YAŞAR UNIVERSITY
GRADUATE SCHOOL

MASTER IN ARCHITECTURE THESIS

AN APPROACH FOR ENERGY-EFFICIENT BUILDING FACADES: BIOMIMETIC ENVELOPE DESIGN AND ARCHITECTURAL INTEGRATION PROCESS IN DOHA

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MASTER OF SCIENCE IN ARCHITECTURE

PRESENTATION DATE: 09.01.2024

BORNOVA / İZMİR
JANUARY 2023

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ABSTRACT

AN APPROACH FOR ENERGY-EFFICIENT BUILDING FACADES: BIOMIMETIC ENVELOPE DESIGN AND ARCHITECTURAL INTEGRATION PROCESS IN DOHA

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MSc, ARCHITECTURE

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January 2024

With the increasing world population, the need for the environment and buildings is increasing in direct proportion. Most of the energy consumption around the world are buildings that are reconstructed in line with this need. In this context, the responsibilities and duties of the architects are increasing in response to rapidly increasing world population. Today, the environment and buildings designed with this awareness should be constructed on the basis of energy efficiency. For this reason, energy efficient building designs have become one of the issues that have been emphasized over the years. The building façade or envelope systems, which is the part where a building directly communicates with the most basic building block and outdoor environment, has become an indispensable part of energy efficient building designs.

Biomimicry is a discipline that aims to use many systems that have proven itself in all challenging conditions of nature in line with the needs of people. Biomimicry, which deals with the organisms in nature and all the systems and behaviors used by these organisms in their struggle to survive throughout their lives, plays an active role in energy efficient building designs. By imitating the envelope systems that have proven themselves by most living things in nature, it enables the design of a building façade or envelope system. It enables the building to take an active role in the establishment of the balance between difficult outdoor conditions and internal comfort. Although the building facades and envelope systems created with biomimetic approaches produce permanent solutions for the building, it has a costly application process. Therefore, the

building facades or envelope systems developed by using the discipline of biomimicry should be well analyzed well before the application phase. Biomimetic applications that develop with technological developments become more applicable with each passing day. The designs obtained with the developments in both the design process and the evaluation methods are more efficient.

In general, the design process of building facades or envelope systems created with the biomimetic approach is carried out in cooperation with different disciplines and tools. The biomimetic envelope system, while producing solutions for the energy efficiency and comfort needs of the building, the evaluation criterion and the analysis and simulation outputs that support it provide the opportunity to test the designs. With technological developments in computer-aided simulation and analysis tools, architects, designers and engineers can create their designs with more sustainable solutions through biomimimetic approaches. With these developments, it is easier to cooperate with different tools that may have a positive impact on the architectural integration process of designs such as simulation, modeling and analysis programs. In this context, the envelope designs developed are created in a way that is directly solved to the environmental and internal conditions of the building to which it belongs.

Within the scope of this thesis, it is primarily aimed to develop an energy efficient biomimetic building envelope design. During the design of this envelope system, it is inspired by nature that produces systems against difficult environmental conditions. As in the leather, shell, skin, membrane and similar systems that are directly in contact with the outdoor environment in organisms, the facades of the buildings that are directly interacting with the external environment serve as envelope tasks. By imitating nature, the developed building envelope systems aim to ensure the balance between the external environment and the internal environment for various parameters, as in living things. In this context, a high-rise office building located in an extremely hot and arid climate is considered. An office area located on the south side of the imaginary office building, which is the facade that receives the most daylight, was determined as the test box. The biomimetic envelope system design developed within the scope of the study was tested on this test box. This envelope system was inspired by an organism with the same environment conditions as the building and developed in the designated design process. Within the scope of the design process, the modeling of the

test box, the office module, was created in the Rhinoceros 3D modelling program. Developed through the Plug-in Grasshopper program, the envelope system is integrated on the created test box. Grasshopper plugin Ladybug-Honeybee tools were also used in the model integration and analysis process. Simulation outputs have been created to affect the energy efficiency of the building and the envelope system has been developed in the light of them. As a result of simulation and analysis outputs, the biomimetic envelope system obtained under the guidance of design process and evaluation criteria was tested with variable parameters. Different combinations created according to the opening and closing angle of the biomimetic envelope design and the number of ETFE layers were tested. The effect of the developed biomimetic envelope system on the energy efficiency of the existing building was compared. In the guidance of the developed evaluation criterion of the designed building envelope, its extensive effects on energy efficiency and internal comfort have been discussed. This study brings a new perspective on the transformation of buildings with extreme conditions into energy-efficient buildings with biomimetic analyzes. It is possible that the biomimetic envelope system, inspired by nature, creates an idea in future studies and gives a new perspective.

