so, designs can be constantly reviewed and observed in order to help them evolve using the biomimicry design spiral.

Janine M. Benyus, who played a large role in raising awareness of biomimicry, founded the Biomimicry Guild in 1998 to help inform innovative designers about models of nature. Later on, alongside Bryony Schwan in 2006, Benyus founded the Biomimicry Institute to research data found in nature and share it with designers. These institutions work alongside biologists in exploring nature, and advising designers on how to use this information in their design and manufacturing processes. And in 2015 Benyus, Schwan and Chris Allen founded the first digital library of its kind, AskNature, which classifies solutions provided to everyone by nature based on design and engineering in a place where anyone who inquires can find [23].

Another platform that can be used to understand systems of nature and incorporate biomimicry into design processes is Learn Biomimicry. Co-founded by BiomimicrySA (South Africa) and the Biomimicry Institute in 2020, this online educational platform aims to help find creative and innovative solutions to repair the damage done to the planet [24]. This online course system includes predetermined packages that teach basic concepts, biomimicry principles and ways biomimicry can be applied in designs. This way, researchers and designers from all corners of the world can share their knowledge and experience.

It's important to understand nature in order to integrate the concept of biomimicry into designs. This chapter of the thesis analyses biomimicry, which serves as a guide to designers in using nature as inspiration, on a conceptual level. Views of scientists who studied the methods that helped form the principles of biomimicry and ways to implement biomimicry into design throughout history are mentioned and the primary examples of these are given. The biomimicry design spiral is the fundamental approach on these steps and it serves as a guide to follow when applying biomimicry into design. Furthermore, certain institutions and online platforms are mentioned, and they aim to research biomimicry thoroughly while guiding designers in using biomimicry. The goal of this chapter is to serve as a compilation of basic information for other thesis and research papers to use, as well as a conceptual introduction to the biomimicry approaches and levels that this thesis goes into more detail with in the chapters to come.

2.2. BIOMIMICRY APPROACHES IN ARCHITECTURAL DESIGN

Throughout history, mankind has been interested in nature, inspired by nature and has explored the strategies of nature. This information gathered from systems of nature has been used as inspiration for designs in fields such as architecture, engineering, medicine, transportation, textiles and communications. Biomimicry does not aim to copy the solutions of nature directly, its main purpose is to inquire about the basic principles of these solutions and identify the causes of the problems that may arise. Therefore, it is very important to design with support from biomimicry, while always reviewing the principles of biomimicry in every step of the design process.

Biomimicry can be used in one of two ways in design. Design looking to biology is the design approach where a problem is identified in the design process and then a biological source is found in order to solve the problem. Another approach is to examine a biological source and implement the results into design, this is biology influencing design [25]. The analysis of these approaches and their respective examples create a new understanding on the ways how biomimicry can be used in design. These approaches serve as a guide in determining when to use nature in the design process. When getting inspired by nature to find the solution for a design problem, and when taking inspiration from researching the strategies used by organisms and ecosystems in nature, these two different approaches are used to help us understand biomimicry. The fourth chapter of this thesis takes a look at buildings and analyzes which of these two methods were used in their design. In this context, the research on this subject not only helps this thesis, but it also provides aid to any future research.

2.2.1. Design Looking to Biology

Design looking to biology is also known as the problem focused approach or the top-down approach [25]. In this approach the design problem is identified and then the ways in which organisms and ecosystems in nature deal with the problem is observed.

Even when designers don't work with biologists or environmental scientists, they can still analyse organisms and ecosystems in detail to gather biological data and transfer them to their designs. Although interdisciplinary work is important not only when taking

inspiration from the data based on form or behavior of the sources, it is also important with integrating more technical processes such as chemical processes into the design [25].

Michael Helms, Swaroop S. Vattam and Ashok K. Goel from the Georgia Technology Institute explains the six steps of the biological approach to design in the Design Intelligence Lab. This approach is called the top down approach [26]. These steps are visualized based on the research of Helms et al. (Figure 2.8). These steps are as follows:

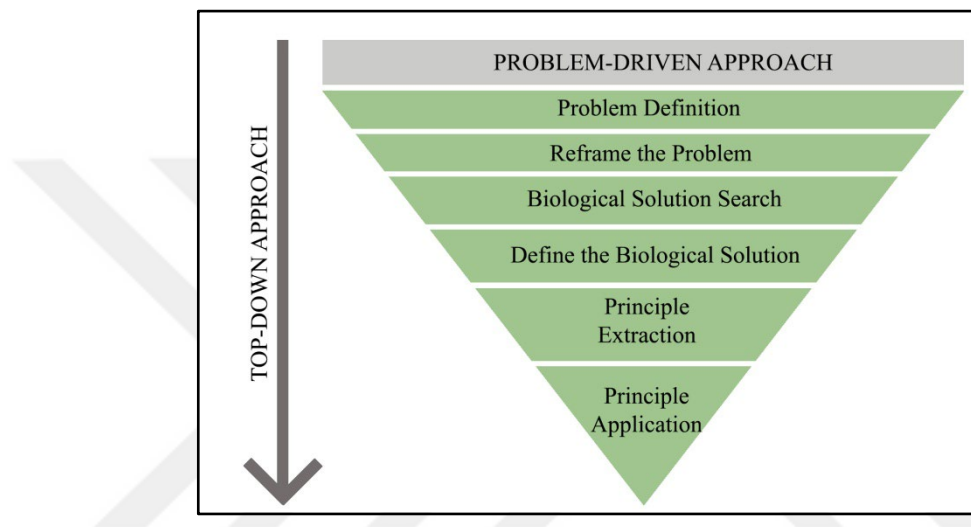


Figure 2.8. Top-down approach (prepared by author).

The first step of the top-down approach steps is focusing on the design problem. A new perspective is gained by utilizing the principles of biomimicry, in order to find a solution to the design problem. After similar strategies in nature that could solve the problem are researched, the findings are applied to the design. This means that the solution to the design problem was inspired by the solutions that the science of biology shows humans in nature.

The bionic car designed by Daimler Chrysler can be shown as an example of design looking to biology. As seen in the steps of this approach, the problem of the design was determined before anything else. Then, the solutions of nature to similar problems were examined. For the bionic car a large but lightweight design was made that would be carried by smaller wheels, and the form of the boxfish was the inspiration in solving the design problems. And the surface tension was minimized by implementing the principle of tree growth into the structure of the automobile. These solutions that were inspired by nature helped make the bionic car lightweight and in turn reduce its fuel consumption when

compared to other vehicles. Thus achieving energy efficiency and integrating sustainable design principles into the design process [27].



Figure 2.9. Design of the bionic car by Daimler Chrysler [25].

An architectural example of design looking to biology could be the facade of the building Torre De Especialidades. Mexico City, where this building is located, was declared as one of the dirtiest mega cities in the world by the United Nations. The air pollution in this city has negative effects on the lives of the people in the city. In recent years, new and exciting designs have been produced to find a solution to this problem. Torre de Especialidades, which is a new hospital building in Mexico City, was designed to help the city's problem by using the pollutants in the air to make harmless chemicals. The facade of the hospital building is covered in a paint that was made from a titanium dioxide based pigment. When the ultraviolet rays from the sun reach the material, it holds in the air pollution and a chemical reaction is triggered which converts the pollution into harmless chemicals such as smoke, water, carbon dioxide and calcium nitrate.

The facade was designed by the Berlin-based architectural firm, Elegant Embellishments, and it consists of a new tile called "proSolve370e". The random and biomimetic pattern of the tiles were inspired by the morphological structure of sea sponges and corals. The properties that helped solve the design problem were the surface structures of sea sponges and corals allow for a better surface suction power and allows them to capture harmful substances from different angles. Every piece of the facade has many different parts that bulge out, helping to capture the harmful gases found in the air. The architects suggest that by using this design, fresher air can be provided for the surrounding area of the hospital while also reducing the effects of air pollution [28].



Figure 2.10. Torre de Especialidades Hospital facade [28].

Designers who use biomimicry as a design method, utilize the concept of biomimicry to create innovative and sustainable products. The approach of design looking to biology can be summarized as, finding the solution to a problem in a project or a design process by looking to nature for an answer.

2.2.2. Biology Influencing Design

Biology influencing design is known as the solution focused or the bottom-up approach. This is the approach where the properties, behaviors and functions of a living being or system in nature, and then the design problem is determined based on the reference taken from nature [25]. Instead of looking for a solution to a specific design problem, this approach uses data collected from biological and ecological research as a guide to possible design problems.

The advantage of this approach is that it provides a solution for a design problem that can be found before it arises as a result of research conducted by biologists or environmental scientists. The process of analysing nature must be led by an expert and then connected to the context of design. Therefore, studies done by biologists and environmental scientists are very important.

A disadvantage of this approach is that biologists and environmental scientists must notice the potential the results of their research have in possibly being a solution in a new design context [25].

Michael Helms and his friends explain this approach with seven steps in the Design Intelligence Lab [26]. These steps are visualized based on the research of Helms et al. (Figure 2.11). These steps are as follows:

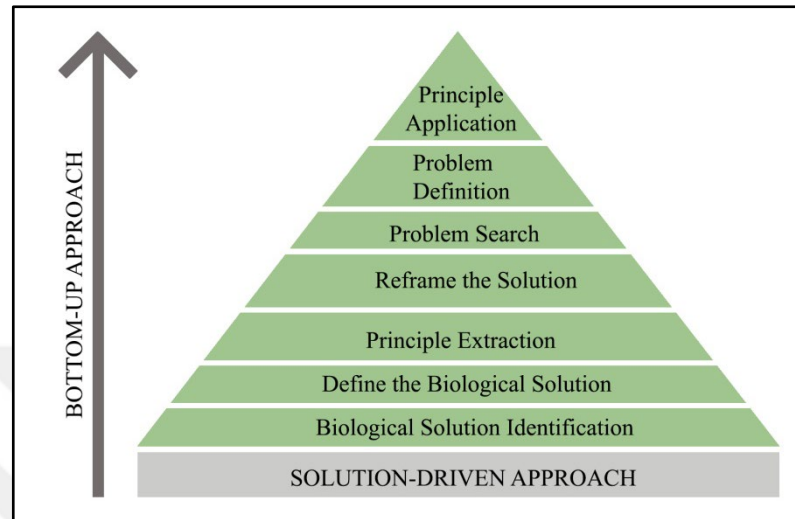


Figure 2.11. Bottom-up approach (prepared by author).

These steps are defined as the exact opposite of those in the design looking to nature approach, or the top-down approach. In the bottom-up approach, the first step is to identify the biological solutions. These results reveal the scientific rule implications of organisms or systems found in nature. The result of the study of nature is then integrated into a design to be a solution to a design problem. This way, biological research is able to be a solution to future design problems.

An example of this approach is the Lotusan paint. The Lotus plant, even though it lives in a dirty and dusty environment, such as a swamp, it always remains clean, its discovery lead to the production of the self-cleaning Lotusan paint. Many innovations were inspired by this property of the Lotus plant after its discovery following its research [25].



Figure 2.12. Lotusan paint, which was inspired by the lotus plant [25].

An example of using the biology influencing design approach in architectural facades would be the BIQ House. This structure is a pilot scheme that was designed to reduce carbon dioxide and carbon sequestration. Scientific research revealed that algae have the property of consuming carbon dioxide and producing biomass, and this led the designers of BIQ House to use micro algae in the glass panels of the facade in order to avoid air pollution. The algae that is produced by the facade, provides urban development with renewable energy in the shape of biomass while also helping to keep air pollution down. The facade system also provides the building with sound and heat insulation, as well as shade. A sustainable design that was conceived using biomimicry is capable of producing energy from its own shell, for storing or using it for its own needs [29].



Figure 2.13. (a) BIQ House, (b) microalgae on glass panels [30].

Even though the biomimicry approach in the design process was the result of biological research, it provides designers with a new perspective on the application of sustainable design principles. Although the two approaches that are being examined are opposites of each other, both use the strategies of nature and they both want to find a design solution. This results in innovative design insights that are sustainable and natural compatible.

In this chapter of the study, the main principles of the two biomimicry approaches; biology influencing design and design looking to biology, and the key stages of these two approaches are being studied. Review of architectural examples and the examples from other sectors that adopt these two approaches lays the basis of design for future designs to use with biomimicry. The architectural facade designs that are mentioned above are categorized by their biomimicry approaches, design looking to biology or biology

influencing design, and this helps in further defining biomimicry examples in the fourth chapter of this thesis. As a result of research it was concluded that the detailed review of the two biomimicry design approaches creates a base for the research of biomimicry levels.

2.3. LEVELS OF BIOMIMICRY IN ARCHITECTURAL DESIGN

For all of history, taking inspiration from nature was strictly done through shape. Organisms found in nature have been mimicked aesthetically and based on their forms, but interpreting their function into design was left in the background. The founder of the biomimicry movement, Janine Benyus, put out the data she found about the biomimicry approaches and levels in order to bring design into a new dimension. Two approaches were examined in chapter 2.2 of this thesis, and the three biomimicry levels to apply to a design problem have been defined as form, process and ecosystem. When observing an organism or ecosystem, form and process are inimitable properties of the organism or ecosystem. Although an ecosystem is also something that can be reviewed to find inimitable properties [25].

Maibritt Pedersen Zari, who watched developments in biomimicry and Benyus' work closely, has proposed a frame that redefines these levels, and aims to understand and clarify the potential of biomimicry while contributing to innovative designs in the structural environment. This frame shown below helps designers to determine the necessary approach they should use biomimicry in order to increase the sustainability of their designs. The frame that is explained here is applicable to both design looking to biology and biology influencing design [25].

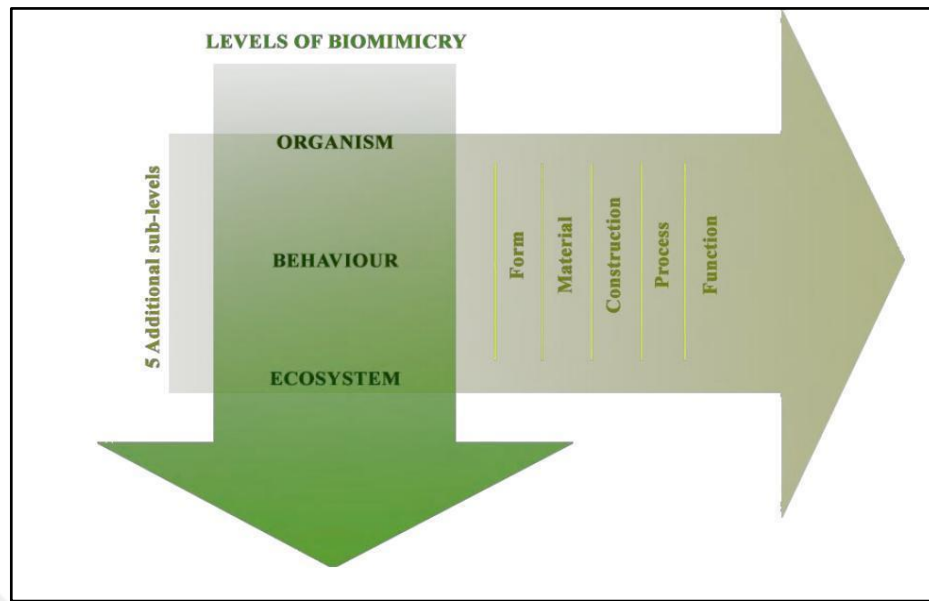


Figure 2.14. Levels of Biomimicry [31].

When the three biomimetic technologies of today are examined the three levels of mimicking can be seen clearly; organism, behavior and ecosystem. According to Pedersen Zari, the organism level refers to design mimicking a specific part, or the entirety of an organism found in nature. The behavior level is the mimicking of the strategies found by observing organisms behaviors or the ways in which they survive. Lastly, the ecosystem level is the mimicking of the whole environment the organism lives its life in [25].

5 more dimensions were also defined for each of Zari's biomimicry levels, and they can all be mimicked. Questions are asked regarding what the form of the design looks like, what materials it is made from, how it is structurally constructed, how the design works throughout the process and what functions it can achieve. The differences between each type of biomimicry are described in "Figure 2.15" shows how to imitate different aspects of a termite, or the ecosystem in which the termite lives [25].

Level of Biomimicry		Example - A building that mimics termites:
Organism level (Mimicry of a specific organism)	<i>form</i>	The building looks like a termite.
	<i>material</i>	The building is made from the same material as a termite; a material that mimics termite exoskeleton / skin for example.
	<i>construction</i>	The building is made in the same way as a termite; it goes through various growth cycles for example.
	<i>process</i>	The building works in the same way as an individual termite; it produces hydrogen efficiently through meta-genomics for example.
	<i>function</i>	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)	<i>form</i>	The building looks like it was made by a termite; a replica of a termite mound for example.
	<i>material</i>	The building is made from the same materials that a termite builds with; using digested fine soil as the primary material for example.
	<i>construction</i>	The building is made in the same way that a termite would build in; piling earth in certain places at certain times for example.
	<i>process</i>	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.
	<i>function</i>	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)	<i>form</i>	The building looks like an ecosystem (a termite would live in).
	<i>material</i>	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.
	<i>construction</i>	The building is assembled in the same way as a (termite) ecosystem; principles of succession and increasing complexity over time are used for example.
	<i>process</i>	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and stores water for example.
	<i>function</i>	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.

Figure 2.15. A framework for the application of biomimicry [25].

Just like how biomimicry levels can be applied independent from one another, it is also expected for there to be some overlap among them. For instance, a system on the ecosystem level is mimicking an ecosystem found within nature. Even though a biological ecosystem is made up of a large number of organisms coming together, the details of the ecosystem level in biomimicry show that it is only able to mimic one organism or one behavior [25].

By using the methods on the table, different organisms can be observed and different design methods of biomimicry can be used. This allows biomimicry focused designs to use the design strategies of nature in their design for not only aesthetics, but also for functionality and applicability.

2.3.1. Organism Level

The organism level refers to the mimicking of a specific organism as a whole, or just a part of it [32]. The species of living organisms in nature have typically been evolving for around millions of years. These organisms that remain in the world survive the ever changing nature of the world with resilience and by using adaptation. And humans use this data from these surviving organisms in order to more efficiently use energy and materials, while solving the problems of society. All of this helps in eliminating the damage to the environment caused by human activity and the structural environment [33].

An example for the organism level is the *Stenocara*, a desert beetle from Namibia. The beetle lives in an isolated desert that doesn't get a lot of rainfall. The organisms that live here beside the *Stenocara* beetle all have to find different methods to survive the longer dry season in the region and to find the necessary water sources. Although rain is rare, there is often fog in the mornings, the design of the beetle's shell instinctually provides the beetle with the food and water it needs to survive. It is able to turn its back against the wind to capture the humidity in the air. Thanks to the hydrophilic and hydrophobic bumps on the back of the beetle, water drops are captured and rolled to the beetle's mouth [32].

Matthew Parkes from KSS Architects took inspiration for a fog separator he proposed to Namibia University's Hydrology Department from the beetle, thus showing the organism level of biomimicry. The designer was impressed by how resilient the beetle was in harsh conditions and used this property in his fog separator device by allowing it to gather water particles from the fog and turning it into water, just like the shell of the beetle [32]. Research shows that the surface of the Namibian beetle's shell was observed and the findings were mimicked to be applied to equipment that aims to extract humidity from fog.

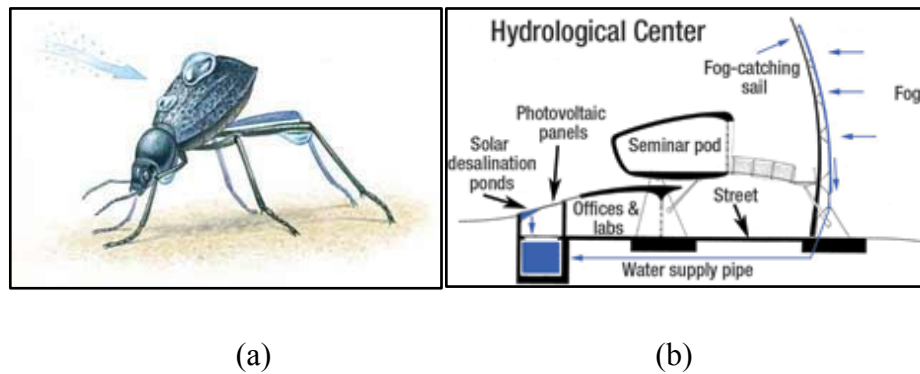


Figure 2.16. (a) The stenocara beetle [34]. (b) Matthew Parkes' Hydrological Center for the University of Namibia [35].

An example of the organism level of biomimicry for form and process would be Nicholas Grimshaw and Partners' Waterloo International Terminal. The train must react to changes in air pressure as it enters and exits the terminal. The glass panel parts in the terminal design were inspired by the layout of a pangolin's flexible scales and it can move according to the forces of air pressure [36].



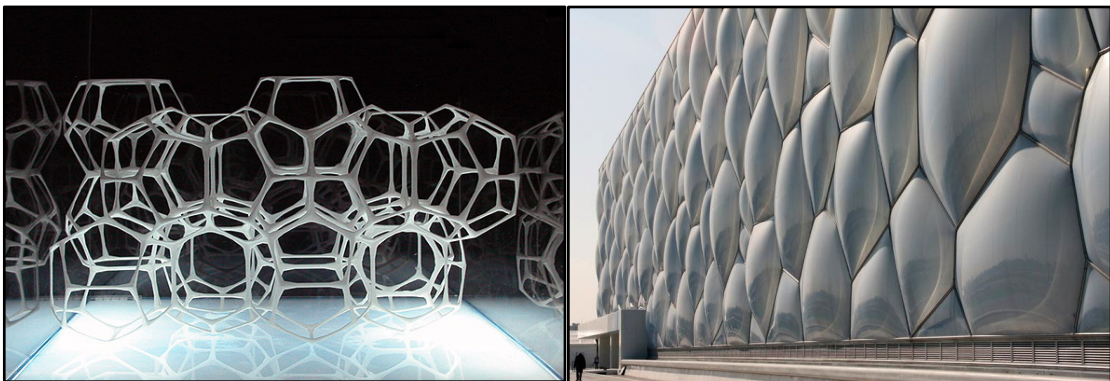
Figure 2.17. (a) Pangolin, (b) Waterloo International Terminal, London, UK [37].

Another example of the organism level is Javier Senosian's home design, the Nautilus, inspired by the shape of a snail. This structure is also known as bio-architecture, inspired by the work of Gaudi and Frank Lloyd Wright. The idea of bio-architecture refers to designing the form of a building organically, according to strategies found in nature. This approach aims to create eco-friendly designs while sticking true to the local history of the structure's environment, traditions and cultural roots [38].



Figure 2.18. The Nautilus residence [39].

A recent example of the biomimicry organism level is the Water Cube, also known as the Beijing National Aquatic centre, designed for the 2008 Olympics. The facade design of the building, which was built in collaboration with PTW Architects and Arup, was inspired by the form of soap bubbles. The Weaire Phelan structure, which was discovered in 1993 by Denis Weaire and his assistant Robert Phelan, has been a guide in the design of the facade. Based on this structure, the shape, transparency, and resistant structure of the soap bubble were abstracted and transferred to the facade. After all, polyhedral cells are brought together on the facade of the Water Cube, giving the structure a homogeneous appearance. [40].



(a)

(b)

Figure 2.19. (a) Weaire Phelan structure [41]. (b) Water Cube [40].

Products or projects designed on the organism level are not designs that benefit the ecosystem as a whole, meaning they are limited to only taking inspiration from the form of an organism, and cannot affect sustainability. In accordance with this, the mimicking of an organism only transfers one property to the design, instead of an entire system, therefore the inspiration is a technological upgrade to the building rather than something integrated into the building as a whole. So, in order to increase sustainability on this level, it is important to carefully research the design strategies of nature and to use inter-disciplinary knowledge in the process [25].

2.3.2. Behavior Level

Humans and organisms in nature experience the same environmental conditions and they must solve some problems that these environmental conditions can bring. Organisms tend to continue their lives in accordance to the carrying capacity and the availability of energy and materials in their environments. The limits set by the duties and responsibilities that organisms have in their ecosystems only allows organisms that can adapt to continue their evolution, while also showing the well-adapted organism behaviors, the organisms and the relationships between species [42].

Organisms that can control the relationship other species have with the sources they need, and in turn change the ecosystem they are in with their own shapes, mechanical ways or by any other means are called ecosystem engineers. Humans are most definitely ecosystem engineers. These beings observe how their surrounding species live and fight in order to survive, and in doing so learn very useful information. The way in which other species in nature find shelter are called animal architecture and they provide ecosystem engineers with examples [43]. For example the North American Beaver (*Castor canadensis*) has a work principle; they transform the landscape into what they need while showing how wetlands are formed and how storing food increases diversity in organisms. This behavior of the beaver helps the ecosystem become more resilient against damage [44].

According to Zari, the behavior level of biomimicry mimics how the organism acts, instead of mimicking the organism itself. It's possible to take inspiration from the relationship between organisms and species as well. Michael J. Maglic, who does research on biomimicry, defines the behavior level in his thesis "Biomimicry: Using Nature as a Model

for Design" as mimicking a specific behavior that an organism uses to continue its life, or mimicking something the organism does on a daily basis [32].

The steps of defining, solving and eliminating design problems are examined in the behavior level. Results are achieved by asking the question of what needs to change in order to solve the problem in the design process.

An architectural example of this biomimicry level is the Eastgate Building in Harare, Zimbabwe by architect Mick Pearce, and the CH2 Building in Melbourne, Australia. Both buildings were designed with inspiration from the strategy termite nests use for temperature regulation, and in doing so creating an interior with a stable heat and a semi-passive ventilation system [25].

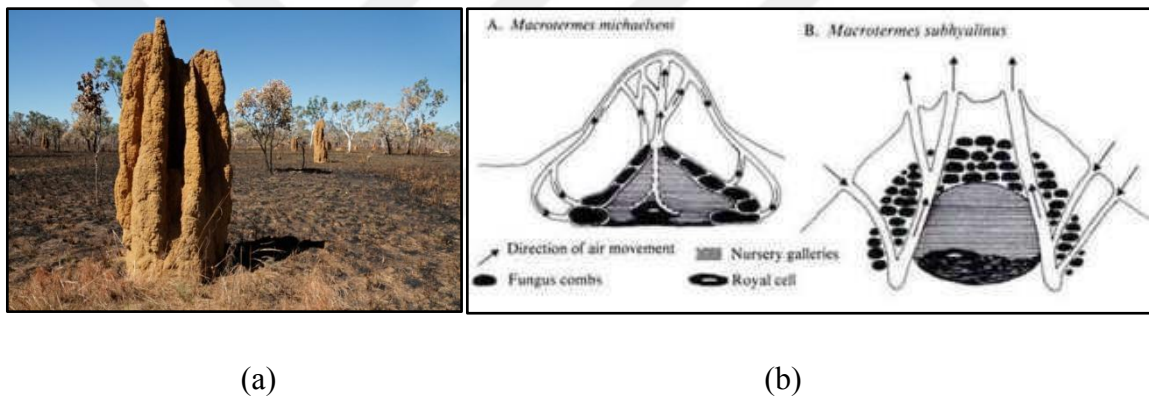


Figure 2.20. (a) Termite nest [45]. (b) temperature regulation [46].