keywords: biomimicry, biomimetic approach, energy efficiency, cooling load, daylight, building envelope designs, building façade designs, nature, inspiration, test box, RhinoCeros, Grasshopper, simulation

ÖZ

ENERJI VERIMLI BINA CEPHELERI ICIN BIR YAKLASIM: DOHA'DA BIYOMIMETIK KABUK TASARIMI VE MIMARI ENTEGRASYON SURECI

NALÇAKAN, BERKAY
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Ocak 2024

Artan dünya nüfusu ile birlikte her geçen gün çevre ve binalara olan ihtiyaç da doğru orantılı olarak artmaktadır. Dünya genelinde enerji tüketiminin büyük bir bölümünü, bu ihtiyaç doğrultusunda imar edilen binalar oluşturmaktadır. Bu bağlamda, hızla artan dünya nüfusuna karşılık mimarların sorumlulukları ve görevleri de artmaktadır. Günümüzde bu bilinçle tasarlanan çevre ve binaların enerji verimliliği esas alınarak kurgulanması gerekmektedir. Bu nedenle, enerji verimli bina tasarımları yıllar içerisinde üzerinde durulan konulardan biri haline gelmiştir. Bir binanın en temel yapıtaşı ve dış ortam ile direkt olarak iletişim kurduğu bölüm olan bina cephe ya da kabuk sistemleri, enerji verimli bina tasarımlarının vazgeçilmez parçası olmuştur.

Biyomimikri, doğanın tüm zorlu koşullarında kendini ispat etmiş birçok sistemi, insanların ihtiyaçları doğrultusunda kullanmayı amaç edinmiş bir disiplindir. Doğanın barındırdığı organizmaları ve bu organizmaların yaşamları boyunca hayatta kalabilme mücadelesinde kullandıkları bütün sistemleri ve davranışları konu alan biyomimikri, enerji verimli bina tasarımlarında etkin rol almaktadır. Doğadaki çoğu canlının sahip olduğu kendisini ispat etmiş kabuk sistemlerini taklit ederek, bir bina cephesinin ya da kabuk sisteminin tasarlanmasını sağlamaktadır. Binanın zorlu dış ortam koşulları ile iç ortam konforu arasındaki dengenin kurulmasında etkin rol almasını sağlamaktadır. Biyomimetik yaklaşımlarla oluşturulan bina cephe ve kabuk sistemleri bina için her ne kadar kalıcı çözümler üretse de maliyetli uygulama sürecine sahiptir. Bu yüzden günümüzde biyomimikri disiplininden faydalanılarak geliştirilen bina cephe ya da kabuk sistemlerinin uygulama safhasından önce iyi analiz edilmesi gerekmektedir.

Teknolojik gelişmelerle birlikte gelişen biyomimetik uygulamalar her geçen gün daha uygulanabilir hale gelmektedir. Hem tasarım sürecinde hem de değerlendirme metotlarındaki gelişimlerle birlikte elde edilen tasarımlar, mimari entegrasyon süreçlerini daha verimli geçirmektedir.

Genel olarak bakıldığında, biyomimetik yaklaşımla oluşturulan bina cephe veya kabuk sistemlerinin tasarım süreci farklı disiplin ve araçların iş birliği ile gerçekleşmektedir. Biyomimetik kabuk sistemi binanın enerji verimliliği ve konfor ihtiyaçlarına yönelik çözümler üretirken değerlendirme kriterleri ve onu destekleyen analiz ve simülasyon çıktıları, tasarım varyasyonlarını test etme olanağı sağlamaktadır. Bilgisayar destekli simülasyon ve analiz araçlarındaki teknolojik gelişmeler ile birlikte mimarlar, tasarımcılar ve mühendisler biyomimimetik yaklaşımlarla tasarımlarını daha sürdürülebilir çözümlerle oluşturabilmektedir. Bu gelişmelerle birlikte simülasyon, modelleme ve analiz programları gibi tasarımların mimari entegrasyon sürecine olumlu etki edebilecek farklı araçlarla iş birliği yapılabilmesi de kolaylaşmaktadır. Bu kapsamda geliştirilen kabuk tasarımları, ait olduğu binanın çevre ve iç ortam koşullarına direkt çözüm olacak şekilde oluşturulmaktadır.