The inspiration for the design of the Eastgate Center was the instinctual behavior of termites building their nests. The building was constructed from concrete in order to hold the heat from the sun all the while being good at insulation. The air that enters the building is either heated or cooled down, according to the temperature of the mass of the building. If the building mass is colder than the air, the air itself is cooled down further. The cooled down air rises towards the chimney and is taken to the different floors and offices in the building on the way. The building consists of two exterior structures and a central glass hub. The central glass structure also benefits from the heat transfer of the exterior structures. This way, ventilation is achieved without using any mechanical heating or cooling systems, thus reserving energy [32].

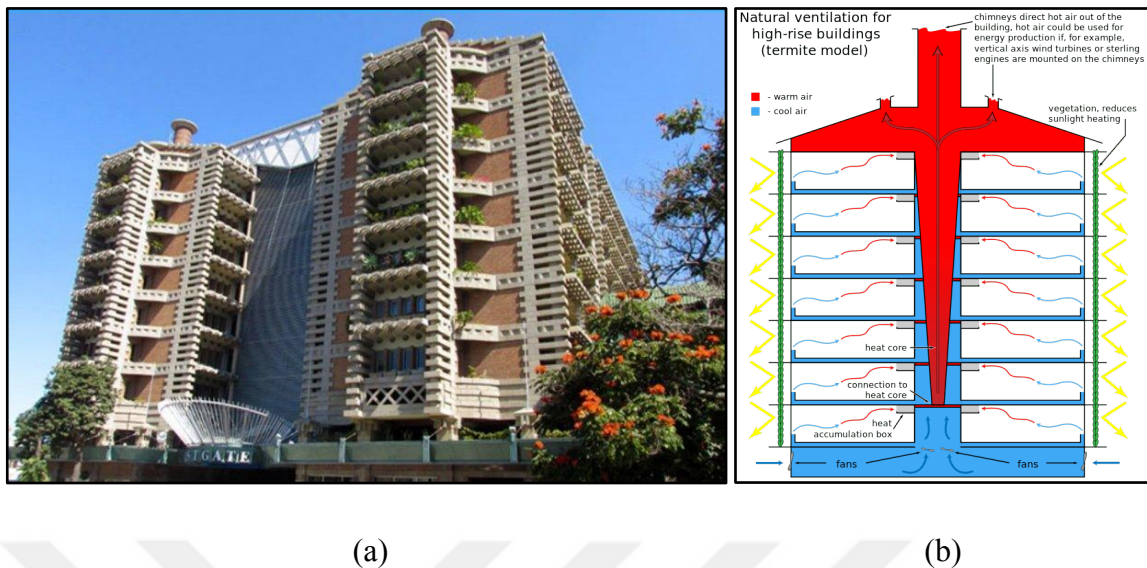


Figure 2.21. (a) Eastgate Center in Zimbabwe [47]. (b) section showing how temperature is regulated [48].

The main principle of the behavior level of biomimicry is transferring the behavior of the mimicked organism during its daily life into the design. The instinctual actions of every living being in nature has valuable data that could solve the design process or the design problem. In this context, architects and designers integrating the instinctual behavior properties of organisms into an architectural structure are knowingly or unknowingly using biomimicry. Although the mind and thinking are utilised in realizing architectural projects, the feeling that appears in the conceptualisation phase of the architectural design is similar to organisms unconsciously doing things that benefit themselves. Therefore, it's possible to say that biomimicry discovered the connection between the architectural process and behavior of organisms.

When researching the behavior level of biomimicry, a lot of designs inspired by the nests of termites can be found. American philosopher Daniel Dennett, known for his work in philosophy, writing and cognitive science, has found architectural similarities between the constructions of termite colonies and the La Sagrada Familia church in Barcelona, Spain. Daniel Dennett, in his book "From Bacteria to Bach and Back: Evolution of Minds" talks about his thoughts on this subject. Dennett argues that the termite colony does not have a way to guide them or to engineer them, but instead, the nests that resemble castles are made through their evolutionary instincts. La Sagrada Familia's architecture is impossibly complicated, yet Gaudi's plans have been utilised up until the present. Dennett questions

how the termites can coordinate, just like he questions how millions of neurons in Gaudi's brain can coordinate to design the church. He answers this by looking at the evolution of the mind. To him this is cultural evolution, which is affected by our ability to think and the evolution of language [49].

One of the leading evolutionary biologists of the world, Professor Richard Dawkins, is also studying the similarities between these two structures; he started a discussion by sharing the image of the structure built by the termites that resembles a cathedral. He put these two photos next to each other (just like Daniel Dennett argued) and asked if anyone knew what this structure, without an architecture or a plan, was. Researchers that saw this photo made comments about the striking similarities between the unique shape of the termite nest and the shape of the cathedral [50]. When reviewing this discussion it can be seen that the natural ventilation of the nature-dwelling termite nests was integrated into the behavior level of design, and it was argued that the instinctual behavior the termites had when building the nest should also be taken as an inspiration. Therefore, it can be concluded that the design of La Sagrada Familia follows the organism level of biomimicry because it could have been inspired by the shape of the termite nests, but it also follows the behavior level of biomimicry by mimicking how the termites behave while instinctually trying to find shelter.



(a)

(b)

Figure 2.22. (a) Termite nest, (b) La Sagrada Familia [50].

When looking at the Eastgate Center and La Sagrada Familia, it can be seen that both of them were influenced by the behavioral movements of termites when building their nests.

In the Eastgate Center building, the behavior of the termites and the form of the nests are both used in order to provide natural ventilation to the ventilation system of the building. And in La Sagrada Familia, at first sight the similarity with the nests seems to be only in appearance, but research shows that the design and construction process of the church was influenced by the behaviors of the termites as well. Both of these buildings took advantage of the behavior level of biomimicry and used nature as a source of inspiration.

The applications of mimicking on the behavioral level must comply with the ethical rules in the context of humans. Not all organisms in nature behave in ways that would be appropriately implemented into human design. This comes with the danger that the models of consumption and exploitation of mankind might be applied in mimicking the behaviors of other species. For instance, it may be ethically appropriate to use termite behavior in supplying a building design with natural ventilation. However, it would not be appropriate with universal human right to try to mimic the social structure of termite colonies with humans. Mimicking in social and economical parts of society must not be done unless sufficient research is made. It is instead more appropriate to integrate organism behaviors into buildings in order to increase the sustainability and renewability environment [25].

2.3.3. Ecosystem Level

The ecosystem level refers to the mimicking of a specific ecosystem that exists in nature. The way in which the ecosystem works successfully is explored and the necessary elements and principles that it uses to achieve this are defined [32].

According to Benyus and Vincent, mimicking ecosystems is an important method of biomimicry. The term ecomimicry refers to the mimicking of ecosystems in design; the term is a combination of the words ecology and mimicry. Ecomimicry considers the designs of nature and strategies as superior to any human design in every way, and in this context, it is a method that contains the same principles with biomimicry. Ecomimicry mimics the structural properties, functions and processes found in the ecosystems of nature in order to create sustainable design [17].

An example of the ecosystem level is the Lloyd Crossing Project by a team that consists of the Mithūn Architects and GreenWorks Landscape Architecture advisors. The project,

which was designed in Portland, Oregon, aims to maintain the high ecological performance rates by analysing the properties of the ecosystem that surrounds the project [25].

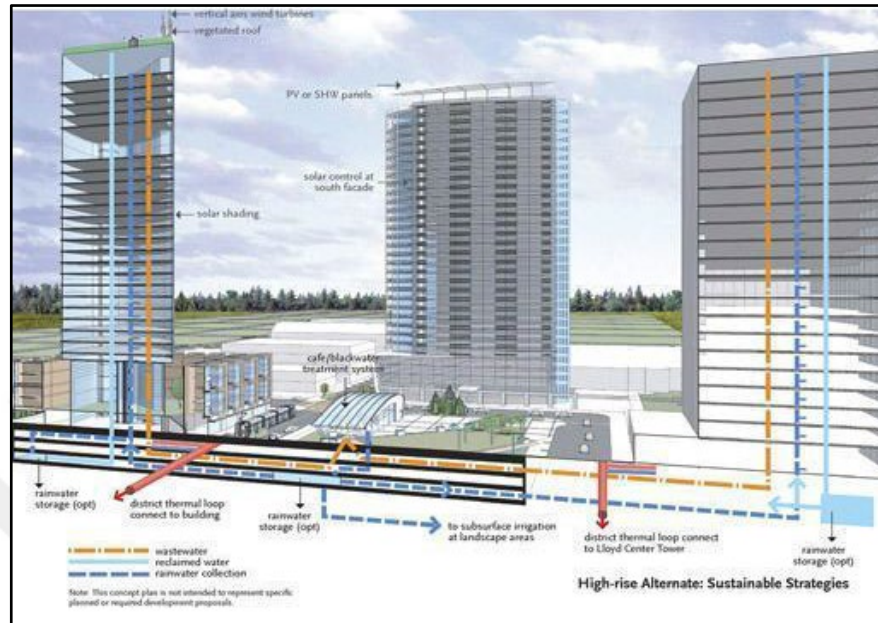


Figure 2.23. Lloyd Crossing Project, Portland, USA [51].

Another example of the ecosystem level is Zira Island Master Plan, designed by the founder of BIG Architects, Bjarke Ingels. Zira Island is an island project in the crescent bay that is located in the capital of Azerbaijan, Baku, and it aims to be a self-sustaining island that is independent from imported resources. The shape of the project was designed to symbolise the seven most important mountains in Azerbaijan. The architect defines this island as a desert devoid of vegetation, water and resources. Several new sustainability technologies were used to create an independent ecosystem on the island.

Zira Island benefits from the fact that Baku is a wind city by using the energy from wind turbines to the desalination facilities. These facilities desalinate the sea water to supply the necessary freshwater and the water is used to heat and cool down the building. And the excess water is used to provide water to the vegetation on the island. The solid material left behind in the desalination process of the water is used to fertilize the plants. The facade and the roof also contain discharge pipes and photovoltaic panels to generate electricity for the island. Thanks to these properties, the island became a self-sustaining and independent ecological system. The strategies utilised in Zira Island inspire many large scale sustainability awareness projects all across the world [32].



Figure 2.24. Overall concept of master plan [52].

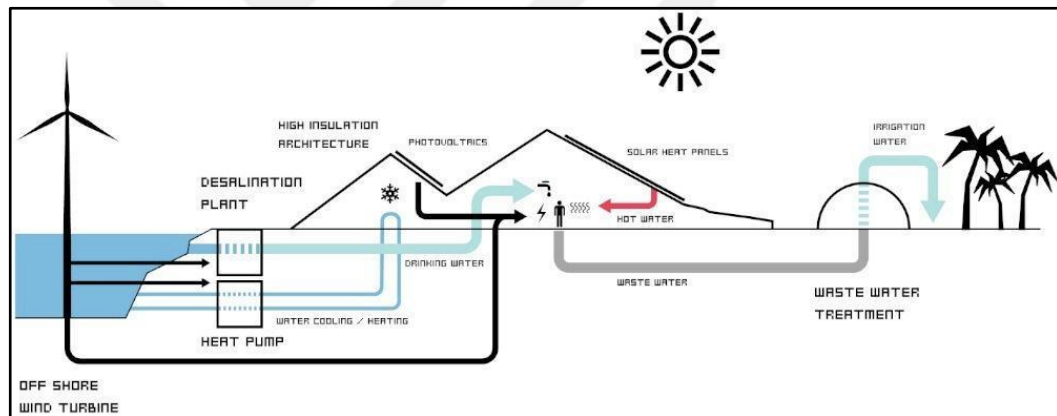


Figure 2.25. Section displaying sustainable technologies [52].

This research shows that designing at the ecosystem level includes both biomimicry levels due to the fact that during the mimicking of an ecosystem, the shape and behavior of the organisms within that ecosystem is useful to the design process. This is seen as an advantage of the ecosystem level. Another advantage of the ecosystem based biomimetic design is the fact that, as seen in the Lloyd Crossing project, it is applicable to a series of time and location measures. This defines the baseline criteria of how sustainable and innovative design must be formed.

Another advantage of this level of biomimicry, in addition to the previous ones, is the fact that it has effects above the general environmental performance levels. Ecosystem based biomimicry can be applied both metaphorically and in a practical and functional sense.

Metaphorically, even when designers don't have much in terms of ecological information, they can use general ecosystem principles as inspiration for their design [1]. The principles that were formed after the comparison of interdisciplinary knowledge were detailed by Pedersan Zari and Storey [53]. If the structural environment is designed with the idea that it works as a system, or on a metaphorical level, it is expected to behave like an ecosystem, it might increase the performance of the structural environment [54].

Mimicking the functions of an ecosystem allows for ecology to be understood on a deeper level and it serves as a way for environmental design to not harm the cycle of biogeochemical substances in the planet. Architects must increase the interdisciplinary teamwork while creating structural environments with disciplines such as biology and environmental science. An understanding of design such as this challenges the traditional understanding of architecture, especially the typical limits and processes of a project. Kibert, when mentioning many other researchers of this thought, criticized this approach due to issues understanding ecosystems and the process of modelling, and he argues that mimicking nature in human design is one-dimensional and not complex [55]. Benyus defends that this thought could be right when it comes to structural environments, but the mimicking of known facts about the ecosystem in design would not get in the way of increasing sustainability [1].

Research shows that by looking at the approaches and levels of the biomimicry concept, it is not a method that is limited to only mimicking form or shape. Biomimicry is a multifaceted concept that integrates systems of nature and organisms' behaviors and processes into designs. It also works alongside fields of science such as biology and environmental science, thus increasing interdisciplinary sharing of knowledge. The harmony between human and nature in structural design allows for more innovative and sustainable designs to be made.

The information shared and example projects given in this chapter that examines the levels of biomimicry serves as a fundamental approach on which levels of biomimicry can be used in design. Organisms and ecosystems found in nature inspiring designs on organism, behavior and ecosystem levels helps the principles of biomimicry to be utilized and used as a guide in designs. This chapter serves as a guide when determining which biomimicry levels were used when analyzing architectural examples in this thesis that use biomimicry in their facade systems.

2.4. INTEGRATION OF BIOMIMICRY IN ARCHITECTURE

Making designs by being inspired by nature is as far in the past as human history. Mankind survived in natural spaces such as caves, piles of boulders and tree barks, in order to be protected from external forces and to satisfy their needs for shelter. And when they settled down permanently, the first shelters were constructed. Natural formed shelters that look like caves or tree barks were created after observing shapes found in nature and attempting to mimic them. This shows designers that the technique of getting inspired by nature was also used in architecture, as it is used in many other fields today. Architecture is a man-made concept that creates the silhouette of the structural environment, it regulates the relationship between humans and nature and it creates a functional space. Architecture also harms nature during the action of construction, and today, repairs are attempted to the damaged relationship between humans and their surroundings. Looking to nature for solutions to these problems that are faced in our physical surroundings plays a role in minimizing the damage done to the relationship with nature and in creating more livable spaces for people.

Observing organisms and systems in nature and using them as inspiration for design serves very effectively in solving the problems of the design process. The forms, colors, textures, lives, behaviors and many other properties of living beings in nature are analyzed and used in architectural design. In this context, biomimicry is a field of science that is not only used by architecture to determine the shape of a design, but also as a design strategy and a design method that can lead to sustainable designs being made. Adopting the principles of biomimicry in design would foreseeably allow the architects of today and tomorrow to innovate their designs' forms and functions.

Architectural trends that were inspired by nature came about with the start of the Renaissance, which put the use of natural forms in design to the forefront. In Baroque and in Rococo design, decorative elements were copied from nature and formed in an organic way. Mimicking nature in embellishment is defined as interpreting the colors, textures and patterns in nature when designing facades or the skin of a building [56].

The first examples of biomimicry in architecture are the designs of the Eiffel Tower and the Crystal Palace, which were designed by mimicking nature. The Crystal Palace was

inspired by the amazon lily flower and it was designed by the greenhouse architect Joseph Paxton in 1851. The large and strong leaf of the amazon lily flower, that can carry great weights, was taken as inspiration when trying to make the building, which was made with heavy iron and glass, look lightweight and elegant. The endurance provided by the forked structure of the leaf proved efficient in placing glass on top of the steel structural system [57]. The architect adopted the organism level of biomimicry when using nature in design by mimicking the form of the leaf in this structure inspired by the amazon lily flower.

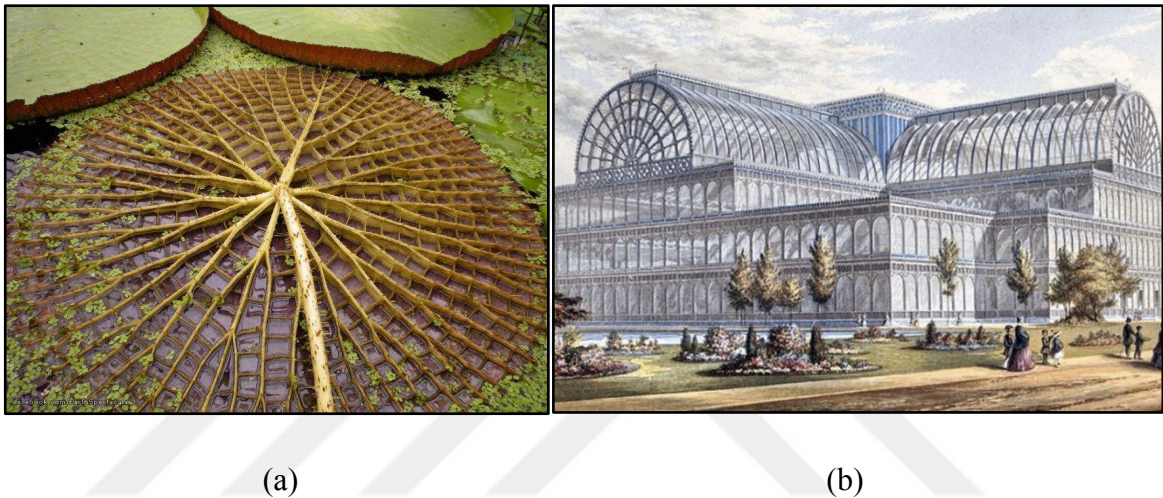


Figure 2.26. (a) Amazon lily [58], (b) Crystal Palace [59].

And in the end of the 1880s, when designing the Eiffel Tower, Stephen Sauvestre and Gustave Eiffel examined the femur bone and got inspired by the hollow shape of the bone and came up with the structural skeleton that supports the tower's eccentric loads [57]. It can be concluded that the organism level of biomimicry was utilised because the design of the Eiffel Tower took inspiration from the structural form of the femur. The shape of the bone also helps the form and structural system of the tower.

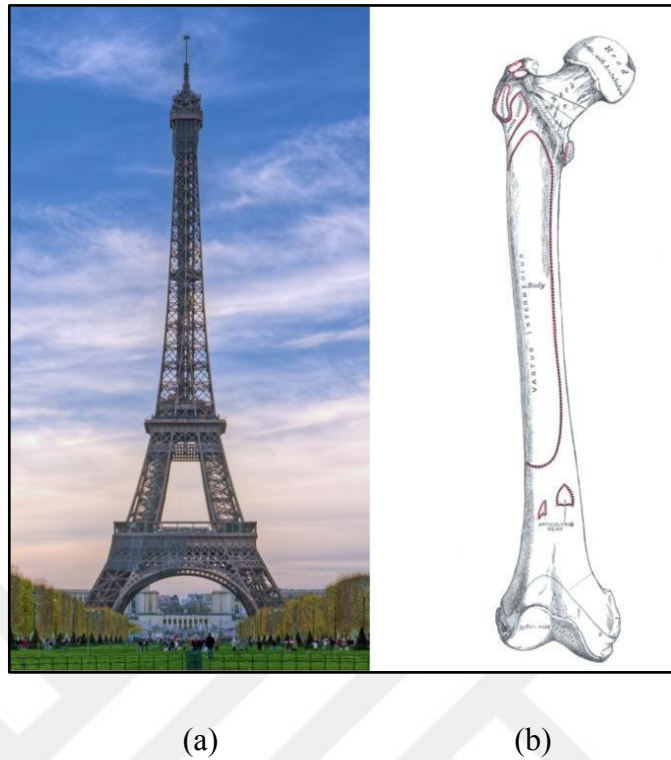


Figure 2.27. (a) Eiffel Tower, (b) bone [60].

In the 19th century, architect Antoni Gaudi made his designs by taking inspiration from nature, by using biomimicry. Gaudi sees the trees outside his workshop as his mentors and he argues that nature should be the inspiration of architecture. He explains this thought as follows; "If nature is God's creation and if architectural forms take inspiration from nature, then the best way to honor God is to look as his creation does" [61]. It can be seen that Antoni Gaudi mimicked forms of nature in many of his works' exterior and interior spaces. In this context, research shows that most of Gaudi's works were designed using the organism level of biomimicry.

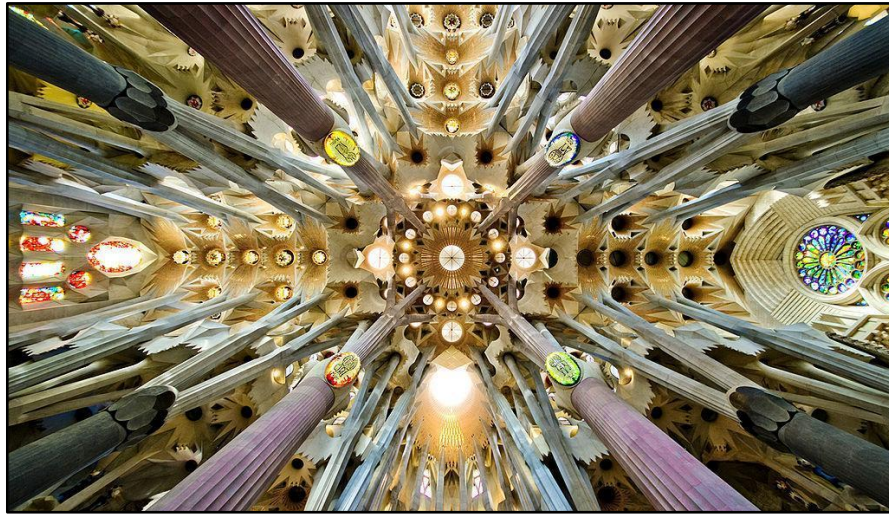


Figure 2.28. A view of Antoni Gaudi's masterpiece, La Sagrada Familia [62].

After Gaudí's approach, biomimicry entered the world of architecture, and many architects used nature as the inspiration for their designs in simple and form-related ways. Frank Lloyd Wright, who uses an architectural design trend called organic architecture in his designs, formed the shapes of his designs in accordance to the nature of the materials used. Fallingwater, designed by Frank Lloyd Wright, is seen as an eco-friendly structure with its form and the materials it uses. Another work of the architect is the Johnson Wax building, which looked at lily pads in the design process and used the shape of this leaf of a flower in the column of the structure. Even though the structure is morphologically similar to the flower, it has no similarities when it comes to function. Therefore, it can be seen that Wright used biomimicry for interpreting appearance in this design [3]. Thus, the research shows that Wright used the organism level of biomimicry when designing these buildings. This means that the behavior of the organisms that inspired the buildings had no impact on the design, and the inspiration only affected the form of the design.

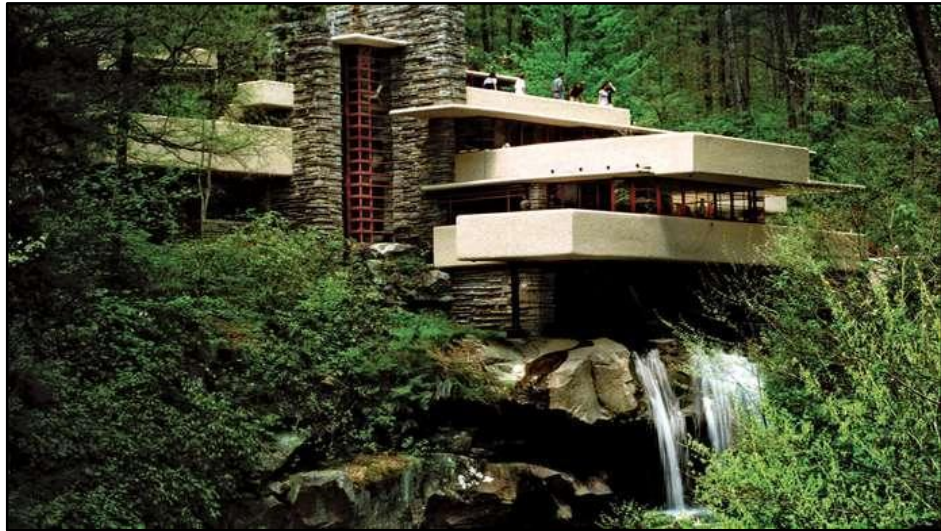


Figure 2.29. Fallingwater designed by Frank Lloyd Wright [63].

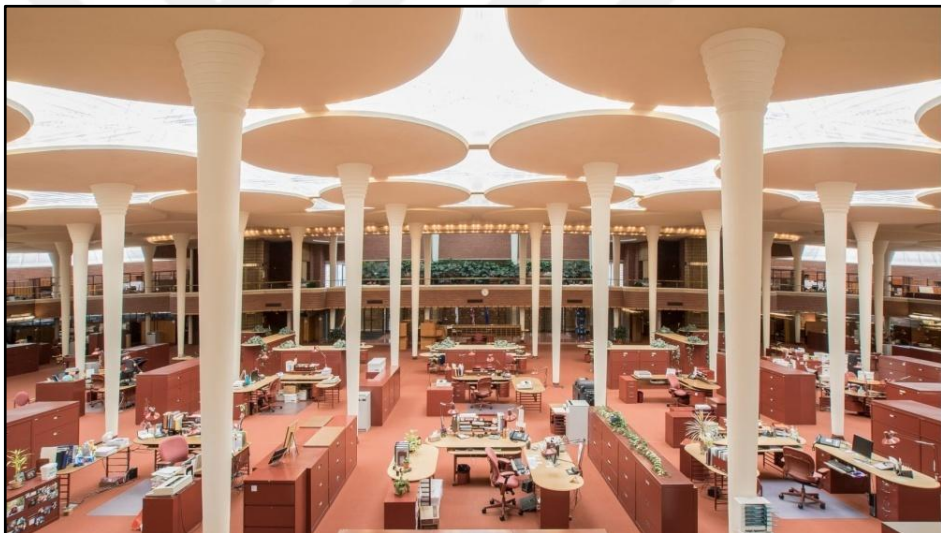


Figure 2.30. The Johnson Wax offices designed by Frank Lloyd Wright [64].

Due to the innovative methods and advanced technology in the 21st century, the use of biomimicry in architecture has provided a transition from shape transfer to function transfer. In accordance with this, the benefits of biomimicry in the field of architecture is mostly seen in structural, facade, building envelope and plumbing systems. Spanish architect and engineer Santiago Calatrava, known for his nature influenced designs, uses the functional assets of the forms of nature in his designs. Calatrava's designs are influenced by animal skeletons in aesthetic ways and in functional ways. Milwaukee Art Museum, completed in the year 2001, mimics form in the structure while benefiting the building with new functions, thus becoming an example of biomimicry based architectural

design. Calatrava was influenced by the shape and behavioral principles of the wings of a bird in this design. The structure is similar in form to the wing of a bird and the collapsible roof system allows for controlled entry of sunlight into the interior [65]. Since Calatrava took inspiration from both the form and function of the wings of a bird and its principles of flight in this design, it is a design that integrates biomimicry on both the organism level and the behavior level.

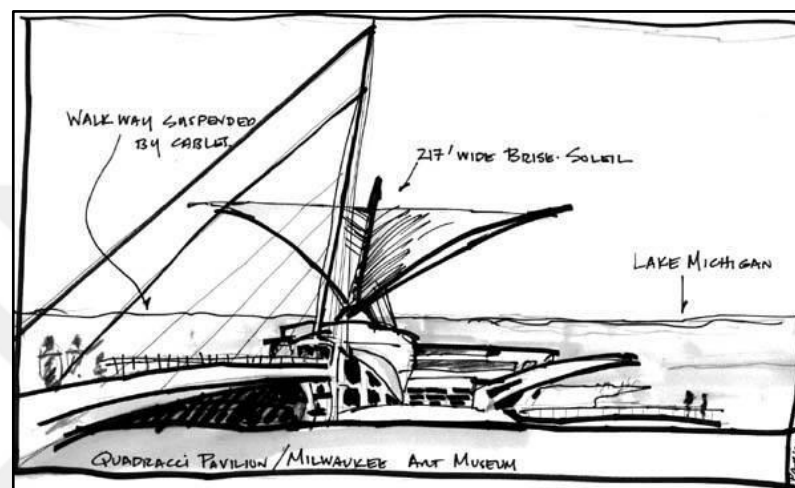


Figure 2.31. Design sketches for Calatrava's Milwaukee Museum [66].



Figure 2.32. Milwaukee Art Museum dynamic roof system [66].

English architect who works in biomimetic architecture, Michael Pawlyn, observed the life methods and systems of many living beings in nature in order to look for answers to problems that people face in the world and he came up with design solutions. He made some very sustainable and innovative designs that serve as examples of ecological

architecture due to this understanding of design. One of them is the Eden Project, found in England and designed by Pawlyn and his design team. The Eden Project is valuable in showing what people can achieve when working together with nature. The structure is made up of a connected series of geodesic domes and these units are connected with steel pieces. The inspiration behind this system is the form of the wing of a dragonfly and its working principles. The domes (biomes) serve as greenhouses; containing thousands of species of plants living and being grown, protected in their natural environments. The Eden Project is a nature education center that strengthens the relationship between people and nature by offering the beauty found in nature while educating visitors about sustainable design [67].

The Eden Project is a structure that aims to not only get inspired by an organism or a system, but instead it aims to create an entire ecosystem. The domes were designed to mimic the tropical rainforest climate and the Mediterranean climate. In this context, the Eden Project designs on the ecosystem level of biomimicry.

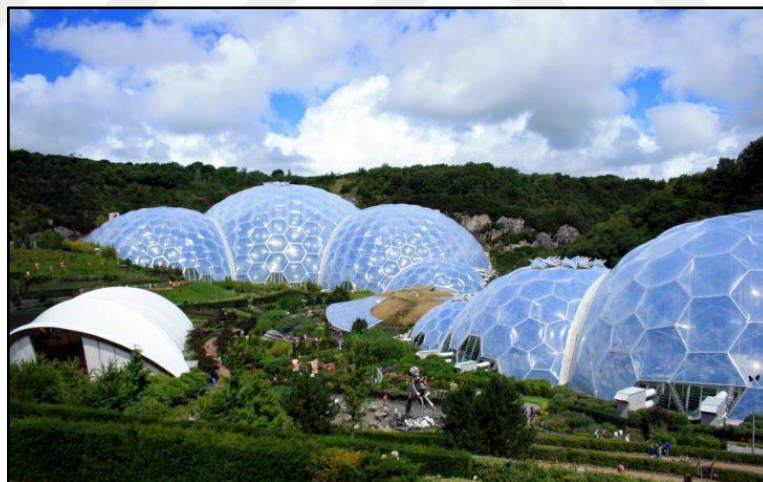
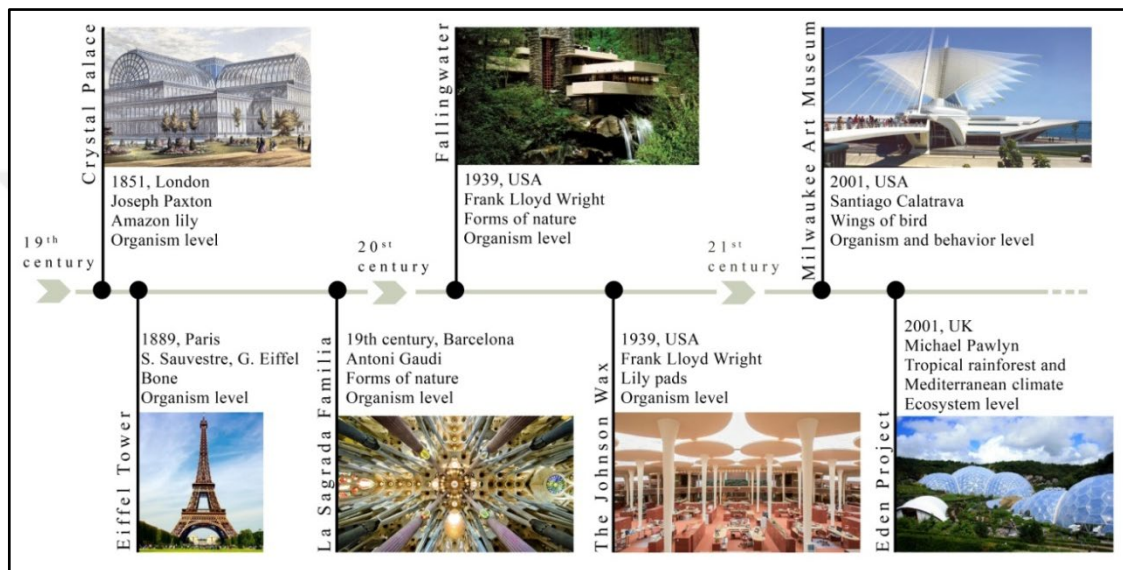


Figure 2.33. Eden Project [68].

As seen in the "Table 2.1" below, examples of biomimicry in the field of architecture examined in this section are visualized chronologically. In this context, when looking at the building examples based on biomimicry throughout history, it is seen that designing inspired by nature exists in every period and that architects integrate biomimicry into their designs in many areas such as facade, structure, and interior design. Although the field of biomimicry was a design method that only affects form in architecture in ancient times, it has been used as a method that affects functionality with the development of technology.

In addition, this situation can be seen as the transition from the organism level to the behavior and ecosystem level of biomimicry in the 21st century. As a result, it is concluded that the use of biomimicry in designs in the 21st century has evolved, thanks to the analysis of examples of biomimicry in architecture throughout history.

Table 2.1. The evolution process of biomimicry in architecture (prepared by author)



The goal of this chapter, in the light of examples of biomimetic design that were influenced by nature given in this chapter, is to learn what benefits using nature as a guide in the architecture discipline has on the relationship between people and nature, and what strategies guide these designs. Research shows that biomimicry as a method of architectural design offers solutions to many of the problems of architecture with its principle of mimicking nature in order to learn. Therefore, it is concluded that biomimicry based design, thanks to the advancements in technology, can allow for sustainable architecture in contexts such as material use, construction technologies and aesthetic reasons.

In the second chapter of the thesis, biomimicry is examined in a conceptual way. It contains the definition of biomimicry, its principles, its conception period, important sources of it in literature and the views of its leading researchers. Then, biomimicry approaches and levels used to integrate biomimicry into design are examined and defined using some notable examples. These subtopics contain answers to questions such as which criteria must be followed when designing using biomimicry, what parts of the inspirational

organism or system needs to be examined, and what methods should be used in applying the determined organism into the design. And in the last subtopic, the integration of biomimicry in the architectural field is reviewed, laying a foundation for the architectural facade chapter of this thesis. Furthermore, analysing each step of biomimicry with examples helps to understand the effects of biomimicry on design. Therefore the goal is to define the relationship between the concept of biomimicry and design, while introducing biomimicry to designers.



3. THE RELATION BETWEEN THE ARCHITECTURAL FACADE AND BIOMIMICRY

When looking at a structure in architecture, the facade is the first part that is observed aesthetically and formally. The building facade, when analysed along with the living spaces and natural spaces that surround it, is a field of research that consists of many design problems. This situation shows that facade design is an important field of design that is open to innovation in the architectural sense. For this reason, the third chapter conducts a conceptual analysis of the architectural facade. Chapter 3.1 of the thesis defines the facade and shows its evolution throughout the historical process. Furthermore, effective factors in facade design and criteria for sustainable facades are analysed. The field of biomimicry that researches the relation between skins of organisms found in nature and building envelope, aids facade design in sustainable architecture. This is why chapter 3.2 of this thesis analyses architectural facades that used biomimicry as a method of design. Also, views of scientists that work in this field are shared and projects using skins of organisms as inspiration are mentioned. This research creates a foundation for architectural facade technologies that take advantage of sustainability and advancements in technology. In this context, chapter 3.3 of the thesis researches responsive architectural facades that are able to respond to environmental effects thanks to 21st century technologies that are adaptable and are designed using smart materials. In this chapter, responsive facades which are frequently used today are introduced and their design criteria are stated. Furthermore, responsive architectural facade technologies are analysed using examples. In conclusion, responsive facades that use biomimicry as a method of design are the topic of research in this thesis and they are examined in detail.

3.1. THE CONCEPT OF ARCHITECTURAL FACADE

The architectural facade is the first element of structure that facilitates the relationship between the building, its natural surroundings and its users. In the field of architecture, it is very important to examine the concept of facades and to learn its design criteria. In this context, the definitions of the concept of facades in literature are first to be examined. The

architectural dictionary defines facade as any side of a building, but especially its front-facing side. In other words, the facade is named by where its facing or what purpose it serves, road facade, sea facade, view facade, south facade, entry facade, and so on. In addition to these, it is also defined as the perpendicular view of a building from infinity [69].

The envelope of structures, or the building facades are not just the exterior of the building, it also serves a functional purpose that changes based on operational, structure, stylistic, ecological and sociological factors [70]. The facade is also one of the most important structural elements that contribute to the energy budget and comfort parameters of a building. In accordance with this, these days designing facades has become one of the main ways to use technologies and strategies that ensure the minimal consumption of other resources, while satisfying the users of the building [71].

Looking at the definitions above, it can be seen that the architectural facade is very important when it comes to the identity of the built environment. In this context, analysing the evolution of the concept of facades throughout history conveys the concept of facades while also explaining the beginning of the design criteria of today. This research does not go into detail in the chronological advancements in every period, instead only focuses on periods of time where most distinct changes have occurred. The use of materials, form, function and techniques of these periods are mentioned.

The field of architecture progresses in parallel with human development. The concept of facades, which has different importance in different periods of time, continues to develop throughout the historical process according to the changes in techniques, materials and styles of today. The architectural facade has gone through changes regarding its transparency-opacity, meaning, definition, and design throughout history according to the environment and culture that surrounds it. In this evolution, the outer layer of structures was sometimes made up of thick, solid walls, and sometimes thin and transparent dividers. Changes in the element of architectural facades may have been seen through different methods and forms, but they all share similar qualities that changed the architectural interface.

In prehistoric times, humans have lived their lives in cave-like dents and gaps. Due to the use of lightweight and easily accessible materials found in nature, the facades in these

times are made up of a thin layer [72]. These societies that are referred to as primal tended to decorate these surfaces of these structures with painterly techniques. Therefore, the use of design to create a certain impact on surfaces of structures has been seen since very early times [73].

The concept of architecture was strengthened when humans settled down and it first showed itself in the Ancient times. In the early civilizations, temples, graveyards and palaces were built based on the beliefs and places of worship of the people. Structures in the ancient times had a great impact on the enrichment of architectural facades and the transference of the culture of that time to the future generations. One of the leading examples of these structures are the pyramids that are the most important of Ancient Egyptian mythology, and the ones that survived to this day [74]. Properties of Egyptian architecture show that durable, gigantic and magnificent structures were made. Analysis of these structures arrived at the conclusion that this architecture was made up of elements that do not serve a function. The first examples of Greek architecture were ruled by balance and symmetry. Structures were made close to human scale and with simplicity in the forefront. Later, this simplicity was lost and visually striking temples were built. Examining Greek temples show that interiors and aesthetics were less important than making sculptural structures that are sharper, livelier and larger than any other [75]. The facades of these times are made up of columns and thick confined masonry. Stone, which was often used in building, is not only a symbol of past life, but a symbol of the activities of mankind [76].



Figure 3.1. Parthenon, 5th century BC, Athens, Greece [77].

Technical advancements seen in the Rome period are reflected in the facades of structures. Roman architects used the previously known arches in a new method with the rounded arches. Stone was in the forefront again as a structural material, and advanced information of materials, load bearing systems had new forms appear such as buttresses, vaults and domes. The facades were made up of load bearing elements, openings (doors-windows) and the forms that were used [78].



Figure 3.2. Roman Colosseum, 1st century AD, Rome, Italy [79].

When looking at Gothic period architecture, the important structures of this time are vertically tall cathedrals with monumental identities. Pointed arches, ribbed vaults, and flying buttresses used in the facades are some of the structural elements of this time [80]. In Gothic architecture, walls ceased to just be load bearing elements and the use of tall window openings lead to stained glass being used to cover them. Colorful glass used in structures both provided an aesthetic appearance while also creating a spiritual and mysterious environment. The stained glass found under the arches of medieval cathedrals has existed in our lives namelessly for all of history, and they are seen as existing curtain walls [81].

Italian architects, who named Gothic arts as Barbaric arts, started the Renaissance movement in Florence. While the Gothic period represents the dark ages, the Renaissance represents the mindful and logical cerebral age [80]. In structures found in Renaissance architecture, the ratio-scale and balance-harmony are prevalent. Ornaments used in this time separated the facade both vertically and horizontally [78]. The example found below

shows the use of three different kinds of decorations with Doric in the ground floor, ionic in the middle floor and Corinthian in the top floor.



Figure 3.3. Palazzo Rucellai, 1451, Florence, Italy [82].

As opposed to the Renaissance period, the Baroque period architecture showcases fluid, dynamic and unusual forms being used. The innovation in the facade was achieved by using concave and convex forms in the exterior. Architectural elements are systematically broken and bent without thinking about their function [80]. This shows the decorations used in the facade do not serve a purpose. There are no innovations in construction methods or materials used in the Baroque period, rather it adds to architecture more variety in form. The masonry system used in the construction of buildings found in this time became a method of construction that was used for a long time, thanks to its material performance and its artistic properties.

Until the age of enlightenment (18th Century) the adopted styles of architecture were used for hundreds of years and new methods of construction were not needed. Research has found that different facade designs that came about in architectural styles of different times were not related to technology, and they were only changes in form, independent from their function.

Exterior walls being made of natural stone or brick masonry lead to the creation of a free standing exterior envelope that is independent from the interior. When the historical process is observed, the idea of creating spaces for function appears relatively recently, in the 20th century. Facade designs that had no relation between exterior appearance and the theme in the interiors later became facade designs that were an expression of the indoor spaces. The historicist movement began in the beginning of the 18th and 19th century in Europe and effectively led to Greek temples being rebuilt with new functions such as municipal buildings, museums, and parliament buildings. And in the 19th century, new blueprints were used and designs were made with functionality in the forefront. The exact application of appearances of the past in the exterior facade designs of buildings does not create a reference for the future, and it is a criticism of the historicist sensibility that states designs must abide by the philosophy of design [76].



Figure 3.4. British Museum, 1753, London, England [83].

Use of new structural materials began with the mechanization that came with the industrial revolution and in parallel with advancements in technology. Iron steel, glass, and near the end of the 19th century, reinforced concrete entered constructions and brought along big changes for architecture [80]. These changes in society and economics are therefore represented in architectural facades. Crystal Palace, which was built in 1851, is a leading transparent structure among the transparent buildings of the time with the effect of its material use and its functionality. It was not just the fact that the materials used were new,

but it also followed a pre-produced construction method and it is the building that was the first construction that was done through assembly [84].

With the impact of the world wars, mass movements happened in the 20th century. This has led to the idea that architecture and design should respond to the needs of society and the idea that it can be enjoyed by anyone [75]. In conjunction with these ideas, new construction materials and techniques were adopted, and thus the Modernism period began where a plain architectural style was prevalent [85]. As seen in the figure below, one of the examples of the modernism period, Villa Savoye, and in the Bauhaus building the form is simple and plain; the same simplicity is also in the forefront in regards to window arrangements and use of color. In this period where facades were rid of decorations, it can be observed that functionality reigned supreme in architecture.



Figure 3.5. Villa Savoye [86].



Figure 3.6. Bauhaus Dessau [87].

One of the icons of modern architecture is the TWA Terminal building, built by American architect Eero Saarinen in 1962. The architect used biomorphic forms to capture the concept of flight by using the form of the wings of a bird in his design [88]. In this context, the conclusion has been reached that the facade and structural form of the TWA Terminal Building was designed with inspiration from biomimicry. The idea of symmetry, which is prevalent in modern architecture, and movement, which inspired the design process, can be seen in even the smallest details of the structure. This structure was built during the hardships of the aftermath of war, so it is no longer used as a terminal today, but it still serves as a hotel [88]. The structure, which was built in the period of modern architecture, shows that architectural structures made in the same period can portray different styles and understandings.



Figure 3.7. TWA Terminal, John F. Kennedy Airport, New York, 1962 [88].

The uniformity and rules that were expected from design products in the modern period ceased to meet the needs of the users. Near the end of the 20th century, with the effect of the economy new architectural movements started to appear. Beginning in the 1970s, the architects of the times started to construct structures that resembled the machines they took inspiration from. And in the Postmodernism period that started in the 1980s and its 'High Tech' movement showed in its details the advancements of technology, and followed an expressive and sculptural ideology. Structures of this period were far from traditionalism and they tended to use stairwells, elevators and plumbing tubes in the exterior facade of the structures [80]. These structures, which resemble machinery when observed from afar, can be determined as the foundation of the skyscrapers that are built today.



Figure 3.8. HSBC Building, Hong kong [89].

Today, the concept of facades does not have a beginning or an end, and it is becoming a surface that is in relation with the whole of the architectural product. Facades, which were just the exterior wall of an architectural product in the past, now have evolved into a permeable interface. The surface of the structure may also be designed apart from the load bearing system, and it can cover the structure as a whole and create new compositions anywhere from the ground to the roof [90]. In this new form, advancements in computer technology and new ideologies found in design and construction are affecting the changes seen in architectural surfaces. This allows for the architectural product to both be symbolic and attainable, while also being renascible.

The transformation in the design process of the architectural facade is in direct relation to the technology used in the design and manufacturing processes. In contemporary times, the facade is not just an element of the structure, but an individual object within the structure and a part of the architectural product as a whole. Alongside this, the emergence of new materials and their effective use in construction, creates a holistic effect in architectural products, from the ground up to the roof. In this context, the concept of facades has transformed through time and ceased to just being a part of the appearance or a load bearing element, and became one of the most important parts of the building as a whole.

One of the changes introduced in the modern period for the facade is the use of new materials while creating surfaces. For example, certain heat sensitive layers of materials were installed onto the facade surface, and systems were developed that could open and

close with heat changes thanks to their mechanisms or the gaps on their surfaces. This way, motion was achieved on the exterior while controlling the amount of light and heat that can enter the interior. In this regard, the conclusion is made that responsive facade systems have become a preferable facade design system as it creates comfort in the interior while benefiting the relation it has with the environment. Responsive facades are analysed in detail in chapter 3.3 of this thesis.

Advancements to design and construction methods of architectural facades continue today. As a result of these advancements, digital technology, moving systems and different ratios of floor-mass-roof in regards to the environment all prove useful when designing an architecture product. This research shows that both static structural elements and moving systems are used to achieve this. The fact that the speed and movement that the technological period has added to the daily lives of people can also be observed in the facades of the built environment, can be viewed as the architecture adapting to current times.

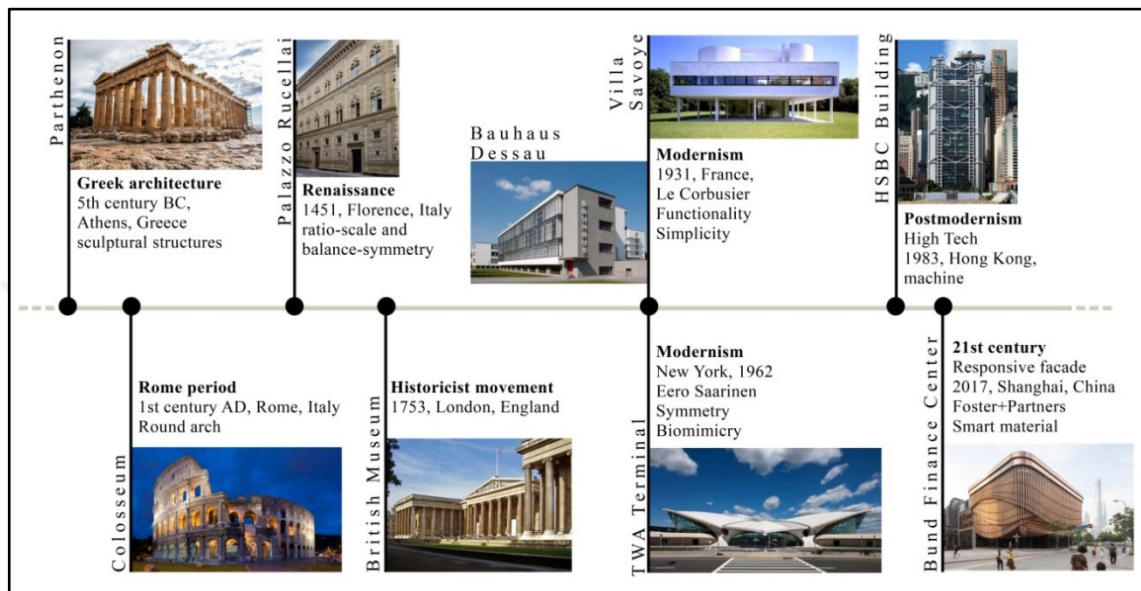


Figure 3.9. Bund Finance Center [91].

With the innovations 21st century architecture brought along, the classical understanding of a facade by the public has disappeared. Architects are creating structures with the architectural styles they are influenced by and with their own free will. This diversity can be seen in the facades of architectural products. Advancements in information technologies are not only seen represented in the form of architectural facades. In this context, digital,

responsive and sustainable innovations for future designs allow for the creation of environmentally conscious and long lasting products.

Table 3.1. A timeline of architectural facade (prepared by author)



The understanding of the concept of the architectural facade's roots comes from how its place was questioned and how it evolved throughout history. As seen in the "Table 3.1" above, the analysis made in this section of the periods that caused significant changes in the architectural facade is visualized. As a result of the analysis, it is seen that the ornaments used on the facade in ancient times did not have a function, but when the facade began to be purified from ornaments, it became functional. In the 21st century, the facade evolves with technological developments and acts as an interface that establishes a holistic relationship with the building, reacts to external conditions, and meets interior comfort conditions. These formal and functional changes of the facade guide the determination of the design criteria of the 21st century. In this context, one of the goals of this chapter is to analyse the relationship between the facade and the architectural product as a whole, and the leading parameters in its design.

Facades are an important part in structural element systems within the built environment created by architects and engineers in order to meet the needs of the users and to provide certain environmental performances. For this reason, the criteria for facade design must be well determined. The facade of the structure is important aesthetically for the general

appearance of the building, and functionally, to ensure the needs of comfort of the users are met. The heat transfer, movement of air and moisture, blocking noise and pollution, controlling intake of sunlight are some of the performances that are expected from the facade. The most important factor that must be determined for these performances and to meet user needs is energy use [92].

A building is a systematic whole that is made up of many parts including the facade. The building envelope, which is one of the subsystems of the structure, is made up of the roof and the facade. The roof and the facade that make up the envelope of the building creates a balance between the interior and exterior, meets the user needs and keeps the environmental effects under control. The effectiveness of the facade systems are dependent on the cooperation of the ventilation, sunlight intake control, insulation and energy systems of the building. This relation is seen in "Figure 3.10 " below, adapted from Schittich [84].

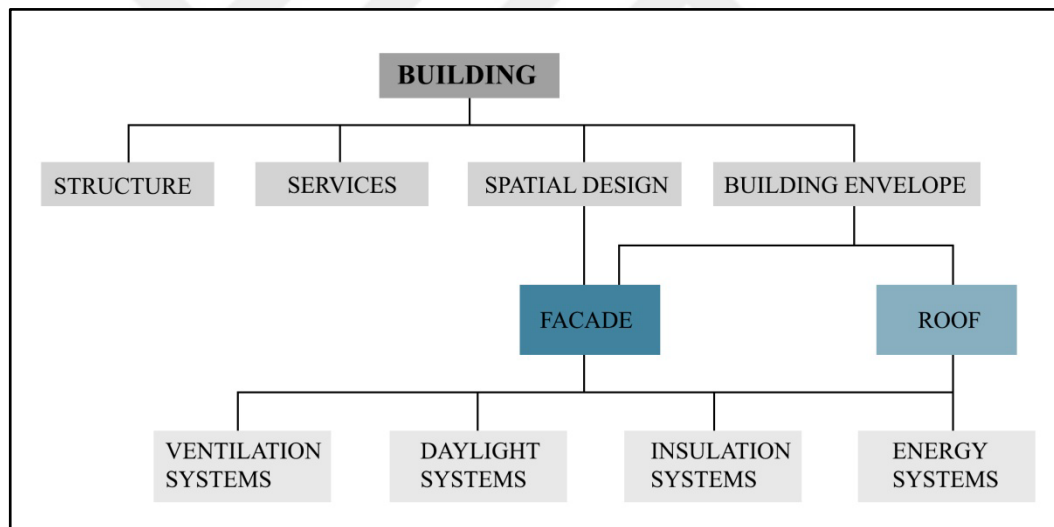


Figure 3.10. The relation of the facade with the other building systems (prepared by author).

The relationship between the facade, which is a part of the building envelope, and the other elements of the building must be determined from the beginning of the design process. Even though the most apparent function of the facade is to protect the building from external effects, other needs of the space must be taken into consideration during the design process. Facade designs used today meet the technical requirements that are brought with advancements in technology in an aesthetic way. Furthermore, energy efficiency, sustainability, multi-functionality, cost, recyclability, and other matters are also important

for the design process of the facade. In this context, the conclusion is made that in order for the facade to meet the expected performance requirements, it must be designed while taking into consideration the other subsystems of the building. The design approach makes the facade an inseparable part of the building in direct relation with the structure, shape, services and use of the building.

Research shows that when the element of facade is analysed, using it as a system, and breaking it up into parts allows for the facade system to be controlled in the design process and for it to be in harmony with the other elements of the building. The factors in which this system is influenced by during its design are classified as follows in the "Figure 3.11" adapted from Schittch [84]:

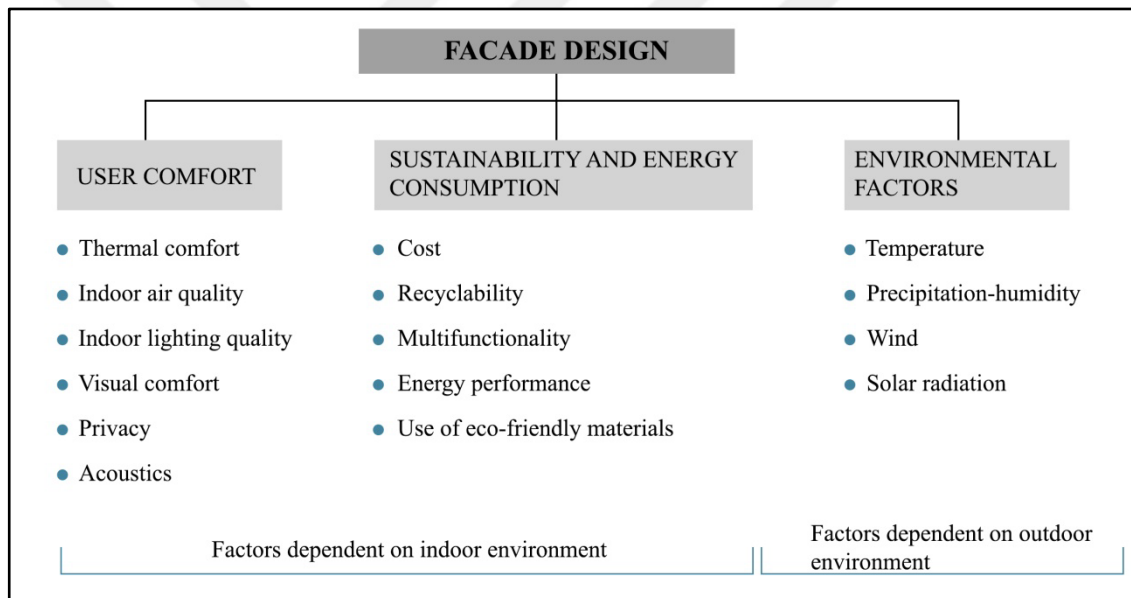


Figure 3.11. Factors that influence facade design (prepared by author).

Facade design requires technical equipment in order to meet user comfort needs and to protect the building from external effects. Factors that provide user comfort are; thermal comfort to regulate interior heat, interior air quality to ensure sufficient interior ventilation, interior lighting quality in order to create shade and to avoid shininess, privacy in order to create a safe space, and interior acoustics in order to ensure sound insulation. Aside from these, determining factors such as sustainability and energy consumption affect facade design in order to minimize energy use. Also, factors such as the use of recyclable materials, avoiding excess material, use of materials with no negative effects on the environment or the use of green materials are all important in facade design in regards to

sustainability. Being modular to adapt to the location, the climate and the ever changing user needs, allowing for restructuring, cost of production and lifespan costs are all factors taken into consideration with the general cost among the rest of these factors.

The shared property of these effective factors of building facade design are the creation of facades with multiple components and the energy requirement to apply these factors to the facade. This portrays the importance of energy efficiency and sustainability in facade design.

The facade is the communicator that achieves balance between the interior and outdoor spaces in regards to the relationship between nature, humans and structures. In this context, sustainability, which is intertwined with concepts such as ecology, environment and energy, is one of the important parts of design today. In regards to sustainable buildings there are many criteria that must be used in the literature. These criteria are inspected by some certificate programs that are organized and they are applied beginning with the design phase of the structure. The criteria for these certificates and applied to the buildings as a whole are not mentioned in this work, instead the relationship between facades and the concept of sustainability itself is examined. This chapter mentions some conceptual definitions in order to determine the effect of sustainability on the architectural facade and criteria that might influence its design process. Furthermore, the subject of sustainability is examined in regards to the concept of facades, and baseline design steps that must be followed in designing facades are mentioned.

Sustainability is defined as the continuous use of natural resources while ensuring that these resources are inherited by future generations [93]. Sustainable architecture at its core is to protect nature and to live harmoniously with nature. Work done by using this idea started showing its effects in the 1970s. In 1972, "The Conference on the Environment" took place in Stockholm, the capital of Sweden. This was the first large conference on matters of international environment organized by the United Nations and a declaration was released at the end of this conference that is seen as a pivotal point in the development of international environment politics [94]. Even though the concept of sustainability wasn't directly mentioned in this conference, matters of protecting the natural environment were mentioned. This conference serves as a guide to future works.

As mentioned before in this thesis, the concept of "Sustainable Development" was first defined in the Brundtland Report, prepared by the World Commission on Environment and Development in 1987, as "Meeting the needs of the present without compromising the ability of future generations to meet their own needs" [94]. With this report and with the conferences and works done after it, there have been important steps taken in order to rid the world of poverty and to meet the requirements of future generations.

The subject of sustainability must be taken into consideration from multiple angles for the built environment. The main principle of the concept of sustainability is to find solutions which provide the protection of the natural balance, keep the cost of construction and maintenance affordable and create a comfortable indoor space. Therefore, building facades, starting from their design phase, must exist as part of a whole with the environment, materials, economics and their users. For this reason, the building facade must be designed with a design method that works harmoniously with the building and the environment in order to meet the needs of the users in the best way and to keep energy use minimum, in both its construction and management processes. Schittich and his friends (2006), states that the questions found below are helpful as a guide that provides a sustainable path for questions of designers [95]:

- "Can the building facade be adapted to changing user needs?"
- "What is the profile of the total energy concept of the building? Can the storage units respond to excess shifts in temperature?"
- "What are the options of using environmental energy? Are there specific ways for direct or indirect use of solar energy? Is it possible to achieve sufficient ventilation within the building envelope using natural ventilation? Is there an option to avoid excess changes in facade temperature in the summer? Is there an option for an integrated source of energy?"
- "Is the use of materials with low primary energy use possible? Do these materials require special maintenance, or are they especially long lasting?"

These questions serve as a guide, and when they are taken into consideration and answered while designing a building facade, a sustainable facade can be designed. This allows for buildings to be designed that can transform energy, that can adapt to changing needs and

environmental effects, that achieve comfortable ventilation and heat, and that have a good relationship with its users and its environment.

According to John Yowell, who does research on the sustainability of the architectural envelope, a sustainable facade is not just an exterior surface, but a filter, much like the skin of a living being, that accepts or rejects the space with regards to the needs of its body. Yowell developed certain strategies by questioning how a building envelope must function in order to be more efficient. According to this the sustainable building envelope must [96]:

- Protect from natural effects,
- Be manufactured in an environmentally friendly way,
- Not be detrimental to the natural environment after its use,
- Integrate multiple systems within a thin layer,
- Properly regulate heat, ventilation and water,
- Be adaptable to its local environment and be ready to respond to it, and
- Be beautiful.

A building envelope that is designed according to these criteria, determined by scientists who are conducting research on building facades, can be sustainable. Architectural facade designs have been used a lot as a research topic in recent years in order to improve the performance of the energy used, improve interior comfort and be sustainable. Aside from this, the main design criteria for a facade to be sustainable are shown in the Table as a diagram. A sustainable building facade is determined to have to include properties such as water storage, heat storage, frost resistance, controlled reflection, carbon regulation and adaptability [97].

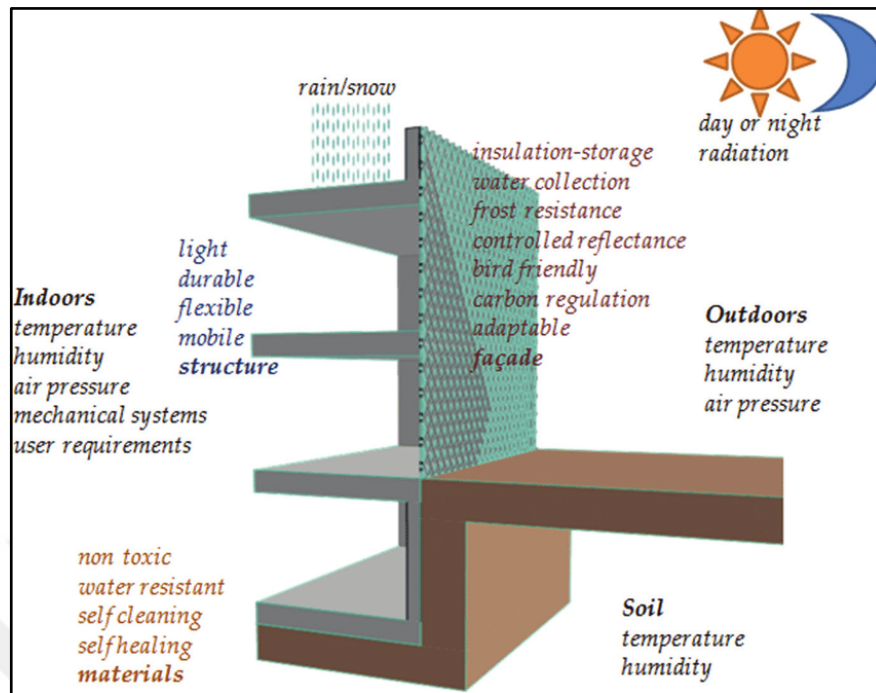


Figure 3.12. Design principles of a sustainable facade [97].

Research shows that the sustainable design of architectural facades and, therefore, of buildings is an important design method for both minimizing damage done to nature while also ensuring that the comfort needs of the users are met. In this regard, an important subject of the architectural design process is the integration of the concept of sustainability and therefore using the optimal amount of resources, thus creating buildings with low ecological footprints. When looking at nature with this in mind, it is seen that using these strategies reuses resources without depleting them and no harmful substances are produced as a byproduct of chemical reactions. Also, manmade spaces are, at large, dependent on external energy resources, while the main energy resource of nature is the sun and gravity, therefore nature must be taken inspiration from. In other words, nature holds several clues for mankind to be able to lead more sustainable lives. In conjunction with this, using strategies found in nature when designing buildings, or taking advantage of the principles of biomimicry are both found to be methods that must be used in order to create a more sustainable future.

One of the goals of this thesis is to approach architectural facade design using biomimicry in order to facilitate all of these subjects and to aid the creation of sustainable facade designs. For this reason, this chapter examines the concept of facades and sustainable

architectural envelope design criteria. Furthermore, integrating biomimicry into facade design has been used as a method in recent years in order to take advantage of systems and solutions of nature in architectural design. This is why the goal is to analyse projects that include the relationship between the element of facade and biomimicry in their designs and the analysis of those buildings are both important in understanding biomimicry and to facilitate the use of biomimicry as a design method in future facade designs.

3.2. ANALYSIS OF ARCHITECTURAL FACADES WITHIN THE CONTEXT OF BIOMIMICRY

Today, the architectural facade is not only a protective surface on the outside, but a functional part of the structure that aims to provide aesthetic appeal. Alongside this, facade design aims to elongate the lifespan of a building by using more durable materials. These are the reasons why the architectural facade must be viewed as an adaptable layer of the building that ensures the energy efficiency and thermal comfort of the building. Working together with other disciplines is helpful with designing buildings with facades that are more durable, functional, resilient and ecologically efficient.

Research concludes that the field of biomimicry aids the architectural design process with creating sustainable and eco-friendly designs, and it serves as an important guide in using the strategies found in nature. In this context, embracing the approach of design looking nature can affect building facades in several different ways. Biomimicry design criteria can be used in designing a functional or aesthetic form, producing a functional material for the construction of a facade, adding a new function, using new techniques in design [97]. Facades designed with these criteria in mind must follow the steps of biomimicry properly. One of the main goals of biomimicry based design is to transfer clues found in nature into the design every step of the way. With regards to that, it is possible to create a product that uses an architectural facade with the design criteria of biomimicry and follows the design techniques of the 21st century.

The architectural facade assumes the responsibility of transferring information and energy with the natural environment. The function of exterior shells found in nature and the exterior envelope found in architecture are similar in more ways than one. Facades, which define the characteristics of a building, are similar in design to the skin of the organisms

found in nature, and their exterior shells, this leads to innovative and smart facade systems being produced. The application of strategies developed by organisms to fight off external effects into the facades of buildings is seen as a benefit of the field of biomimicry to architecture.

While comparing the functions of the skins of organisms with architectural similes during designing biomimetic building envelopes, Gruber and Gosztonyi have prepared a chart (Table 3.2.). Using this chart to compare skins of organisms with architectural elements helps designers with creating biomimetic designs [98].

Table 3.2. Functions of the skins of organisms and analogies in architecture. [98]

Skin function in organisms by/what			architectural analogy
Primary function , happens in the intermediate space between the inside and the outside			
Construct	Provide structure	shell / internal structure with soft body and skin	> building construction
Protect	Protect and enclose inner organs	soft or tensioned layer	> membrane systems
	Mechanical Protection		> hard outer layer
	Self-healing		> self-healing materials
	Protection from radiation		> UV protection
	Protection from dirt	surface characteristics, chemical action	> self-cleaning
	Protection from micro-organisms	surface characteristics, chemical action	> oxidation surface
	Production of insulation	outer layer (hair, feathers)	> thermal insulation
Exchange	Sensing	diverse information	> sensors
	Harvesting of energy	thermal, solar energy	> solar systems
	Control air exchange	oxygen, carbon dioxide	> diffuse systems
	Thermoregulation		> thermal balance
	Regulation of circulation		> thermal balance
	Exchange of substances, prevent loss	nutrients	> filter systems
	Water and humidity - Sweating	water	> cooling
Integrated function , also use of a mechanism already there			
Signal	Appearance in environment	colour, patterns	> communication
	Signalling	colour change etc.	> communication
Integrated function in the intermediate space, can also happen elsewhere in the organism			
Store	Storage of energy	thermal energy	> heat storage
	Storage of chemical energy	fat, sugar	> energy storage
	Storage of humidity		> water storage

The first similar property of both organism skins and building envelopes is creating a boundary between the indoor space and outdoor space. When it comes to organisms the required difference between the two spaces are on one side determined by environmental effects, and on the other side determined by the balance of metabolism, energy and

resources. In architecture, this is about the comfort the facade provides to the user. Protection from mechanical effects, radiation, unwanted substances and other organisms are some of the most important properties that unite skins and building facades. These two boundaries between indoor and outdoor spaces must provide solutions to the acquisition of substances required to live, such as air, water, and food [98].

One of the most attractive properties of organism skins that architects use when taking inspiration for their designs from the forms and functions of biological beings is the fact that it is flexible yet durable [98]. In buildings constructed today, the property of flexibility is achieved by applying double-curved forms to the facade. Symbiosis in nature and ways of communication between living beings can provide solutions required by architecture for crowded and urban spaces.

The adaptation strategies of living beings in nature are determined by changing factors. For example, organisms adapt based on the changes in temperature, air and water, and based on their environment. When these variables are examined separately, a different strategy can be seen used for each of them. The exterior facade walls of a building as an interface consists of the first line of defense of the building; the roof and any external openings of the building. The building envelope and the interior walls have a great effect on the internal temperature and behavior of the building. For this reason, buildings with increased energy requirements and a negative impact on climate change must use materials that respond to variables such as heat, light or moisture [99]. In this context, thanks to biomimicry, buildings should function as the human skin does and start interacting naturally and automatically, without interference from people. This can be achieved by using smart materials in architecture that have biomimetic design, in doing so greatly aiding energy efficient design in architecture.

Organism skins found in nature vary diversely in their function based on the species, these functions include; protection, detection, heat and water regulation. In architecture, facades serve multiple roles as an interface between the user and environmental effects (water, air, noise, light and heat) [100]. Architect Ilaria Mazzoleni, who studied the relationship between organism skins found in nature and building envelopes, led a group of students to take inspiration from animal skins to work on biomimetic building envelopes. By creating these projects, they aim to create a more sustainable building and way of life. These building envelopes that are morphologically and physiologically very similar to the animal

skins they took inspiration from, and they were optimized for their environments. Each project creates the most appropriate building envelope for the space by taking into consideration the thermal, acoustic or visual properties of the space. Out of the eight proto-architecture projects found within this project, the two that are applicable to this thesis are examined, The Porous Skin and S.C.A.L.E.S. Strategies applied in these projects are guiding biomimicry based architectural facade designs.

“The Porous Skin” project takes inspiration from the skin of a hippopotamus in order to provide protection from the sun, permeability and thermal regulation. The goal of this is to control the intake of sunlight and the temperature. The hippopotamus protects itself from the rays of sun by releasing a liquid with sunscreen properties from glands under their skin when they get out of the water. This system was the inspiration for the design of the building envelope in this project. The thickness of the skin of a hippopotamus changes for each part of its body. Similarly, the exterior facade coating in this project has a filtration system for sunlight. The thicker parts serve as a sun curtain while the thinner parts allow light into the interior in a controlled manner. The system, which is made up of moving panels that were designed by combining ideas for regulating heat by using different thicknesses, and regulating water use, was designed in order to achieve user comfort and to regulate interior temperature [100].

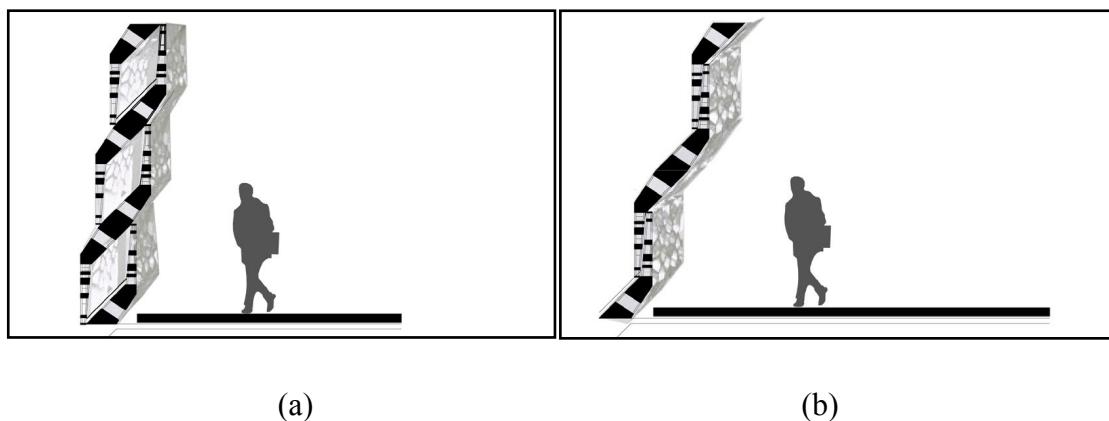


Figure 3.13. The facade system of The Porous Skin project (a) and (b) [100].

The S.C.A.L.E.S. (smart, consistent, active, layered, environmental, system) project is a project that took inspiration from the properties of the side-blotched lizard. The team has design a structure envelope that imitates the behavior and physiological properties of the skin of the desert dwelling lizard. The scales of the body parts of the lizard can vary based

on its ability for movement. The color of its scales is different in its back than its front in order to absorb sunlight. Also, the behavior of the lizard regulates the temperature of its body [100]. All these properties became the design criteria for this project. The physiological form of the skin of the lizard helps with the design of the facade. The behavioral properties of the lizard have been turned into the smart sun tracking system of the building and are run by the hydraulic system. This allows for heat to be regulated based on the comfort needs of the users.

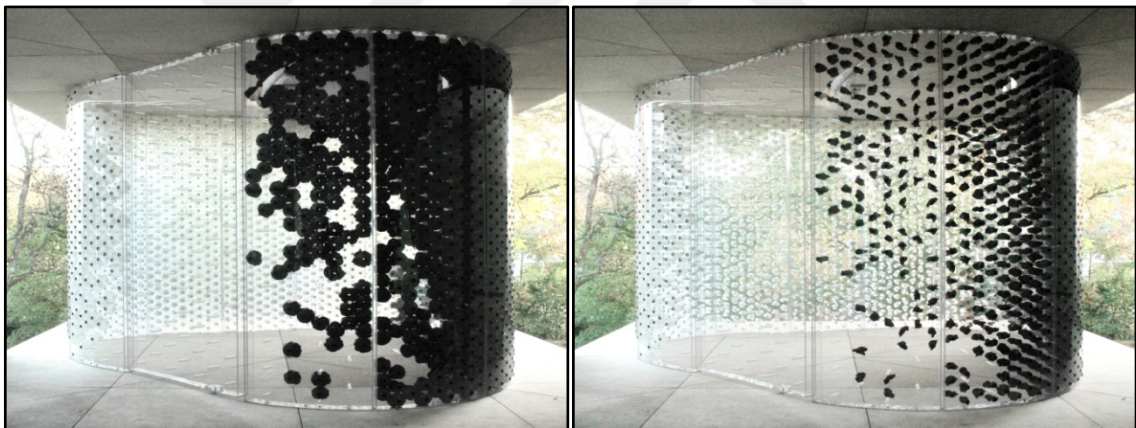


Figure 3.14. (a) Lizard [101]. (b) S.C.A.L.E.S. project [100].

Biomimetic architectural facade designs that are inspired by organism skins are continuously developing in the 21st century. The conclusion can be made that this is a result of advancements in technology and the accessibility of information, advancements in construction methods and interdisciplinary work that comes with those advancements. With the technological advancements that came with the 21st century, some biomimicry based designs are still in their project phases and are continuing their development. One of these projects is the Breathing Skins project, designed by architect Tobias Becker in 2015. This project began as the graduation thesis of Becker in the University of Stuttgart. This technology was later developed by academics and sponsors. The Breathing Skins Project is being displayed now in the city of Mandelbachtal in Germany, in a completely private showroom constructed with collaboration from Simon Huffer [102].

In the Breathing Skins project, organic skins with adjustable permeability have influenced to provide regulation of light, substance and heat flow between the interior and outdoor spaces. The facade of the project imitates the function of skin, especially its ability to

contract and release its pigments and pores. There are 140 air tunnels on every meter square of the facade, these are named "pneumatic muscles" by architect Tobias Becker. These circular apparatus inflate and deflate in order to regulate the permeability of the facade. The pneumatic muscles are placed between two glass surfaces in this system and they only require low pressure to function. This way, the architect states that a minimal amount of energy is required to create a functioning breathing facade [103]. In the project which is a product of responsive architecture, the pneumatic muscles can provide an adjustable amount of air, light and visibility. The facade changes as the parameters change and this creates an enriched interaction between the external environment and indoor space [102]. The facade technology tracks the direction of the sun in order to provide shade for indoor spaces and public spaces and allows for new strategies of natural lighting to be developed. This benefits sustainability while creating an artistic facade design with minimum energy consumption.



(a)

(b)

Figure 3.15. (a) Open and (b) closed visual of the facade of Breathing Skins project [102].

Another one of the architectural facade design examples designed in the 21st century with inspiration from organism skins is the Habitat 2020 Project. The Habitat 2020 Project has a biomimetic facade that integrates technology and biochemical functionality with its materials, and in doing so changing the traditional approach to ideas of buildings and habitats. The Habitat 2020 Project was designed for China and it has a form unlike the usual silhouette of a city. The facade of the structure is not a static system, instead it was designed as a living, breathing skin that can adapt to its surroundings. The skin functions as a membrane that creates a connection between the interior and exterior of the habitat

[104]. The building envelope has a porous form inspired by the stoma structure of a leaf. Leaves photosynthesis thanks to their stoma and they cause perspiration. Likewise, this was applied in the membrane envelope of the building. The building facade allows controlled light, water and air into the interior. It positions itself according to the direction of sunlight to provide natural lighting without the need for electricity. Air and wind is directed towards the building and filtered to provide clean air and a natural climate. It also includes a system that stores and utilizes rain water, and uses the waste produced by the structure as biogas energy for use in other areas in the habitat [104]. This concludes that the project benefits from natural ventilation, lighting and matters of user comfort and energy efficiency. When all of these properties are evaluated, the Habitat 2020 Project connects the interior and the outdoor spaces with an active, breathing, flexible and living building facade. Habitat 2020 has not yet been realized and it guides innovative ideas in new biomimicry based designs.



Figure 3.16. Habitat 2020 [104].

As seen in the projects examined above, the field of biomimicry supports architects integrating the environmental conditions into their buildings and in doing so creating more sustainable and eco-friendly building designs. The Porous Skin, S.C.A.L.E.S, Breathing Skins and Habitat 2020 Projects examined in this chapter all follow a sustainable design approach by taking their inspiration from the skins of organisms when designing their biomimetic facades. Biomimetic solutions applied in these projects take advantage of the technology of the 21st century in order to support architecture in matters such as user comfort, temperature regulation and natural lighting. These projects used the design

methods of biomimicry by getting inspired by the physical and behavioral properties of organism skins, therefore they were designed by using the organism and behavior levels of biomimicry. These projects were the source of inspiration for this thesis in bringing together the concepts of architectural facades and biomimicry. Also, the analysed project supports the fourth chapter of the thesis in the determination and the development of the parameters of analysis. In conclusion, this research of biomimicry based designs of architectural facade projects aims to guide and inspire future projects with their sustainability and ecological adaptability.

This chapter of the thesis is examined examples of biomimetic facade designs as an answer to the question why are biomimicry solutions needed to design architectural facades. Aside from the increasing importance of sustainability and energy efficiency, scientists and engineers who work with construction materials are also leaning toward biomimicry based design. It is possible to analyse the effect of biomimicry on sustainable facade design by observing available designs. This is why the research topic of this chapter is made up of projects that took inspiration from the similar function of the external shells of organisms found in nature and exterior surface facades found in architecture. The examination of architectural facade examples that work similarly to skin arrives at the conclusion that biomimicry can support the creation of a built environment that is sustainable and eco-friendly. Furthermore, responsive facade designs that use the technology of today, that affect sustainability and are designed in a way to be responsive to even the slightest variation also support these subjects. In this context, the conceptual understanding of responsive facades and the effect they have on the architectural facade on a technical level has been determined as the research topic of chapter 3.3 of this thesis.

3.3. RESPONSIVE FACADES AS A CONCEPT

The field of architecture is a field that renews and improves itself every day with advancements in technology and innovative approaches in design. Recent developments in the field of architecture have come about with general acknowledgment of the concept of sustainability and increase in technological development. In this context, the 21st century, where the advancements of technology and sustainability have been reflected on the field of architecture, is the period of time this thesis focuses on. Architects today, with the effect

of changing environmental and climate factors, are focused on designing more conscious, ecological and sustainable designs. When these parameters are taken into consideration, the first place of interaction on a building, which is the facade, is important to have new design strategies. Facade design not only regulates levels of comfort in the interior and connects the building to the environment, but it is also important for energy saving and efficiency. Architectural facade concepts being designed as interactive parts of a building that reacts to variables and even changes in climate, helps with the building of a responsive built environment. The facade must adapt to the changing factors in the environment and it must be thought of as a living element of the structure. Thus, this chapter defines the concept of a responsive facade, which is often heard in 21st century designs, and its place in contemporary architecture is examined. Also, technological advancements used in responsive facade designs and their benefits to sustainability are stated.

The rapid consumption of the energy and fossil fuels of the world and the climate changes that bring are both influencing every industry to renew their ways of manufacturing and consumption. Design approaches that are responsive to environmental issues are also being developed in the architectural field, which has undeniable effects on the natural environment. The goal of this approach is to design buildings that use recyclable materials in their construction, that use environmentally friendly materials and are benefiting the sustainability of the natural environment. The biggest benefit of these buildings to the natural environment is the positive effect they have on energy saving. This ideology, which has been embraced in contemporary times, has influenced all steps of the building design process and is influencing architects to work more towards sustainability. In this context, the concept of architecture that can respond to environmental factors has come about.

The term responsive architecture was first coined in a 1970 book by Nicholas Negroponte "The Architecture Machine". The article "The Semantic of Architecture" written in the same year and the 1975 book "The Soft Architecture Machine" both hold their place in the literature as important sources in defining responsive architecture and manufacturing it. Negroponte suggests that responsive architecture is the natural byproduct of the integration of the power of information sciences to settled environments and as a result it created better performing and more rational building [105].

Even though ideas of Negroponte still hold true in concept, not enough information and suggestions were put towards to realize these ideas [106]. Most research and applications

that came after the works of Negroponte were only interested in aesthetics rather than functionality; therefore, no structures were made that truly utilized the concept of responsive architecture. Although, with the advancements seen in computer technologies since the second half of the 20th century (1980s) have made important developments in responsive architecture possible. Thanks to the developing technologies, external factors are easily track able and moving structures and materials that can respond to these factors were produced. Later, the use of smart materials in architecture allowed for buildings in which smart materials were used as sensors or actuators to do the same thing without the need for computers. Today, advancements in robotics systems and artificial intelligence have allowed the concept of responsive architecture to be more functionally applicable [107].

One of the most well-known and important examples of responsive facade design is the 1988 building in Paris, Institute du Monde Arabe, by architect Jean Nouvel. The Institute, which was a synthesis of the east and the west, works as a bridge between the two cultures and two histories [108]. The architect designed the panels in the facade of the structure by taking inspiration from Middle Eastern motifs and therefore the concepts of smart materials and traditional architecture were brought together. The southern facade of the structure is covered in 30.000 light sensitive moving metal diaphragms that protect from the sun [109]. This system uses photovoltaic sensors and hydraulic actuators that allow controlled sunlight into the building and reduce shine from the sun. This building therefore uses smart materials and preferable properties of the environment to save energy. Institute du Monde Arabe also has the properties of biomimicry based architectural facades, which is the research topic of this thesis. The structure, which takes inspiration from the lens-like form of an eye, has a retractable mechanism that, research has concluded, was designed through the behavior level of biomimicry. In this context, the biomimicry based on design of responsive facade systems are beneficial to being adaptive to nature and being sustainable.

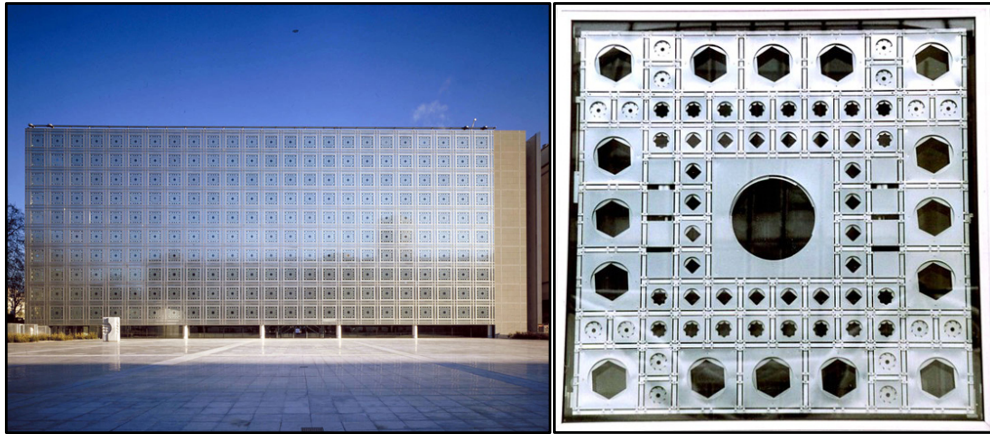


Figure 3.17. Institute du Monde Arabe [110].

The facade of Esplanade Theater in Singapore, designed by DP architects in 2002, is another example of biomimicry in responsive facade design. Biomimicry was used as a design method in the new design added to the glass facade in order to eliminate the negative effects of the first design of the building. The design was inspired from spikes on the durian fruit from Singapore to protect the building from excessive sun exposure. The facade of the building has sun shields created from aluminum and placed according to the angle of sunlight. These can be adjusted in response to the movement of the sun. In this way, energy use is reduced by providing natural lighting and protection against heat in the interior [23]. Although the Esplanade Theater facade design is responsive to sunlight and indicates biomimetic facade property, it was disagreed from the analysis criteria in the fourth chapter of this thesis, due to the limited movement of the panels on the facade.

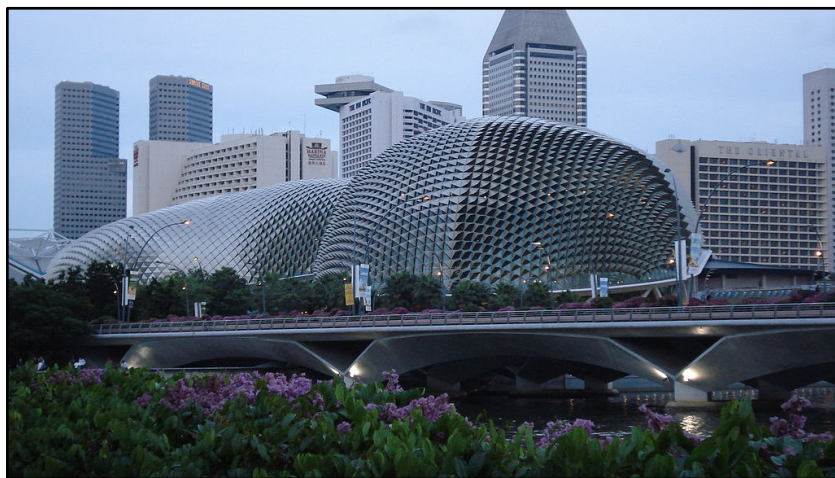


Figure 3.18. Esplanade Theater in Singapore [111].

Important work in the 21st century, in the field of responsive architecture is being conducted by the president of "Robotic Architectural Media & Bureau for Responsive Architecture", Tristan Sterk [107]. Sterk, combined the ideas of Negroponte with the advancements in the fields of artificial intelligence and robotics and proposes a current architectural model that meets the needs and wants of users [106]. In the work of Sterk, the building is separated into two main parts, spaces that provide services and the building structure that include the protective building envelope. The effects of user needs and wants can be seen on the design of the spaces and structures in this work. In conjunction with this, and as seen in the "Figure 3.19", a hybridized control model is proposed that connects user needs with the elements of the building and their responsive behaviors. This is how user requirements arrive at the structures and spaces and they are either approved or denied here after evaluation. This model has created an exemplar architectural building envelope in how a responsive facade system can work. In this example, the building envelope is designed with structural tensioner elements that are made up of sensors, actuators and micro detectors, and is managed by hybrid control networks. As seen in the "Figure 3.19" below, the internal partition system is a moving wall that has been installed onto a track. The resulting architectural form is a response to user needs through the limitations of the environment and the space [106]. The research done by Sterk shows that the user's needs and wants are very important in designing responsive facades and spaces. As a result, architecture which utilizes responsive facade design benefits the design of building facades that are reactive thanks to sensors, actuators and trackers, as a result of the analysis of user input.

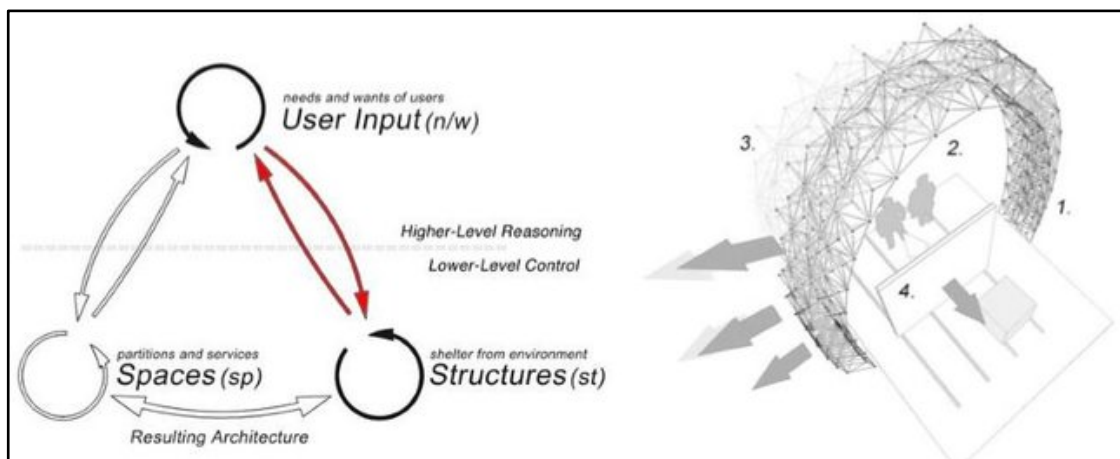


Figure 3.19. Sterk's hybridized control model and the architectural form [106].

When looking at work done in the field of responsive architecture, it can be seen that a building facade design that responds to the environment is effective. This is why designing the building facade, which is the first part of the building that interacts with the environment, with a responsive architecture approach can bring about new technologies and strategies. In this context, it is important to examine responsive architecture facade designs and any technological advancement in this field. Responsive facades take the most advantage from energy sources such as the sun and the wind in order to find heating, cooling, ventilation and lighting solutions. Protection from these energies is also required in order to ensure the comfort of the interior. Facades designed in a way that is in conjunction with this can adjust themselves and have a self-controlling system. This is how they can adapt to changing external factors in order to create comfortable indoor spaces, thus saving energy by using responsive facades in buildings.

It is important to know the technology used in order to have a deeper understanding of responsive facades and guide designers. A scan of the literature on responsive facades shows that there is no clear categorization on the technologies applied to facade systems. Thus, this chapter analyses the technologies used in responsive facade systems categorized with the findings of the research of Negar Heidari Matin and Ali Eydgahi [112]. Data is given regarding how these technologies are used today, without giving technical details of these technologies. The examination of these technologies is important in order to understand how far responsive facade technologies have come and for future research to take benefit from them.

Responsive facades are accepted as smart systems that have properties such as response time to environmental effects, adaptation and learning ability. Generally, the performance of a facade system is affected by the detection, control and interaction technologies of the used smart material technologies and structural technologies. Several research papers on this topic help the categorization of these technologies. Responsive facade system technologies are categorized in literature as follows, mechanical technology, electro-mechanical technology, passive technology, information technology, and material-based technology [112].

- **Mechanical Technology:**

When responsive facade systems were first used, mechanical technologies were utilized to both provide user comfort and building efficiency. In those times, machines were seen as tools of perfection and architectural components were designed as machines [113]. This understanding led to buildings being seen as multi-functional mechanisms that worked under the influence of mechanical principles. With the increase in mechanization seen in the industrial revolution, the first steps towards creating responsive facades were taken by using pulleys, hinges, reels, cables and gears in facades [112]. As seen in the figure below, an example of mechanical technology in responsive facades would be the hand-operated blinds system of Kaufmann House, which works without requiring energy resources and according to the needs of users. Building users could operate these systems manually and they had limited levels of adaptation, and had limited use by differently-abled people due to it being dependent on human power. Also because of their lack of resilience to environmental effects, the fact that they erode quickly and their maintenance being costly, mechanical technologies left their place to system controlled technologies. [114].



Figure 3.20. The hand-operated facade of the Kaufman House [115].

- **Electro-mechanical Technology :**

In the end of the 20th century, the use of electrical components and control mechanisms began in architecture and advancements were made in facade systems. These systems allowed the use of electro-mechanical technologies in responsive facades. Detection,

interaction and key control technologies in facades were first used in remote control doors [116]. With advancements in electrical systems, blinds, which used to be hand operated, lead to the design of algorithm based engine run mechanisms of facade components.

The Institut du Monde Arabe building by Jean Nouvel, which was mentioned in this chapter, can be given as an example of electro-mechanical technologies used in responsive facades. Sensors and actuators on the facade of the structure allow for the controlled entry of sunlight into the indoor space. The Al-Bahr Towers in the United Arab Emirates is another example of this technology being used in a responsive facade system. Al-Bahr Towers uses the tallest computerized facade with its 150 m height. This responsive facade is being controlled by a Building Management System (BMS) and it tracks wind speed, light intensity and levels of rainfall and adjusts the placement of the panels found in the facade as a result. Institute du Monde Arabe and Al-Bahar Towers, Arap were designed by their countries according to the traditional motifs of Islamic-Geometric Patterns, and they are important examples of high performance facade system designs. These buildings are seen as the relation between culture and modern facade system technologies [112]. Additionally, both of these structures use biomimicry as their design method, therefore they are included in this research topic. The building Al-Bahr Tower was designed in the 21st century with new technologies, therefore it is in the fourth chapter, being examined for biomimicry design strategies and responsive facade technologies.

As a response to the advancements in technology in the 21st century, electro-mechanical technologies have been used at large in facades. Contemporary period facade systems work through central control systems that use local weather data and data from other types of sensors in order to function. An example of such a system is the Council House 2 Building, the Q1 Headquarters Buildings, and the Ocean Pavilion. These structures are related to biomimicry and are therefore analysed in detail in the fourth chapter of the thesis.

The electro-mechanical technologies used in responsive facades are advanced and safe technologies. These are technologies that have the advantage of modular design components, affordable starting materials and central control systems. Some disadvantages of these technologies are the complexity of the mechanical pieces, risk of failure due to friction, difficulty of replacing parts, high maintenance and repair costs and high energy consumption [112]. This is the reason designers have moved onto more affordable

technologies. An alternative to electro-mechanical technologies used in responsive facades is passive, information and material based technologies.

- **Passive Technology:**

Passive technologies, used in responsive facades, remove the need for electrical or manual power and use natural sources such as wind, water or sunlight to operate. Passive responsive facades have the advantage of not requiring mechanical or electrical power, and are far from being drab in appearance due to them being connected to natural conditions. On the other hand, these low cost and low maintenance technology passive facades are dependent on weather conditions and are not controlled within their system, so they can have unexpected reactions [112].

An example of passive technology used in responsive facades can be the facade design of the Pittsburgh Children's Museum, made by artist and sculptor Ned Kahn, with collaboration from the KoningEizenberg firm in 2004. The facade of the building is made up of thousands of semi-transparent plastic squares that move with the wind in order to improve the optical quality in the interior. The facade design includes adjustable use, recyclable materials and passive shading. The facade, which was designed with a passive approach, is beneficial to the sustainable social change of the neighborhood around the building [117].

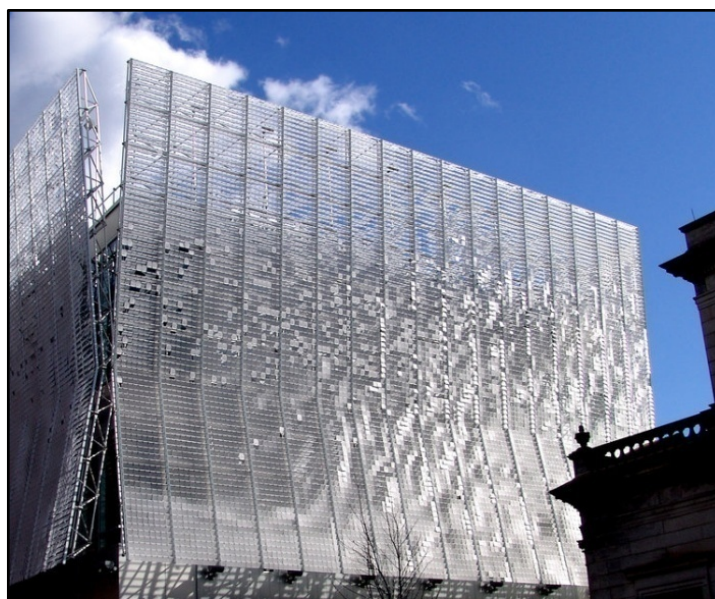


Figure 3.21. Pittsburgh Children's Museum [117].

- **Information Technology:**

Information technology used in responsive facades uses the control system of electromechanical systems. In responsive facades that use this technology, micro detectors are used that control the interconnected panels. Local sensors found in the facade allow the actuators to provide data to the micro-detectors for the functionality of the facade [118]. An example of information technology would be the Media-TIC Building, which was built in 2011 by Enric Ruiz Geli, and is the first facade system that has a control system without a central unit. The facade, which was designed with the eco-efficient material ETFE, has sensors spread across it that track heat and light from the sun. The coating that provides heat efficiency is within a triangular frame, and has a pillow-like inflating and deflating motion reactions [119]. When the facade is inflated, it provides heat insulation and helps with saving energy. The motion of the facade also affects the appearance of the facade.



Figure 3.22. The Media-TIC building facade design [119].

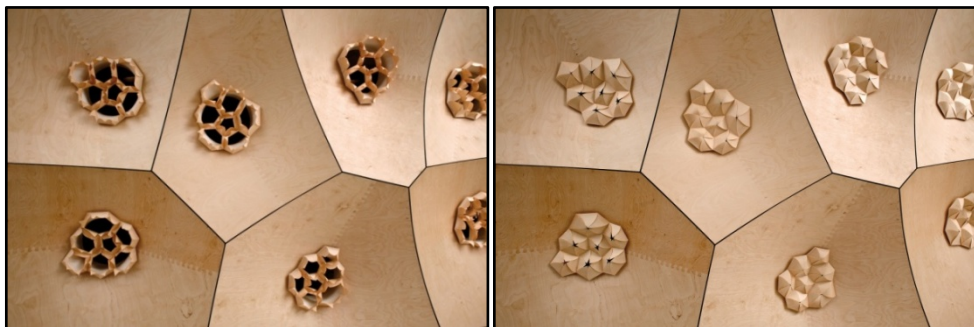
- **Material-Based Technology:**

Advancements in material sciences have brought new techniques to the design of responsive facades. The materials used in these facades serve as actuators or sensors, therefore taking the place of mechanical or electro-mechanical components [112]. With the advancements in technology today, new materials are produced that are responsive to humidity and sunlight. An example of this is the responsive facade design of HygroSkin-Meteorosensitive Pavilion built in 2013 by Achim Menges Architect, Oliver David Krieg

and Steffen Reichert. The facade, which used biomimicry as a design method, took inspiration from spruce cones' ability to open and close based on humidity to design movement of the wooden components. The porous form of the facade is controlled by the elastic bendability of the thin layers of plywood. The responsive facade design can respond to changes in humidity on sunny or rainy days, equal to the humidity within a 30% to 90% scale [120]. This way, a responsive facade design without the need for external power source was achieved. Smart materials may increase facade performance on a micro scale, but they have limited controllability due to their static and unprogrammable reactions to environmental effects. This is why material-based technologies used in responsive facades are used in limited prototypes. This is why they are seen as untested technologies [112].



(a)



(b)

(c)

Figure 3.23. (a) Hygroskin-meteorosensitive pavilion, (b) open facade, (c) closed facade [120].

The analysis of technologies used in responsive facades show that these are facade designs that are reactive to natural factors such as sunlight, humidity and wind and they can be adjusted based on the movements of the users. The advancements of technologies used in responsive facades began with hand operated systems, later used electrical components such as sensors, actuators and detectors. Later, with the effects of sustainability, facade designs were made that used natural resources as a source of power in order to reduce the need for energy. Lastly, with the technological advancements of the 21st century, the use of smart materials in architecture further improves the responsive facade technologies. In this context, it is concluded that the analysis of current technologies used in responsive facades benefits the creation of a new and integrated system. Therefore, it can be proposed that new responsive facade systems, that have low energy consumption, are sustainable and do minimal damage to the environment, can be developed.

In addition to the responsive architectural facades which are a result of the technological advancements of today, different properties of facade designs are being developed and they can transform energy and all benefit sustainable architecture. These architectural facade systems are named differently based on the materials used, structural facade components, their goals and their techniques. Some of these (apart from the responsive facades) are categorized as; kinetic facade, smart facade, biomimetic facade, interactive facade, adjustable facade, and so on [121]. These systems are usually designed by using smart materials and they utilize energy efficiently. Buildings designed with smart materials can be defined as buildings that provide the most efficient space for the user, that minimize management costs and utilize the most advanced technology. The materials chosen in these buildings are expected to improve the ecological performance of the building in regards to the relationship between the environment and the user. This way, these facades minimize energy and resource use, thus minimizing damage done to the environment and benefiting sustainable architecture. The analysis of these architectural facade systems shows that the most contemporary of these systems is the responsive facade. This is why this thesis examines the responsive facade. In addition, a common language is aimed to be created for this thesis by combining the research topics of this thesis that the responsive facades and biomimetic facades.

Responsive architectural facades must be designed with interdisciplinary teamwork. Sterk, who supports this idea, suggests that an architectural product is only possible by multiple

disciplines working together, and that the leading disciplines of this idea are robotics, artificial intelligence and structural engineering [106]. Frazer, who works on responsive structure manufacturing by taking advantage of the biology discipline, states that architectural design products have a lot to learn from nature. Frazer believes that natural ecosystems are systems that have complicated biological structures and they can recycle materials, adapt to changes and use environmental energy efficiently [122]. When these ideas are taken into consideration, integration biology to the design process of responsive facades is the primary solution nature has against the energy consumption of the built environment. In conjunction with this, the use of biomimicry in responsive architectural facades allows for new solutions being provided to any possible issues. The common trait of responsive facade systems and designs looking to nature are creating buildings that are more responsive, harmonious and sustainable towards their environments. Aside from responsibility towards nature, these two fields have similarities in providing a comfortable indoor space to their users. Architects have been designing biomimetic facades in recent years in order to provide comfortable interior and outdoor spaces. As a result, using biomimicry as a design method when designing responsive facade systems is beneficial to sustainability and harmony between nature and the built environment.

The third chapter of the thesis is examined the concept of architectural facades which serve as an interface in the relationship between the building and its environment. Furthermore, design of facades is examined under the scope of sustainability. Later, biomimicry based facade designs are analysed through examples. The research concludes that in sustainable facade designs, transferring strategies found within nature into the design of facades is the primary solution. One of the most prevalent properties of 21st century design is attempting to create an eco friendly and sustainable built environment. This leads to the creation of responsive architectural facade systems that react to environmental effects and are beneficial to saving energy. The analysis of frequently used responsive facade designs of today helps the understanding of the effect of technological advancements on sustainability. Thanks to the research done in this chapter of the thesis, it can be seen that products that are a result of working with biomimicry and using responsive facade systems benefit architecture by giving it eco-friendly and sustainable properties. This is why the analysis of biomimicry based designs of responsive facades is determined as the research

topic of this thesis. In the fourth chapter of the thesis, 21st century responsive architectural facades using biomimicry design strategies are determined and analysed in detail.



4. AN ANALYSIS ON RESPONSIVE ARCHITECTURAL FACADES IN THE 21ST CENTURY INSPIRED BY BIOMIMICRY

The 21st century, called the information age or the digital age, provides technological advancements to the people while developing interdisciplinary methods. The field of architecture, which shapes the built environment, has been affected by these advancements and buildings, materials, products and construction methods are affected by these technologies. Within the context of today, global warming and increase in energy use have made sustainable and environmentally friendly designs more important. Designs that integrate 21st century technologies have low carbon emissions, high quality of life standards, use of environmentally conscious and recyclable materials, low fossil fuel use; thus helping to create cities that apply these factors. Cities designed with this approach allow for a built environment with low energy use and a positive impact on the environment to be created.

Throughout the historical process, buildings and designs have been made to benefit human life by observing how living beings in nature behave in many different conditions. In accordance with this, when the concept of biomimicry is examined, it is concluded that integrating the forms, behaviors and actions of organisms found in nature in order to solve problems in the architectural design process and to reduce the energy use of the built environment is one of the most effective solutions for sustainability. Aside from making designs that are environmentally conscious and sustainable, the field of architecture also assumes the responsibility for providing a comfortable interior space for the user. This is why the principle of biomimicry that aims to use the principles of nature to provide interior and exterior space comforts is seen as a benefit of biomimicry to the field of architecture. Designs using biomimicry as a design approach as a method have developed over the historical process. Biomimicry not only imitates the form and shape of organisms with the technological advancements, but it also includes design strategies that integrate environmental factors and their effects as well as the behaviors and processes of living beings into design. An example of this can be the use of the form structure of a honeycomb as one of the first instances of inspiration taken from nature being applied to design. In the 21st century, behavioral properties of the honeycomb like its textures and integration

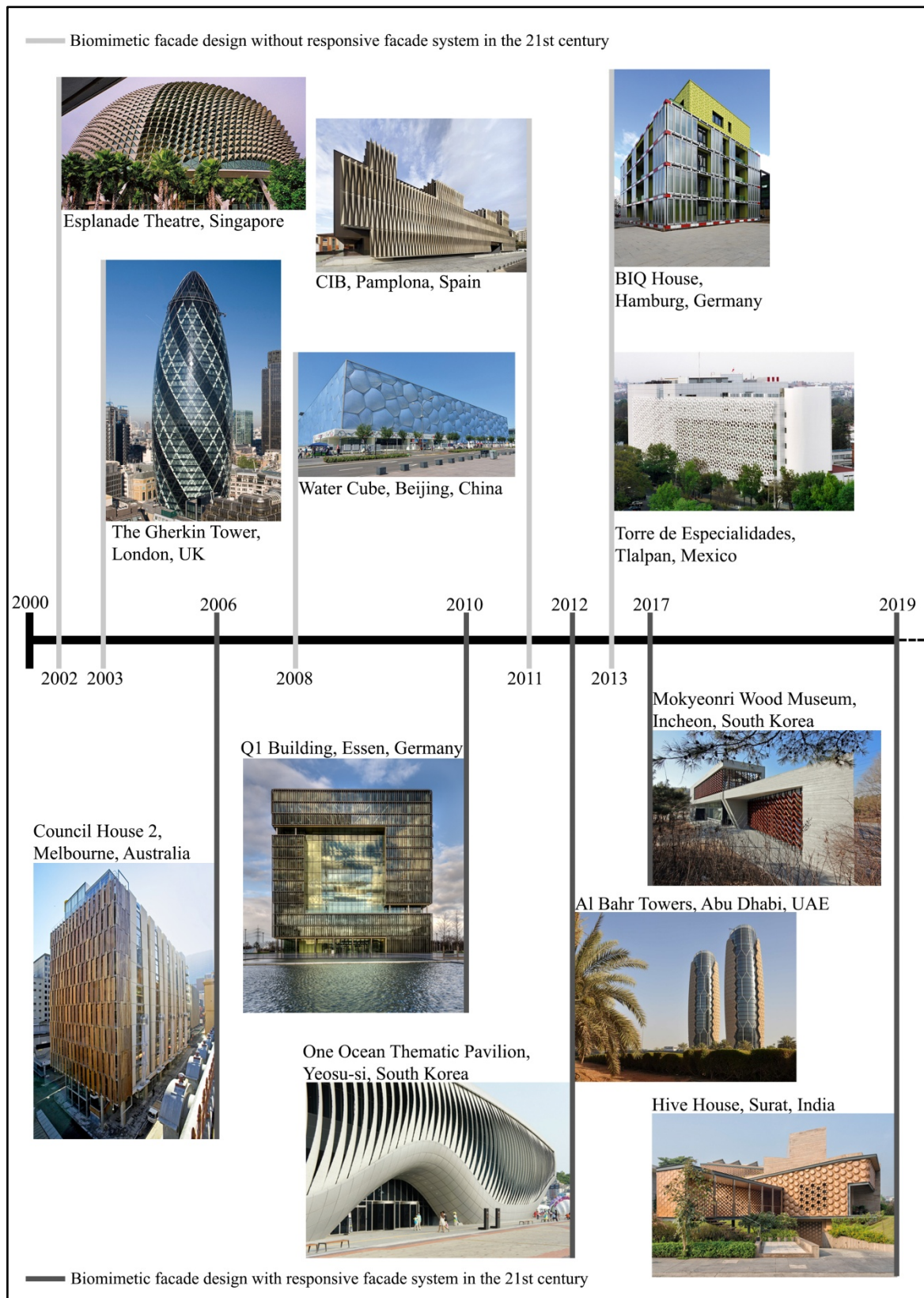
patterns were examined and the collected data lead to the creation of products with the same durable structure. Thus, it is concluded in the 21st century that observing nature and creating designs that take inspiration from or imitate nature, namely biomimicry, has evolved. And the effects of this on architecture show themselves as designs that are environmentally conscious, function similarly to living beings found in nature, are recyclable, environmentally friendly, sustainable and ecologically beneficial.

Research shows that 21st century architectural design is influenced greatly by sustainability and technological developments. This encourages architects and designers to produce new systems and materials. These 21st century developments contribute to the creation of designs of buildings that can react to environmental factors and are equipped with intelligent materials. Facade design, which provides user comfort in buildings, controls the balance of temperature between the interior and the exterior environments, and has a visual impact on its connection to the environment, and it is a field that shows improvement and needs to be investigated. Research has shown that one of the most significant examples of these developments is responsive facade designs. Responsive facades, which are a product of sustainable architecture and technological advancements, is the research topic of the thesis and in chapter 3.3 of the thesis, it is analysed in detail.

In the second and third chapters of the thesis, the relationship between biomimicry and architecture facade concepts is examined, which has greatly influenced designs of today by way of sustainability and environmental consciousness. The concept of biomimicry, which is inspired by organisms found in nature, is seen to be effective in the development of systems in facade designs that can react to environmental impacts and change according to user needs. In this context, the use of biomimicry as a design method for responsive architectural facades can be predicted to contribute to the environment and the structure. Therefore, the fourth chapter of the thesis is analysed 21st-century examples of biomimicry inspired responsive architectural facades. It is possible to give numerous examples of facade designs based on biomimicry. Some examples of biomimetic facades are analysed in other chapters of the thesis without any time period restrictions. These buildings and projects that are being examined are an inspiration for this chapter of the thesis. However, some criteria have been set regarding the chosen examples to ensure the legitimacy of the research and to ensure the effects of the technological effects of today are being taken into consideration and are analysed correctly.

There are two main criteria in determining the buildings that are seen in chapter 4 of the thesis. The first criteria for the chosen buildings is having responsive architectural facade systems that use biomimicry as a design method. Buildings with these criteria are carefully selected for their facade designs that use technology of today, are involved with the concept of sustainability and are designed to react to a specific stimulus. The second criteria aims to better understand current and contemporary changes in the concept of facades by choosing buildings that completed their construction in the 21st century. These buildings were determined by doing a widespread scan of literature with these criteria in mind. This research shows that some examples of 21st century biomimicry based facade designs do not use a facade that is a dynamic system, meaning they do not react to an environmental factor, thus being excluded from this chapter of the thesis. Furthermore, this research concluded that sufficient information was not found for some examples of biomimicry based facade designs and they were excluded from this research. However, some 21st century biomimetic designs were kept in chronological order in the table in order to serve as a guide to further research. With these criteria, the first research was into the effects of developed technology on facade design, and additionally care was taken to ensure the chosen buildings had different functions. The functions of these buildings have been grouped by their architectural use in daily life as public buildings, office buildings, exhibition spaces (cultural buildings), museums and residences. In this chapter of the study, the goal is to analyse the design of responsive facades based on biomimicry for different functions, to provide a wide arrange of data for future research and to produce primary information for use in biomimetic facade designs of different functions. After all this research, examples have been determined based on the determined criteria in order to analyse them, these are as follows, CH2 Building, Q1 Building, One Ocean Thematic Pavilion, Al Bahr Towers, Mokyeonri Wood Museum, and Hive House.

Table 4.1. Facade designs that used biomimicry as a design method in the 21st century
(prepared by author).



Buildings with these criteria, responsive facades in the 21st century that use biomimicry as a design method, have been examined based on the three parameters defined by the information gathered in chapters two and three of this thesis

- **Effects of biomimicry on the facade:**

First, the organism or function in nature that inspired the facade design is identified and its similarity to the project has been examined. After that, according to the research of Zari and Benyus in the second part of the thesis, it was determined which of the organism, behavior, and ecosystem levels of biomimicry were used in facade designs. In the same way, it has been determined in the facade designs which of the design looking to biology and biology influencing design approaches of biomimicry. The table, which was created by Zari, benefited the determination process of the levels and approaches of biomimicry. Furthermore, the design strategies of the examples of facades inspired by organisms found in nature in the other chapters (3.2) of the thesis have an effect on the determination of analysis parameters.

- **Responsive facade design:**

In the second parameter, the technologies used in the responsive facade designs of the selected buildings are specified. Which of the mechanical, electro-mechanical, passive, information, material-based technologies are used in facade design has been analysed based on the research done in chapter 3.3 of the thesis [112]. Furthermore, observations are done to identify which environmental factors or stimuli the facade design responds to and which technical solutions it brings.

- **Effects of facade design on sustainability:**

The energy efficiency, thermal comfort, natural lighting of the facade design is analysed based on its benefit to the concept of sustainability and to nature.

As a result of all this research, chapter 4.7 of the thesis provides a table that contains the architectural properties of the buildings (architect, year, location, function), a summary of their analyses and analyses of their photographs.

4.1. COUNCIL HOUSE 2

Council House 2 building in Melbourne, Australia is a 10 story administrative building that completed construction in 2006 and was designed by Mick Pearce and Design Inc. The design process of the building was done through new strategies based on the basic laws of nature [123]. The building is defined in literature as the first building in Australia to use biomimicry as a design method and bring sustainable design to new levels. The facade design of the CH2 building uses the best possible way to provide technological solutions in a limited space for the requirements of 21st century common use workspaces and their functional needs. This building is researched in further detail in this chapter of the thesis because the facade design is based on biomimicry, it is a frontier structure in terms of sustainability in the region and it is a product of new developments in technology.

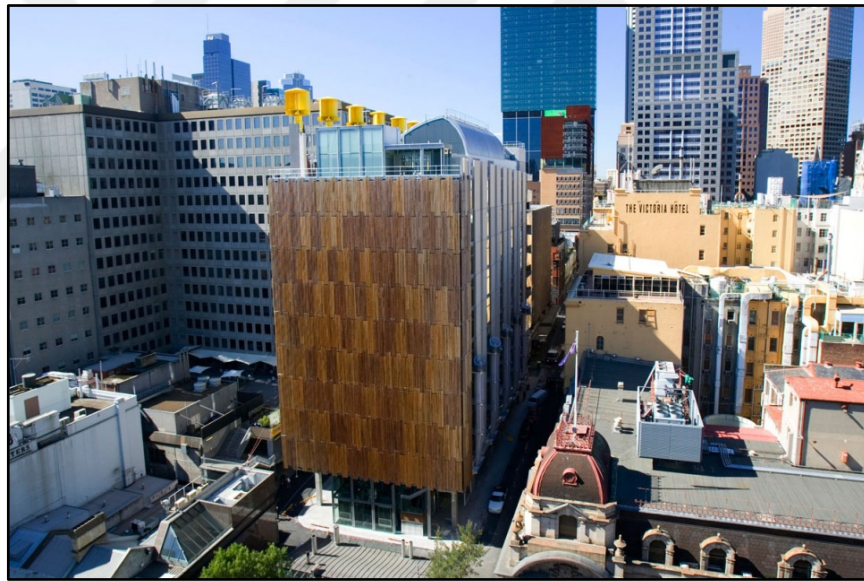


Figure 4.1. CH2 building, Melbourne, 2006 [123].

When the CH2 building has been analysed, it is seen that the concept of biomimicry affects the entire building. The base design of the building imitates the bark of a tree, thus stepping outside the box of traditional approaches to sustainable building design. Furthermore, for the thermal comfort of the building, the passive ventilation and heat regulation seen in termite mounds has been imitated. The sewage water from the CH2 building is cleaned and used as a evaporation based cooling mechanism inspired by the principle termites use to carry water [25]. It is concluded that the building design used the

organism and behavior levels of biomimicry due to the fact that it used the method in which termite mounds use to solve heating and cooling issues and the structural form of the tree. Furthermore, when the design process of the building is examined, it is determined that the biomimicry approach used was design looking to biology.

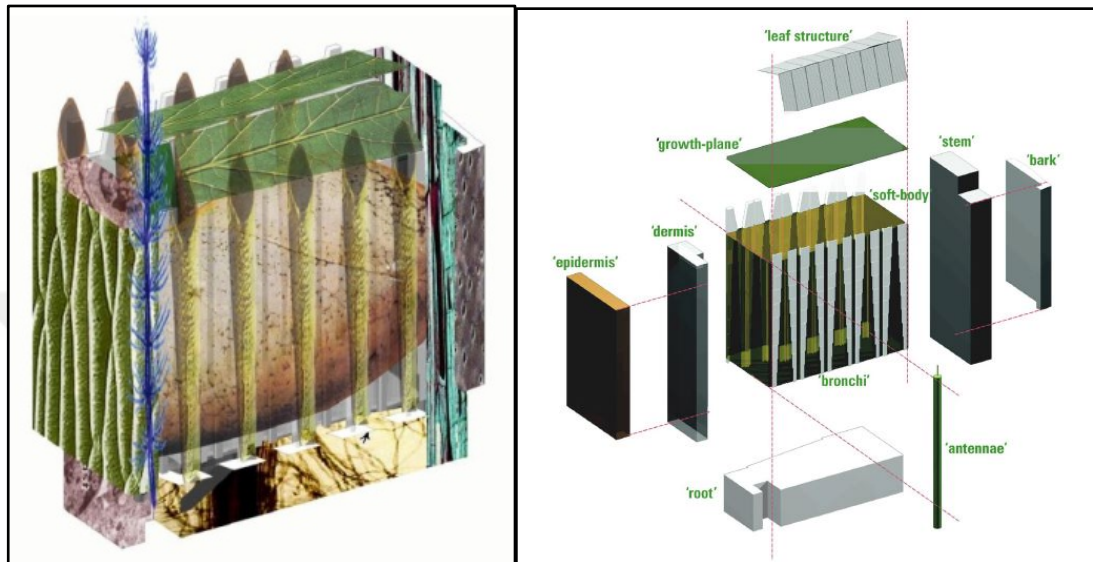


Figure 4.2. The emergent design concept and the natural analogy [124].

The west facade of the building, overlooking the main street, is inspired by the epidermis of the tree and recycled wooden shutters were used, controlled by photovoltaic cells. The shutters placed on the facade open and closed based on the angle in which sunlight hits them, thus creating thermal comfort. This movement is powered by photovoltaic roof panels placed on the roof, absorbing solar energy and converting it to electrical energy. Furthermore, the roof of the building also includes wind turbines to use the natural energy resource of wind [107].

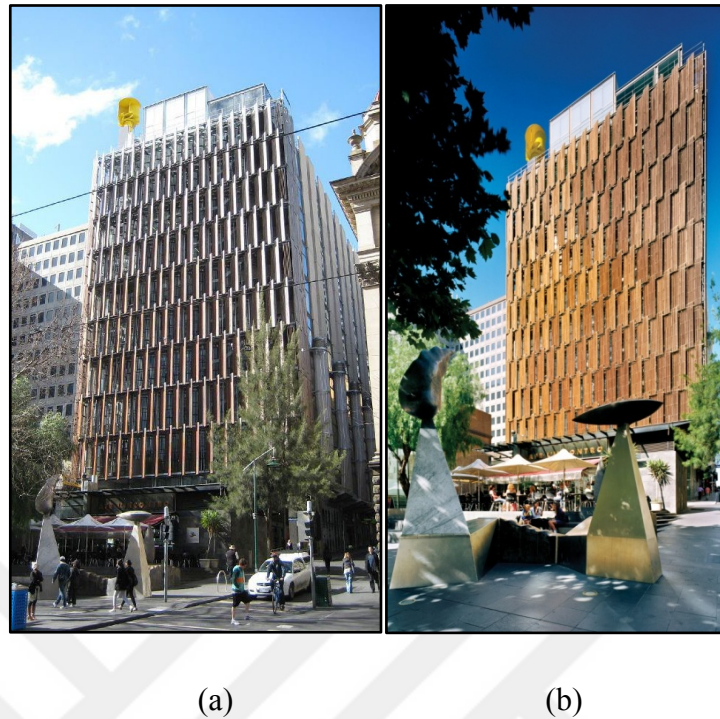


Figure 4.3. (a) Open shutters of the west facade of CH2, (b) closed shutters [125].

On the north and south facades of the building, the bronchus of the tree was taken inspiration from and these were applied as wind pipes, allowing air ducts on the outside of CH2 building [124]. The south side of the building has five shower towers where water droplets evaporate slightly while consuming energy, thus cooling the air. For the thermal comfort of the building, ventilation shafts have been placed on the north side, which is the direction in which most direct sunlight reaches the building, due to the location of Australia. Hot air from dark colored vents to absorb heat on the north side of the building is replaced with cold air from light colored vents on the southern front [126]. This ensures the thermal comfort of the building by positioning the ventilation pipes in the correct position and color. In addition, the air circulation can be controlled and managed in accordance to user needs and requests. The eastern facade of the building where services and restrooms are located was designed with inspiration from the tree bark; it has a protective envelope property of filtering light and air [124].



(a)

(b)

Figure 4.4. (a) The north facade, (b) the south facades of CH2 building [125].

The building includes a responsive facade design; especially in the western facade, the vertical pieces react to external effects by performing a turning motion. These shutters provide the users with shade and create a healthy climate within the building, while also creating an aesthetically pleasing appearance to the facade. The facade design of the Council House 2 is run by a central control system that is programmed to work using local weather conditions, heat sensors and light sensors [112]. The facade design can respond to environmental effects through sensors and hydraulic actuators, thus making it an example of electromechanical technologies being used in responsive facade design.

Melbourne Council House 2 is an award winning building for its reductions in CO₂ emissions and power and water consumption. The building discharges dirty air at night in order to provide the users with %100 clean air during the day. Additionally, research shows that by using natural ventilation and lighting, the building has an energy savings rate of %65 [124]. All these parameters allow for a building design that can work without human intervention by storing solar and wind power to later repurpose them as other types

of energy, turning wastewater into usable water and using advanced technology and smart building technologies.

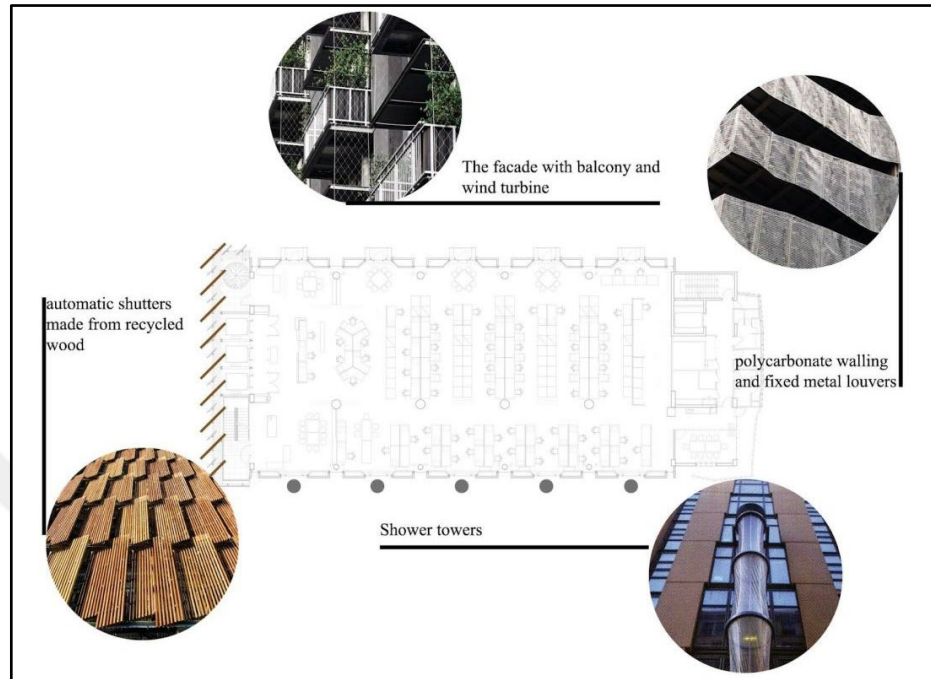


Figure 4.5. Facade Design Diagram of the CH2 Building (prepared by author).

In conclusion, the facade design of the CH2 building is seen as being inspired from the structural properties and behaviors of termite mounds and trees, while designing on the behavior and organism levels of biomimicry. This design method was used in the western facade, where wooden shutters allow for controlled sunlight into the interior space with their opening and closing mechanisms, and also supporting ventilation as a responsive facade. The facade design of the building allows for natural lighting, passive ventilation and water storage. Thus, combining responsive facade systems with the concept of biomimicry contributes to architecture and nature in terms of providing environmentally conscious, energy-efficient, and sustainable design criteria.

4.2. Q1 BUILDING, THYSSENKRUPP QUARTER

The Q1 building is the office building in 2010 in Essen, Germany, designed in collaboration between JSWD Architekten and Chaix - Morel et Associates architectural groups for the ThyssenKrupp company. The Q1 building is the central building of a

campus consisting of squares, green areas, connecting roads and 13 buildings. It reinforces the appearance of metal and glass, openness and transparency, of the other structures within the campus. The Q1 building is the most important building in the campus, it is also the most visually striking structure in the region due to its facade design [127]. The facade design of the building uses biomimicry, taking inspiration from bird feathers. The building, which also has a responsive facade design, uses metal shading elements that are referred to as feathers, and that can move in response to environmental factors. In this context, the Q1 building is analysed in detail in this chapter of the thesis because it combines 21st century responsive facade technologies with the concept of biomimicry.



Figure 4.6. Q1 Building, 2010, Essen, Germany [128].

The Q1 building is located in a humid and rainy climate. The issue faced in the facade design of the building was being able to protect the building envelope from the rain while allowing sufficient sunlight into the interior space while not having a negative impact on the aesthetic needs of the users. Architects have benefited from nature to solve these problems and were inspired by bird feathers in the design of the shading system. Bird feathers have small shafts and spikes that work in a micro scale in order to render the skin waterproof and to close the pores. Furthermore, the feathers are formed integrated with each other, diagonally covering all the pores on the skin of the bird [129]. Similarly to this, the facade design of the building was inspired by the performance techniques of the bird feathers in its shading system. It is concluded that this is how the facade design benefited

from the behavior level of biomimicry. Additionally, the biomimicry approach of the facade design has been determined as design looking to biology.

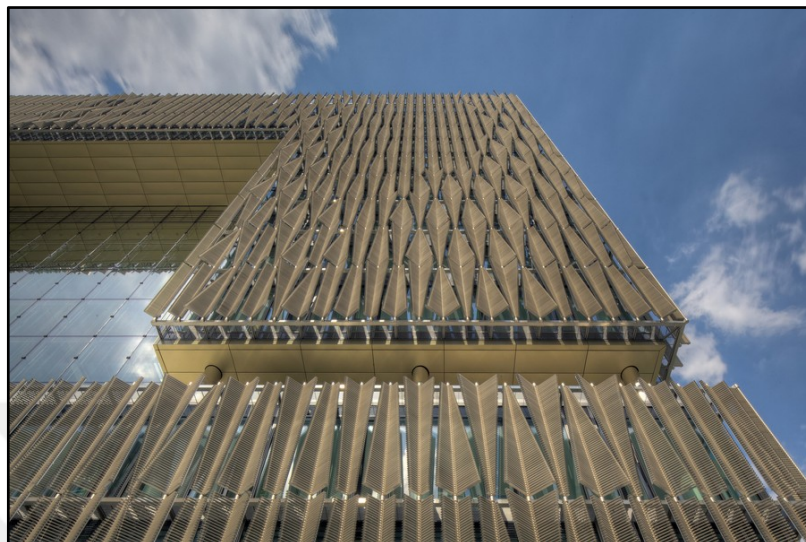
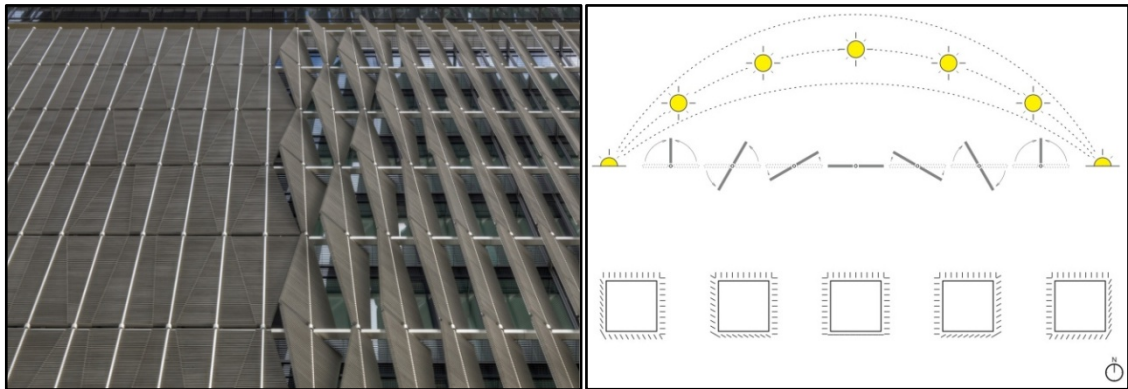


Figure 4.7. The Q1 building facade [128].

The facade of the Q1 building is made up of three layers. The textile layer on the interior reduces shine on the inside, the middle consists of a thermal glass curtain and on the exterior, there is a kinetic sun shading element. The dynamic facade design is automatically controlled and is made up of 400.000 stainless steel slats [129]. These slats are placed on a vertical axis and the movement of the shutters that can move on two axes are controlled directly by engines. The shutters follow the movement of the sun and are triangular and rectangular in shape; they can turn anywhere between 0° and 90° angles. This movement is conducted from signals taken from an air station mounted on the roof of the building [127]. In this context, the Q1 building uses electro-mechanical technologies in responsive facade design by integrating it with the concept of biomimicry [112]. The light sensors and engine based actuators in the facade designs allow the shutters to move in response to environmental effects.



(a)

(b)

Figure 4.8. (a) Q1 building facade, (b) diagram of rotational movement of metal feathers [128].

In this architectural facade design, the controlled use of solar energy provides light and temperature comfort. The facade of the building, which has a large atrium, is covered with 2mm thick metal feathers, and even when these feathers are in closed position, the structure gets natural light, thus decreasing artificial lighting costs [127]. The building has many awards for its environmentally conscious identity thanks to how it makes use of natural resources to provide properties such as energy efficiency, heating and cooling through a central ventilation system, reusing geothermal energy and rainwater.



Figure 4.9. View of the panorama window at Q1 building [128].

In conclusion, the behavior level of biomimicry was used in the design of the shading elements of the Q1 building. The sunlight sensitive system controls the shutters in the designs, thus showing that the building has a responsive facade design. Therefore, the Q1

building has been designed with responsive facade systems and using the concept of biomimicry, by benefiting sustainable architecture through natural lighting, thermal comfort and energy efficiency.

4.3. ONE OCEAN THEMATIC PAVILION

One Ocean Thematic Pavilion is a permanent exhibition building completed in 2012, designed by Lukas Galehr and others in the Soma Architecture company for the Yeosu Expo 2012 in South Korea. The concept of the building is the theme "The living Ocean and Coast". The design aims for the union of nature and city, by allowing the visitors to experience the simplicity and depth of the ocean. The design of the main entrance of the building uses a biomimetic approach to design and the facade was designed with moving cover glass pieces. The other facade, which has vertical cones, defines a curved shoreline between the water and the land [130]. The building, which is the result of 21st century technological advancements, uses biomimicry as a facade design concept and is analysed in this chapter due to its reaction to environmental effects.



Figure 4.10. One Ocean Thematic Pavilion, Yeosu, 2012 [130].

The design of the Thematic Pavilion takes inspiration from the principles of elastic strain seen in plant motion to design a new kind of kinetic facade system. The main inspiration for the facade is the opening motion of the leaves in the perch of the bird of paradise flower (*strelitzia reginae*) found in South Africa. Bird of paradise flowers open their leaves downwards through a lateral rotation to ensure pollination. This motion inspired the design

of the facade material called Flektofin®. In addition to this design, fiberglass polymers (GFRP) were added to increase durability and provide a low bending rigidity. This is how the facade design can easily turn on a lateral direction [131]. The facade design was inspired by the turning motion of the leaves of the bird of paradise flower, therefore the conclusion is made that the design was conducted using the behavior level of biomimicry. Additionally, since it is inspired by the material designed as a result of analysis of the motion of the plant, the biomimicry approach has been determined as biology influencing design.

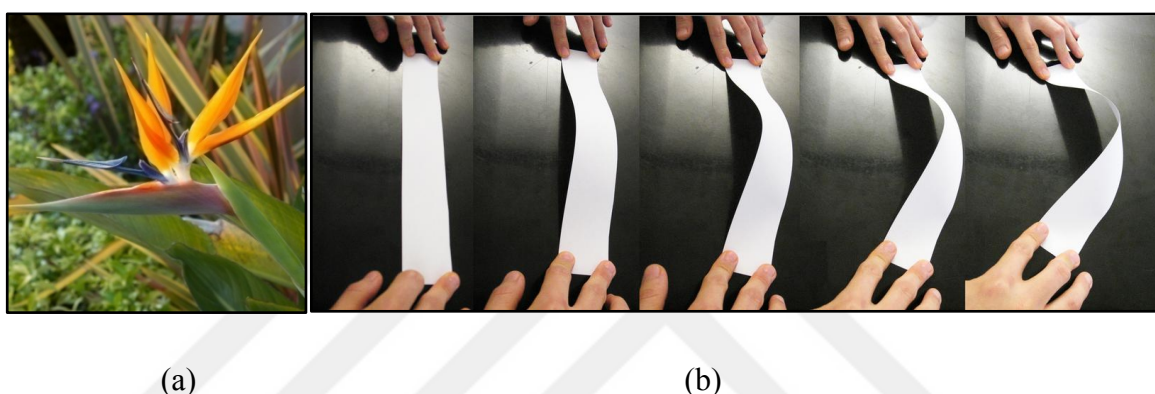


Figure 4.11. (a) Bird of paradise flower [132]. (b) the lateral turning motion that was the inspiration [133].

The facade of the One Ocean building is made up of 180 fiberglass lamellas made from fiberglass reinforced polymers that are 140m in length and vary in height from 3m to 13m, and are opened and closed by a servo motor. The lamellas are slightly curved and are 9 mm in thickness and 125 cm in width. Each of the lamellas are moved by actuators found in the upper and lower edges of the facade. This system is run by solar panels found in the roof. The movement of the lamellas controls the light in the interior foyer and exhibition space [97]. The length of the lamellas in the facade affects their opening angle. The taller a lamella is, the higher its opening angle, thus increasing the amount of space affected by light [130]. Additionally, the facade automatically closes when there is strong wind in the region of the building, which seldom happens, and it is lockable. This is how the building has the property of being undamaged in the face of the strongest storms.

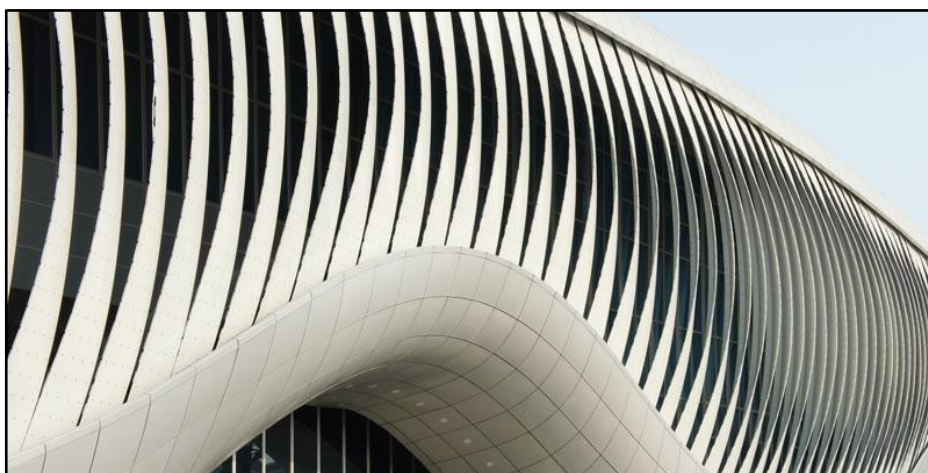


Figure 4.12. Responsive architectural facade with mobile lamellas [134].

The moving lamellas of the building can work separately from each other in accordance to climate changes and user needs, while also creating moving patterns throughout the facade. Furthermore, after sundown, LED strips in the interior side of the lamellas light up, reinforcing the aesthetic appearance of the facade [131]. The building is an example of electro-mechanical technologies being used in responsive facades due to its response to environmental effects with the actuators and sensors found in the facade.

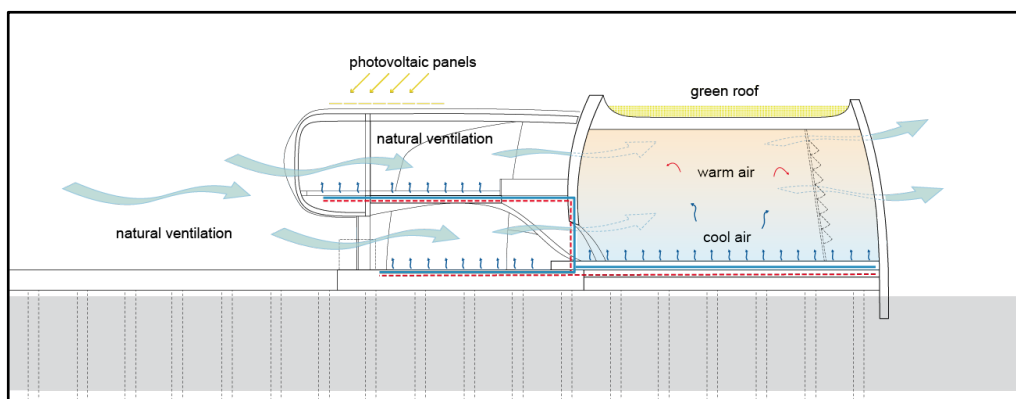


Figure 4.13. Interior ventilation and heat diagram [134].

In conclusion, the facade design of One Ocean takes inspiration from plant motion, thus being designed on the behavior level of biomimicry, and moving lamellas were used in the facade. The sunlight and wind responsive facade design provide natural ventilation and lighting. Additionally, the solar panels on the roof allow the building to produce energy. Thus creating a sustainable architectural envelope through providing energy efficiency with facade design.

4.4. AL BAHR TOWERS

The Al-Bahr Towers are two office buildings constructed in 2012 in the UAE capital Abu Dhabi. The building, designed for Abu Dhabi Investment Council in collaboration with Aedas Architecture (now AHR) and Arup, is 145 m tall and 29 stories. The design concept of the Al Bahr towers is based on the combination of biomimicry, local architecture and performance based technology. The concept of Mashrabiya in Arab culture was the inspiration for the moving facade design of the building and a responsive facade system responding to changes in climate has been used. The building, which has the largest computer controlled dynamic facade, is defined as an aesthetical and cultural reflection of 21st century technological advancements [135]. The sustainability and conscious cultural approach of the Al Bahr towers was awarded by the Council of Tall Buildings and Urban Habitat with the 2012 Tall Building Innovation Award [136]. The evaluation of these properties show that the building has a responsive facade design that reacts to environmental effects through the use of the concept of biomimicry as a design method, thus allowing it to be analysed in this chapter of the thesis.



Figure 4.14. Al Bahr Towers, Abu Dhabi, 2012 [135].

The facade design of the Al Bahr towers was designed as a contemporary interpretation of Mashrabiya to create an innovative and aesthetically different shading system. Mashrabiya, which is used in Islamic architecture, reduces shine and heat gain while also providing privacy by using a wooden caged shading method. Additionally, the bio inspiration of this system is flowers that can adapt to the direction in which they get sunlight from. In conjunction with this, the facade of the Al Bahr Towers are made up of rows of translucent parasol-like elements that open and close based on the angle of sunlight [136]. The folding

concept of the dynamic shading element is explained with a simple origami model showing how the triangular pieces function [135]. In this context, the building takes inspiration from the movement adaptive flowers perform due to sunlight, thus concluding that the design was made through the use of the behavior level of biomimicry. And the approach to biomimicry is defined as biology influencing design.

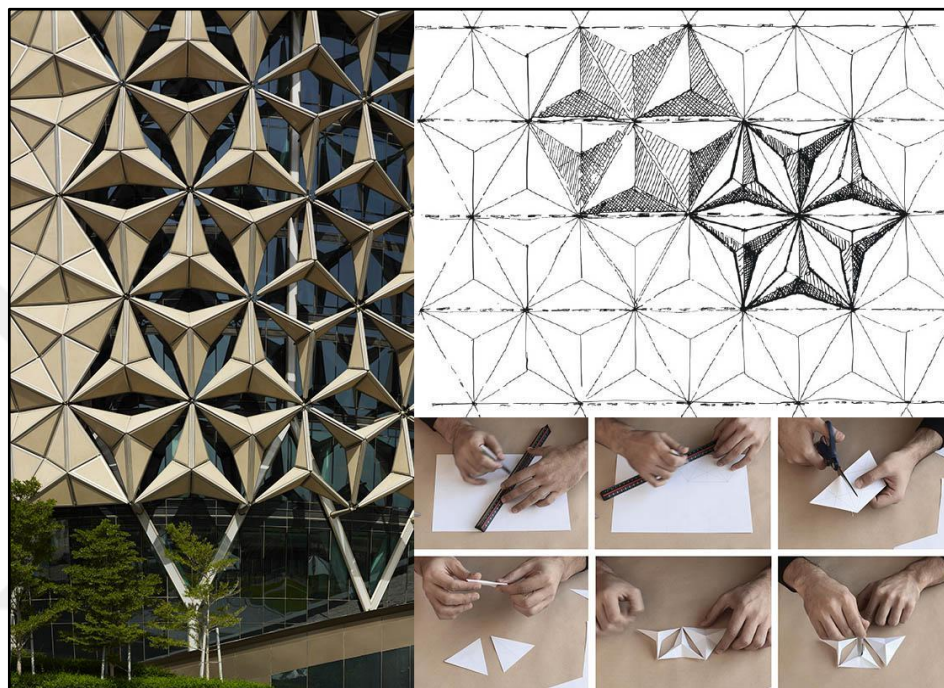


Figure 4.15. Bio inspiration for the shading element and the principle of its opening motion [135].

Mashrabiya (shading elements) in the facade of the Al Bahr Towers cover every side of the building except for the northern side. There are 1049 Mashrabiya in each tower and are mounted on beams 2m away from the glass facade. Each triangular piece on the facade is made from stretched pieces of fiberglass covered with PTFE (polytetrafluorethylene). The responsive facade is controlled by a preprogrammed central Building Management System (BMS) to block sunlight on the facade. This system is run by a vertical hydraulic actuator that opens and closes in parts throughout the day. Furthermore, several sensors are used to determine changes in weather to open the units. Additionally, the form of the towers have also been designed to provide the best amount of shading. The circular form around the core is more narrow on the bottom and top of the tower, while being wider in the middle. This has an important effect in reducing sunlight alongside the shading elements [136].

The facade design of the Al Bahr towers is an example of electro-mechanic technology being used in responsive facade design.

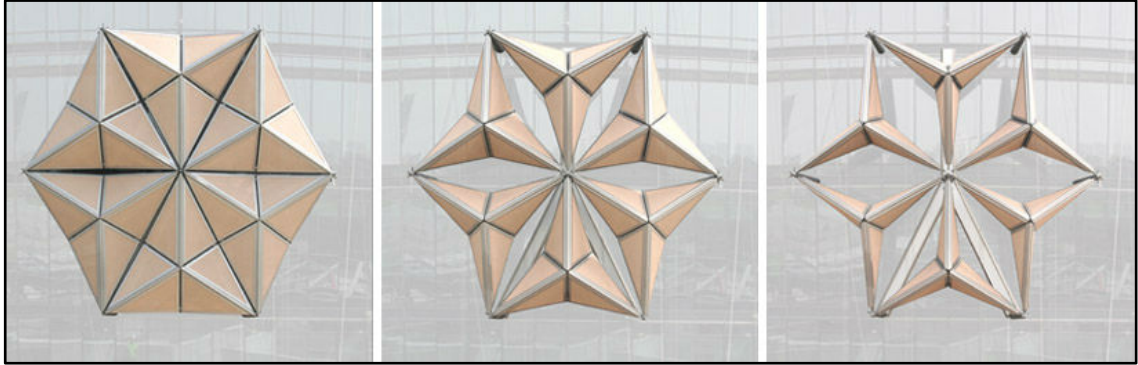
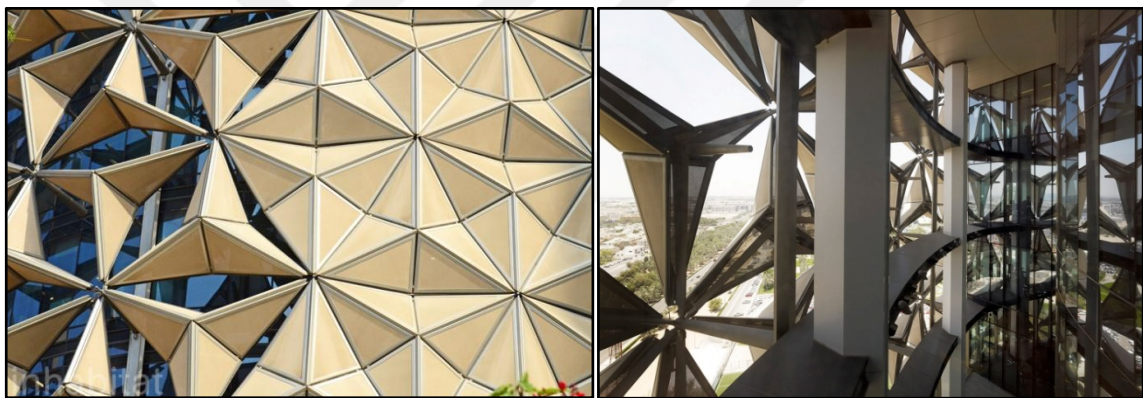


Figure 4.16. Open and closed states of the shading elements [137].



(a)

(b)

Figure 4.17. (a) Exterior and (b) interior detail of the facade [135].

The dynamic facade of the Al Bahr towers reduces the need for heavily processed glass, thus reducing the need for artificial lighting and mechanical air conditioning. In doing so, it reduces energy use while creating a pleasing appearance and thermal comfort [135]. The low use of artificial lighting in the building and a more than 50% reduction in solar gain results in a 1,750 tonnes reduction per year in CO₂ emissions. This results in designing a responsive facade through sustainable solutions [136].

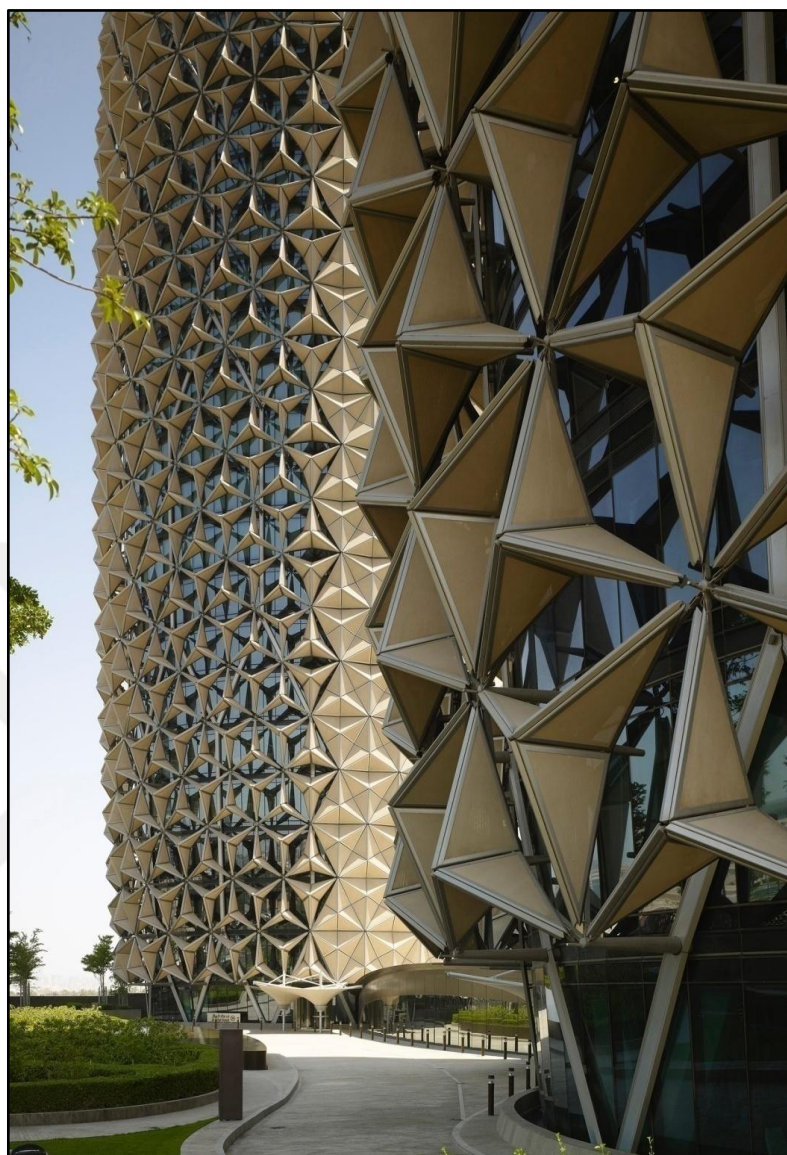


Figure 4.18. The motion of the shading elements on the facade based on sunlight [138].

In conclusion, the facade design of the Al Bahr Towers was used the Mashrabiya concept inspired by the motion of plants that can adapt to sunlight, and designed on the behavior level of biomimicry. The responsive facade of the building works with a mechanism of dynamic shading elements that open and close based on the movements of the sunlight. Furthermore, a contemporary implementation of the concept of Mashrabiya develops a sense of continuity with the past, while also being an effective method of use for biomimicry in responsive facade design. Therefore, the moving system on the facade provides sustainability through natural lighting, temperature regulation and energy efficiency.

4.5. MOKYEONRI WOOD MUSEUM

Mokyeonri Wood Culture Museum is a building designed by Seoul based architecture studio Soft architecture lab and architect Eunju Han in Incheon, South Korea. The wood museum is on a 549 m² construction site and the construction was completed in 2017. The name of the project Mokyeonri refers to the harmony between roots of different trees that consists of a series of architecturally defined spatial experiences portraying the different properties of wood. The Mokyeonri Museum was designed as an exhibition space where visitors could feel the wood and the trees with all of their senses [139]. The project is located in Incheon Grand Park. For this reason, the design concept has been planned around symbolising the arboretum by integrating it into the architecture and to allow for the trees in the forest to be sensed. In this context, the building is seen as a reflection of nature and the conclusion is made that it was designed based on the concept of biomimicry. The facade design of the building was designed as an interactive wooden wall and it is included in this part of the thesis due to its reaction to environmental factors.



Figure 4.19. Mokyeonri Wood Museum, South Korea, 2017 [139].

The facade design of the Mokyeonri Museum was inspired by the shape and movement of the leaves in the forest through their architectural abstraction. In conjunction with this, Ambience Wall (interactive wooden panel) was designed by taking inspiration from the falling of the sunlight between the leaves and the movement of leaves in the wind. In contrast with other wood museums, this allows for the guests to see, hear, smell and touch

the wood through the architectural ambience while experiencing the forest first hand [139]. The facade of the museum takes inspiration from leaves, thus concluding that it was designed through the organism and behavior levels of biomimicry. Additionally, the biomimicry approach has been determined as design looking to biology.

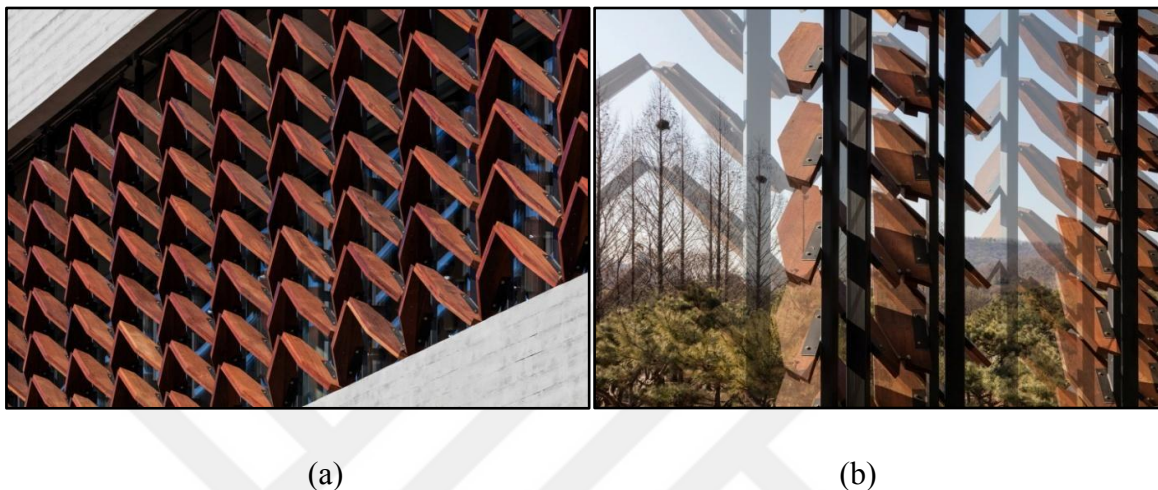


Figure 4.20. (a) Museum facade inspired by leaves, (b) movement of the panels [139].

The wooden panels in the facade design of the Mokyeonri Museum are made from six sided 'leaves' hanging from one point constructed of a hardwood called Merbau and a metal frame. These panels are hung in pairs attached in one end. The facade, which is positioned based on the wind and is sunlight sensitive, is moved via a mechanism. The distance between the vertical pieces can be changed through a pulley system powered with an engine in the facade design [140]. As a result of this, the 4m to 30m Ambience Wall that can move on rails has been created. The wooden panels on the facade move based on the position of the sun, thus controlling the amount of sunlight in the interior space. The wooden panels in the facade design of the museum are powered by an electric engine, thus making this an example of electromechanical technologies being used in responsive facade design.

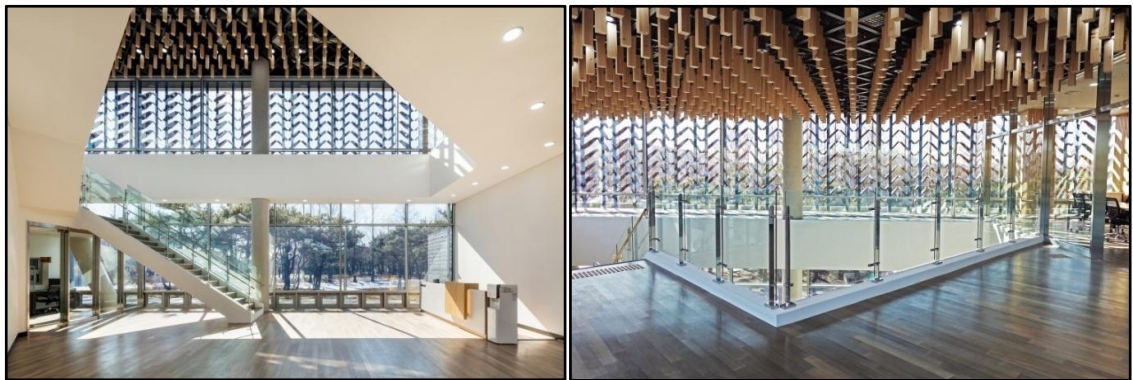


(a)

(b)

Figure 4.21. Wooden panels on the facade (a) and (b) [139].

The kinetic ambient wall technology designed by Soft architecture lab reacts to ever changing factors such as time, weather and user movement and manages each factor [141]. This technology used in the facade design of the building goes outside the current building concept and creates an interaction between the users and the building. Thanks to the Ambience Wall, which parametrically reflects the weather and human actions in the region, reinforces the communication between the interior and exterior spaces. Therefore, an innovative, responsive and creative facade design is created to experience wood.



(a)

(b)

Figure 4.22. A look at the ambience wall from the interior of the museum (a) and (b) [139].

In conclusion, the Mokyeonri Wood Museum has a facade inspired by the shape and behavior of leaves found in nature, therefore it has been designed on the organism and behavior levels of biomimicry. The facade is responsive to sunlight and wind, the movement of the wooden panels provide the interior with natural lighting and ventilation.

The location of the building affected the materials used in the facade design, making the building fit in with the nature around it. When all of these are evaluated, it is seen that this facade design benefits sustainability through energy efficiency.

4.6. HIVE HOUSE

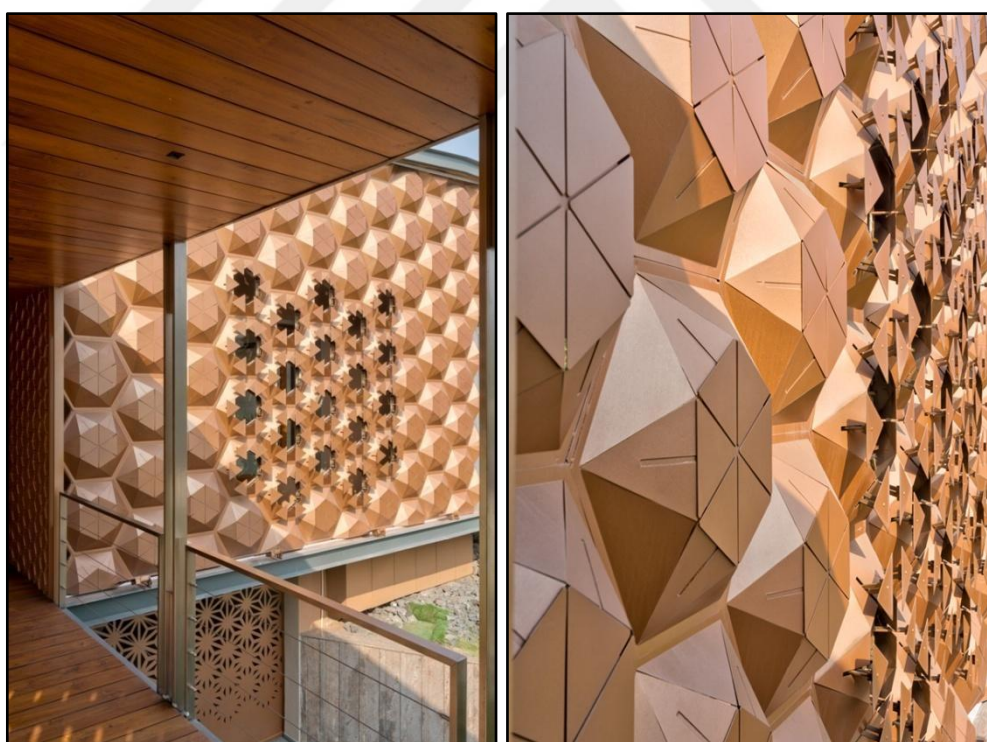
Hive House is a house project completed in 2019 in Surat, India, by Monarch Champaneri and others in Openideas Architecture firm. The building has a gross size of 600 meter squares and it has 2 stories. The design concept of the Hive was creating a smart, adaptive and sustainable family home [142]. Through the design process of the building, nature was taken inspiration from multiple times and biomimicry principles were used. The facade surrounds the common spaces of the ground floor, it not only uses biomimicry, but it also has properties of a responsive facade [143]. A thorough research was conducted around user needs and requests through the design process. The users worked together with the architects by conducting a study covering everything from structural materials, landscaping, sustainability requirements and a one year long solar energy plan. This research and design criteria resulted in a technologically based smart structure constructed out of metal. In this context, Hive House is an example of responsive facades that use biomimicry through the technological advancements in the 21st century.



Figure 4.23. Hive House, Surat, 2019 [142].

The facade design of Hive House is based on structural resilience, transformability and biomimicry. The geometry of the facade was inspired by the structural hexagonal forms seen in honeycombs and carbon crystals. This is also the inspiration of the name of the project [142]. It is concluded that the building was designed on the organism level of biomimicry, because the facade design only took inspiration from nature in its form. Also, the biomimicry approach has been determined as design looking to biology.

The hexagonal fractals inspired by organism forms in the facade design of the building are made up of smaller hexagonal fractals that are made up of six equilateral triangles. All of these triangles include a solar sensor and use a mechanism to open and close based on sunlight. The movement of the mechanism found in the facade was designed with the working principle of bus doors in airport buses [143]. The use of solar sensors in the responsive facade of the building shows that electro-mechanical technologies were used in facade design.



(a)

(b)

Figure 4.24. Repeating hexagonal modules in the facade (a) and (b) [143].

Only the strategically placed fractals on the facade of the building are made to move. Also, the part of the facade that covers an entrance bridge and a ground floor bedroom is made in

a design consisting of different thicknesses of hexagonal circles. This design eliminates the harshness of the sunlight that enters the space [143]. Since dynamic facade design moves based on the movement of the sun, it also affects the visual appearance of the indoor and outdoor spaces.

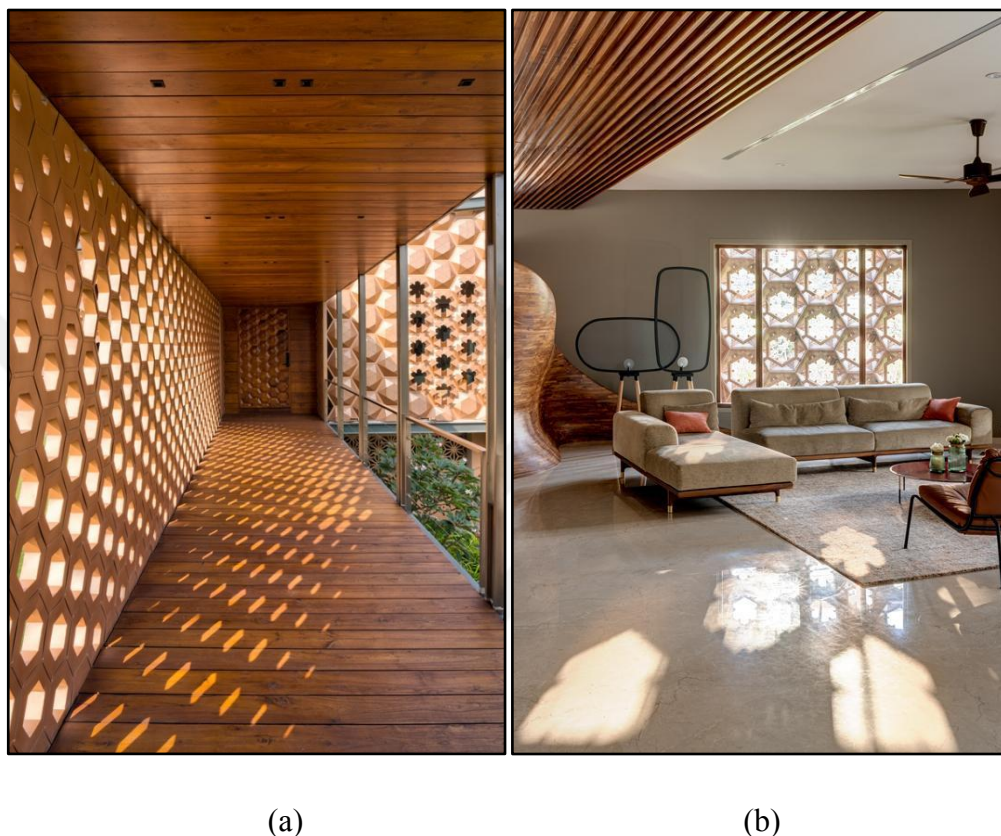


Figure 4.25. (a) Entrance bridge, (b) the effect of sensor based triangles on the interior [142].

The Hive House has a responsive facade design that reacts to environmental factors, thus creating better lighting quality and thermal comfort in the interior. Thus benefiting sustainability and nature by providing heat regulation, natural lighting and energy efficiency.

In conclusion, the facade design of the Hive House used biomimicry as a design method and the design was done through the organism level of biomimicry by taking inspiration from hexagonal shapes found in nature. The metal hexagonal fractals in the facade of the building have a sunlight sensitive mechanism, and allow the sufficient amount of sunlight into the space to ensure thermal comfort. This shows that the building has a responsive

facade design. The integration of the organic forms found in the facade design of the building with technology shows that the concepts of biomimicry and responsive facades can provide daily living spaces with dynamism.

4.7. AN EVALUATION OF THE ARCHITECTURAL FACADES ANALYSED IN TERMS OF RESPONSIVE FACADE AND BIOMIMICRY

The main goal of the thesis is to analyze the benefits of biomimicry as a design method for designing facades to sustainability, nature and architecture. Research concludes that the combination of the concept of biomimicry and responsive facade systems using present day technology greatly benefits sustainability, nature and architecture in visual comfort, thermal comfort and energy efficiency. In this context, the fourth chapter of the thesis analyzes biomimicry based responsive facade designs that were inspired by nature and can respond to environmental effects to benefit sustainability, and were built in the 21st century. Building facades fulfilling these criteria were identified after extensive research and 6 of these buildings with the most contemporary and innovative facade designs were chosen for fulfilling these criteria. Care was taken to ensure variance in the functions of the chosen buildings. Thus, in the subheadings of the fourth chapter the following buildings were analyzed; CH2 Building, Q1 Building, One Ocean Thematic Pavilion, Al Bahr Towers, Mokyeonri Wood Museum and Hive House. In conclusion of all these analyses a table was compiled showing the common properties and differences between these buildings.

The buildings analyzed in the fourth chapter of the thesis were analyzed on three parameters. First, The table shows the architectural properties like location, year, architect, function and photograph of the buildings. Then the effect of the first parameter, which is biomimicry, on facade design is examined. In this parameter, the inspired organism, level of biomimicry, biomimicry approach and the properties of the organism that were integrated into the design (meaning the similarities between the facade design and the inspired organism) are analyzed. The information in this part of the table is determined based on the research in chapters 2.2 and 2.3 of the thesis. The second parameter used in the table has been determined as the analysis of the responsive architectural facade design. In this parameter, the environmental factor the facade responds to, the material of the

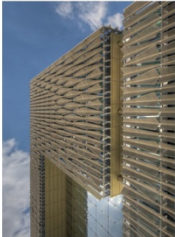
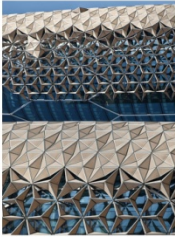
facade, the applied technology and the technical elements of the responsive facade system are analysed. This part of the table was determined based on the subjects in chapter 3.3 of the thesis. The third parameter is the analysis of the effects of the facade design on sustainability. This parameter examines the benefits of the facade design to sustainability. These findings were determined by the analysis of the relationship between the concept of architectural facades and sustainability in chapter 3.1 of the thesis. The 6 chosen buildings have been compiled in chronological order in "Table 4.2".

As seen in "Table 4.2" below, all of the chosen examples have a responsive architectural facade system that utilizes biomimicry and are buildings that were completed in the 21st century. To ensure a broader perspective on the effects of the strategies of nature in facade design, 6 different buildings were chosen by carefully assessing the following;

- Ensuring variance in the inspired organisms to analyze the effects of different biological organisms on facade design
- Ensuring different biomimicry levels and approaches are used when the abstracted properties of the inspired organism are being integrated into the design
- Ensuring the technically different use of materials and systems in facade design (turnable, dynamic shading elements)

These buildings were analysed based on the parameters determined in chapter four of the thesis.

Table 4.2. Analysis of the chosen biomimicry based responsive architectural facades
(prepared by author).

	COUNCIL HOUSE 2	Q1 BUILDING	ONE OCEAN-PAVILION	AL BAHR TOWERS	MOKYEONRI MUSEUM	HIVE HOUSE
Facade image						
Location	Melbourne, Australia	Essen, Germany	Yeosu, South Korea	Abu Dhabi, UAE	Incheon, South Korea	Surat, India
Year	2006	2010	2012	2012	2017	2019
Architects	Mick Pearce ve DesignInc	JSWD Architekten, Chaix - Morel et Associates	Soma Architecture	Aedas (now AHR) and Arup	Soft architecture lab	Openideas architecture
Building Function	Administrative building	Office building	Exhibition center	Office building	Museum	House
Inspired Organism	Termite mounds and trees	Feather	Bird of paradise flower	Adaptable flowers and Mashrabiya concept	Leaves	Honeycombs and carbon crystals
Level of Biomimicry	Organism and Behavior	Behavior	Behavior	Behavior	Organism and Behavior	Organism
Biomimicry Approach	Design looking to biology	Design looking to biology	Biology influencing design	Biology influencing design	Design looking to biology	Design looking to biology
Design Inspiration of Biomimicry	-The passive ventilation, heat regulation, and water storage from termite mounds - The ventilation mechanism and light transmittance from the bark of the tree	-The performance techniques that protect the skin of the bird feathers	- The lateral rotation movement of the leaf of the bird of paradise to ensure pollination	- Movement of flowers that can adapt to the direction of sunlight	- The falling of the sunlight between the leaves and the movement of leaves in the wind.	- Hexagonal forms found in nature, such as honeycombs and carbon crystals
Environmental Factor in response	Sunlight	Sunlight	Sunlight and Wind	Sunlight	Sunlight and Wind	Sunlight
Facade Material	Recycled wood	Stainless steel	Fiberglass lamellas	PTFE, fiberglass	Wood made from Merbau	Metal
Responsive Facade Technology	Electro-mechanical technology	Electro-mechanical technology	Electro-mechanical technology	Electro-mechanical technology	Electro-mechanical technology	Electro-mechanical technology
Responsive Facade Elements	- Recycled wooden shutters controlled by photovoltaic cells - Dynamic mechanism based on the angle at which sunlight hits	- Metal shutters that can turn between 0°-90° angles following the movement of the sun - Light sensors and motor-based actuators	- Fiberglass lamellas that can be opened and closed, responsive to sunlight - Light and temperature sensors, motor-based actuators	- Dynamic shading element run by the hydraulic actuator and sensors responsive to sunlight	- Ambience Wall that reacts to changing environmental factors - Mobile wooden panels run by an engine	- Light sensor-based hexagon fractals that can open and closed
Outcomes for Sustainability	- Air is 100% filtered - Natural lighting and ventilation saved by 65% - Storage of water - Shading for visual comfort - Recyclable facade material - Energy efficient	- Reduced artificial lighting costs - Natural lighting - Thermal comfort - Energy efficient	- Natural ventilation - Natural lighting - Energy efficient	- Reduction use of artificial lighting - More than 50% reduction in solar gain - Reduction in CO2 emissions - Natural lighting - Thermal comfort - Energy efficient	- Natural lighting - Natural ventilation - Energy efficient - Environmentally conscious	- Thermal regulation - Natural lighting - Energy efficient

When the chosen buildings were analyzed based on the first parameter, meaning biomimicry, it is seen that their main source of inspiration is organisms found in nature, or organic forms. It is concluded that four of the building examples use plants or the behavioral and structural properties of leaves of plants as inspiration. The Q1 Building takes inspiration from the feathers in the animal skin, and the techniques it uses to protect the skin of the animal have been implemented to the facade. While Hive House hexagonal forms found in nature have been integrated into the geometry of the facade. In this context, when the levels of biomimicry in the facade design of these buildings are analysed, biomimicry was used more often in its organism and behavior levels to integrate the strategies of the living beings to facade design. The ecosystem level of biomimicry, from the levels of biomimicry examined in chapter 2.3 of the thesis, refers to the imitation of the whole of the natural environment the organism lives in, therefore it is seen that this level of biomimicry is not utilized in these facade designs. This shows that the integration of the structural and behavioral adaptations of an organism is more easily integrated into design than the ecosystem level. In conclusion, the evaluation of the facade designs has set forth that the air, heat, light, and water regulation strategies of both animals and plants were integrated into the responsive facade systems.

When the approaches of biomimicry for the chosen buildings are analyzed, the biomimicry approach for four of the buildings (CH2, Q1, Mokyeonri Museum, Hive House) has been determined as design looking to biology. The other two (Al Bahr Towers, One Ocean) are determined as biology influencing design. In facade designs based on biomimicry the first step in general is determining the design problem, then the solution organisms in nature have for similar problems is analysed to integrate them into the design. The other two facade designs use the approach of biology influencing design due to them integrating a specific property into design after biologically researching the facade material Flectofin and the concept of Mashrabiya. This approach is based on biological research, thus concluding that, in architecture, a more problem focused approach was used.

The second analysis parameter of the chosen buildings examines their responsive facade designs. In accordance with this, all of the chosen buildings were found to have responsive facade designs that move based on sunlight. The facade design of the One Ocean Thematic Pavilion has the property of self-locking in strong winds. Although this property detects the strength of wind, it does not show the property of moving based on the direction of the

wind. Furthermore, the Mokyeonri Wood Museum takes inspiration from leaves in its facade design; the wooden panels gently close before going back to their initial position whenever the wind blows. For this reason, it is concluded that in addition to being responsive to the movement of sunlight, these two building facade designs are also responsive to the wind. It is seen that, in general, 21st century responsive facade designs tend to be designed as systems that can only respond to one stimulus such as sunlight.

As seen in "Table 4.2", the facade designs of the chosen buildings all have moving facade systems that are run and controlled with a sensor, actuator or an engine. In conjunction with this, the analysis in chapter 3.3 of the thesis of technologies used in responsive facades, determines that all of the chosen buildings utilize electro-mechanical technologies. Electro-mechanical technologies used in responsive facades are seen as the effects of the technological developments of today and of sustainability to architecture; though it is concluded that there are disadvantages, such as high power use, malfunction risk of mechanical parts, high repair and maintenance costs.

When the facade designs of the chosen buildings are analyzed on materials and systems used, it is seen that they have been integrated into the design as a specifically developed innovative facade design based on the strategies of the inspired organism, or as a glass curtain wall. These systems have been used in the facade design of the buildings as shading elements, facade panels, parasols, ventilation shafts and fiberglass panels. Only the Council House 2 building among the evaluated buildings is seen to use a recyclable material in its facade design by using wooden panels. The other facade designs use durable and insulated materials such as metals, stainless steel, hardwood and fiberglass. The use of these materials in facade design provides a building with a better facade in terms of durability, weight, sustainability and energy efficiency when compared to other commonly used glass curtain-walls of today.

When the biomimicry based responsive facade designs examined in the table are analysed in terms of sustainability, all buildings are seen to allow controlled amounts of sunlight into the interior space by using moving shading elements. In conjunction with this, artificial lighting costs were reduced, meanwhile providing natural light. Furthermore, all chosen buildings fulfill thermal comfort due to their facade designs, while providing heat regulation and natural ventilation. Aside from this, they also bring benefits to sustainability in the context of water storage strategies, waste water management and water saving,

inspired by organisms. These factors reduce the energy use of the building while rooftop systems in some of the buildings allow for energy production. After all these evaluations, it is seen that heat and light regulation provides the most energy efficiency in facade design. The research and the analysis of these facade designs conclude that biomimicry as a design method for designing responsive facades is one of the most effective, innovative and technological methods that can be used to produce energy efficient, environmentally friendly, sustainable and ecological designs.



5. CONCLUSION

Nature has survived for billions of years through its own ideal order and cycles. The cycle within nature and the organisms that live in it have always been an interest to people and guided people to study nature. In this context, people started to take inspiration from strategies developed by nature in order to raise their quality of life and produce efficient designs. Even though the desire to take inspiration from nature appeared in the early ages, the naming of that desire as the concept of biomimicry was suggested by Janine Benyus in the 20th century. Humankind has consciously and unconsciously taken inspiration from nature throughout history and benefited from the concept of biomimicry to solve issues encountered in design.

With the proliferation of the concept of biomimicry and the beginning of its use as a design method, architectural designs have increasingly become more affected by nature. When the examples of biomimicry in the field of architecture were examined, it was seen that an innovative design approach in designing building facades that serve as an interface between nature and the built environment benefits fulfilling the responsibilities designers have toward nature. In this context, different facade designs have been developed in the 21st century with the integration of technological developments and the concept of sustainability into facade designs. In the research, it was concluded that the most contemporary and newest technologies among these facade designs are the responsive facades. The common goal of biomimicry and responsive facade concepts is to create a sustainable and environmentally friendly building. Therefore, it is the aim of the thesis to analyse these two concepts together.

While the aim, scope, and method of the thesis are defined in the first part of the thesis, in the second part, the relationship between the concept of biomimicry and architecture was examined in order to understand biomimicry and correctly apply its principles into design. The study of the approaches and levels of biomimicry has guided the process of finding solutions to problems encountered in architectural design while providing data that allows for the correct implementation of properties of organisms into design. Through biologists and architects working together, biomimicry approaches have emerged, and the integration of biomimicry into the design process was made easier. In addition, the use of biomimicry

as a method that offers solutions to problems in the field of architecture throughout history has been analysed through examples. As a result of the research in this section, it has concluded that biomimicry contributes to the development of innovative approaches by emulating the ideal situation in nature in architecture, thus creating sustainable and eco-friendly buildings.

The architectural facade design is critical in the creation of a sustainable building. The concept of facades is the building element that contributes to the energy efficiency of the building, provides the comfort conditions for the users, and the first visual interaction with the building. In this context, the third chapter of the thesis focuses on the concept of architectural facades and the effects of the technological advancements of today and sustainability on facade design have been studied. The research analyzes biomimetic facade examples that take inspiration from organism skins found in nature and concludes that facades that behave similarly to organisms have a greater benefit to sustainability and nature than the commonly used static facades of today. All of this serves as proof that the use of the strategies found in nature in design is one of the most effective solutions for making sustainable facade designs.

The innovations seen in the field of architecture in the 21st century have allowed the development of responsive facade designs that respond to environmental conditions and contribute to energy conservation. In this context, the architectural facade research has been limited in the 3.3 chapter of the thesis to the concept of the responsive facade. In this section, responsive facade systems were examined and the technologies used were analyzed. It has been concluded that the contribution of responsive facade designs to nature and architecture has increased thanks to the interdisciplinary work. The use of biomimicry as a design method in responsive facade design allows for more interactive, eco-friendly, and energy-efficient designs to be created, thus having a greater impact on sustainability.

Within the scope of the thesis, buildings with responsive facade designs that use biomimicry as a design method in the 21st century are examined. Buildings that can respond to environmental factors with dynamic facade elements, use new technologies, and have sufficient data access, were selected in line with the determined criteria. However, since the 21st century is still ongoing, newer examples continue to be built. In addition, responsive facades that were not built in the 21st century, do not have biomimetic facades design and do not have a dynamic facade system are excluded from the scope. As a result

of the literature review, 6 contemporary buildings were identified for analysis. These buildings are Council House 2, Q1 Building, One Ocean Thematic Pavilion, Al Bahr Towers, Mokyeonri Wood Museum, and Hive House. Selected buildings were analyzed within the framework of the parameters determined in the fourth chapter of the thesis. Finally, a table was presented in chapter 4.7 of the thesis, and building facades were evaluated in the context of biomimicry, responsive facade, and sustainability.

As a result of the research in the thesis, some findings and conclusions were reached. It has been seen that the widespread use of the concept of biomimicry in design can be possible with the increase of interdisciplinary cooperation. Due to the opportunities provided by technological advancements, digital resources, and communication tools of today, interdisciplinary work can be increased. Furthermore, conscious designers can be taught through educational programs that teach biomimicry in the fields of architecture, construction engineering, and design.

One of the findings that emerged from the analysis of the buildings examined in the fourth chapter of the thesis is that buildings with existing responsive facades usually have shading elements that move according to the angle of sunlight. This shows that other environmental factors such as humidity, wind, precipitation, and so on, also need to be a part of responsive facade design. And, in order to protect buildings and users from the very common geological events of today, organisms and ecosystems found in nature can be taken inspiration from to find new solutions to facade design. In conclusion, it can be suggested that responsive facade designs that use the principles and methods of biomimicry in order to avoid the negative effects of natural and meteorological events should be made more common, and they should be designed to react to more than one stimulus.

Advancements in technology and in conditions, as well as the 21st century developments in the field of architecture, shows themselves in designs made with inspiration from nature. From the times when the concept of biomimicry only took inspiration from the observations of the form of an organism, it now has transitioned to a period where the behaviors, textures, and survival methods of organisms are being implemented into design. This is seen when existing buildings are analysed and it is also seen in projects that took inspiration from animal skin examined in the other chapters of the thesis. It was seen after the examination of projects, the use of an architectural facade that behaves similarly to a

living organism or to skin results in a greater impact on sustainability. Although these prototypes are not used as current building systems and are instead kept as experimental works. This may be caused by high production costs or technical insufficiencies. These ideas can be tested as additional designs on existing building systems and developed through revisions for user needs and wishes.

In 21st century responsive facade designs, the property that was inspired by nature in the design were made up of moving elements on the facade that were mostly run and managed by electro-mechanical systems. Responsive facade systems that use electro-mechanical technologies might be more efficient than many other systems, but they are seen as a technology in need of development due to some of their disadvantages. In some of the smaller scale projects inspected in the thesis, some facades use materials that can react to environmental factors like a living organism in order to move, without the need of an electrical system. In conjunction with this, instead of using smart materials that work through a system in the facade design, a reactive material technology that can react to environmental factors without the need for an electrical system might be suggested. It is thought that this will be possible if biomimicry is taken complete advantage of in facade design. In other words, the creation of facade designs that behave like a living organism and are dynamic and interactive can be possible by using the organism and behavior levels of biomimicry in tandem. This can be supported by use of material-based technology in responsive facades, allowing the whole facade to behave as nature does.

The technological advancements of today also affect the materials used. In addition, the concept of sustainability, which is of great importance in the 21st century, also allows for the development of material technologies. Even though these advancements are being implemented in responsive facade systems, it is concluded that the use of innovative materials that benefit sustainability can still be increased. In this context, the use of recyclable, eco-friendly, energy efficient, biodegradable, affordable, and smart materials can be made more common in facade designs that use biomimicry as a design method.

In addition, the use of smart materials that cause energy consumption in buildings has been a matter of discussion for sustainability. Because, although smart materials cause a reduction of artificial lighting and ventilation costs in terms of thermal comfort in the indoor space, the effect on energy consumption is also quite high since it operates with an electrical system. For this reason, as mentioned in the paragraph above, it is thought the

material reacting automatically to external conditions without the need for energy will contribute more to sustainability. Nowadays this situation is going to be possible by using programmable materials instead of smart materials used in facade design today.

The conducted analysis concludes that responsive facades that were designed with nature based dynamic shading elements provide the following sustainable, energy efficient and aesthetically pleasing solutions, reduction of energy use and increase of energy efficiency (through passive ventilation, natural lighting, light regulation), prevention of the emission of harmful gases to nature, prevention of air pollution, water storage and reuse, and visual comfort. The results of the use of biomimicry based facade design proves its undeniable benefits to architecture and to nature.

The concept of biomimicry will continue to give a wider perspective on facade design in the 21st century and beyond. Thanks to the developments in material technology, the organism and behavior levels of biomimicry defined by Zari can be more commonly integrated into responsive facade designs. This will allow the architectural facade to cease being just an external layer of the building, and for it to start behaving like organisms in nature, and transform it into a living shell that does not disrupt the cycle of nature. In conclusion, facade design created with this approach will allow for the creation of a sustainable built environment that enhances the quality of life of all living beings and increases the life expectancy of natural resources. Thus, cities consisting of a static series of walls have the potential to transform into cities that constantly change and behave as if they are alive organisms due to living facades.

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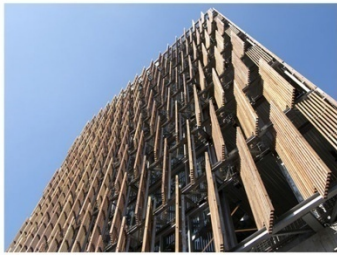
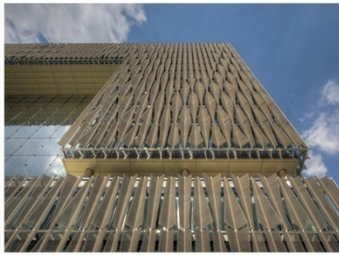
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APPENDIX A: ANALYSIS OF THE CHOSEN BIOMIMICRY BASED RESPONSIVE ARCHITECTURAL FACADE

	COUNCIL HOUSE 2	Q1 BUILDING	ONE OCEAN-PAVILION	AL BAHR TOWERS	MOKYEONRI MUSEUM	HIVE HOUSE
Facade image						
Location	Melbourne, Australia	Essen, Germany	Yeosu, South Korea	Abu Dhabi, UAE	Incheon, South Korea	Surat, India
Year	2006	2010	2012	2012	2017	2019
Architects	Mick Pearce ve DesignInc	JSWD Architekten, Chaix - Morel et Associes	Soma Architecture	Aedas (now AHR) and Arup	Soft architecture lab	Openideas architecture
Building Function	Administrative building	Office building	Exhibition center	Office building	Museum	House
Inspired Organism	Termite mounds and trees	Feather	Bird of paradise flower	Adaptable flowers and Mashrabiya concept	Leaves	Honeycombs and carbon crystals
Level of Biomimicry	Organism and Behavior	Behavior	Behavior	Behavior	Organism and Behavior	Organism
Biomimicry Approach	Design looking to biology	Design looking to biology	Biology influencing design	Biology influencing design	Design looking to biology	Design looking to biology
Design Inspiration of Biomimicry	-The passive ventilation, heat regulation, and water storage from termite mounds - The ventilation mechanism and light transmittance from the bark of the tree	-The performance tech- niques that protect the skin of the bird feathers	- The lateral rotation move- ment of the leaf of the bird of paradise to ensure polli- nation	- Movement of flowers that can adapt to the direction of sunlight	- The falling of the sunlight between the leaves and the movement of leaves in the wind.	- Hexagonal forms found in nature, such as honey- combs and carbon crys- tal
Environmental Factor in response	Sunlight	Sunlight	Sunlight and Wind	Sunlight	Sunlight and Wind	Sunlight
Facade Material	Recycled wood	Stainless steel	Fiberglass lamellas	PTFE, fiberglass	Wood made from Merbau	Metal
Responsive Facade Technology	Electro-mechanical technology	Electro-mechanical technology	Electro-mechanical technology	Electro-mechanical technology	Electro-mechanical technology	Electro-mechanical technology
Responsive Facade Elements	- Recycled wooden shutters controlled by photovoltaic cells - Dynamic mechanism based on the angle at which sunlight hits	- Metal shutters that can turn between 0°-90° angles following the movement of the sun - Light sensors and mo- tor-based actuators	- Fiberglass lamellas that can be opened and closed, responsive to sunlight - Light and temperature sen- sors, motor-based actuators	- Dynamic shading element run by the hydraulic actua- tor and sensors responsive to sunlight	- Ambience Wall that reacts to changing environmental factors - Mobile wooden panels run by an engine	- Light sensor-based hexagon fractals that can open and closed
Outcomes for Sustainability	- Air is 100% filtered - Natural lighting and venti- lation saved by 65% - Storage of water - Shading for visual comfort - Recyclable facade material - Energy efficient	- Reduced artificial light- ing costs - Natural lighting - Thermal comfort - Energy efficient	- Natural ventilation - Natural lighting - Energy efficient	- Reduction use of artificial lighting - More than 50% reduction in solar gain - Reduction in CO2 emissions - Natural lighting - Thermal comfort - Energy efficient	- Natural lighting - Natural ventilation - Energy efficient - Environmentally con- scious	- Thermal regulation - Natural lighting - Energy efficient