Bu tez kapsamında öncelikli olarak enerji etkin biyomimetik bina kabuk tasarımı geliştirme hedeflenmektedir. Bu kabuk sisteminin tasarımı esnasında zor çevre koşullarına karşı sistemler üreten doğadan ilham alınmaktadır. Organizmalarda dış ortamla direkt olarak irtibat halinde olan deri, kabuk, cilt, zar ve benzeri sistemlerde olduğu gibi binaların dış çevre ile direkt olarak etkileşim halinde olan cepheleri de kabuk görevi görmektedir. Doğayı taklit ederek, geliştirilen bina kabuk sistemleri, canlılarda olduğu gibi çeşitli parametreler için dış çevre ile iç ortam arasındaki dengeyi sağlamayı hedeflemektedir. Bu çerçevede, aşırı sıcak ve kurak iklimde bulunan yüksek katlı bir ofis binası ele alınmıştır. Ele alınan hayali ofis binasının en çok gün ışığı alan cephesi olan güney cephesinde bulunan bir ofis alanı, test kutusu olarak belirlenmiştir. Çalışma kapsamında geliştirilen biyomimetik kabuk sistemi tasarımı bu test kutusu üzerinde test edilmiştir. Bu kabuk sistemi binayla aynı ortam koşullarına sahip bir organizmadan esinlenilerek, belirlenen tasarım süreci içerisinde geliştirilmiştir. Tasarım süreci kapsamında ilk olarak, test kutusunun yani ofis modülünün modellemesi RhinoCeros 3D Modelling programında oluşturulmuştur. Plug-in Grasshopper program üzerinden geliştirilen kabuk sistemi, oluşturulan test

kutusu üzerine entegre edilmiştir. Modelin binaya entegrasyon ve analiz sürecinde Grasshopper eklentili Ladybug-Honeybee araçları da kullanılmıştır. Binanın enerji verimliliğine etki edecek simülasyon çıktıları oluşturulmuş ve bunların ışığında kabuk sistemi geliştirilmiştir. Simülasyon ve analiz çıktıları neticesinde, tasarım süreci ve değerlendirme kriterleri rehberliğinde elde edilen biyomimetik kabuk sistemi değişken parametreler ile test edilmiştir. Biyomimetik kabuk tasarımının açılıp kapanma açısı ve ETFE katman sayısına göre oluşturulan farklı kombinasyonlar test edilmiştir. Bunlar ışığında test kutusunun soğutma yükü ve gün ışığı analizleri oluşturulmuştur. Geliştirilen biyomimetik kabuk sisteminin mevcut binanın enerji verimliliği üzerine etkisi karşılaştırılmıştır. Tasarlanan bina kabuğunun geliştirilen değerlendirme kriteri rehberliğinde enerji verimliliği ve iç ortam konforu üzerine kapsamlı şekilde etkileri tartışılmıştır. Bu çalışma, günümüzde ekstrem koşullara sahip binaların, biyomimetik çözümlemeler ile enerji verimli binalar haline dönüştürülmesi üzerine yeni bir bakış açısı getirmektedir. Doğadan esinlenilerek geliştirilen biyomimetik kabuk sisteminin gelecekteki çalışmalarda bir fikir oluşturması ve yeni bir bakış açısı kazandırması olasıdır.

Anahtar Kelimeler: biyomimikri, biyomimetik yaklaşım, enerji verimliliği, soğutma yükü, gün ışığı, bina kabuğu tasarımları, bina cephe tasarımları, doğa, ilham, test kutusu, RhinoCeros, Grasshopper, simülasyon

ACKNOWLEDGEMENTS

I would like to thank my supervisor Assoc. (PhD) Basak Kundakcı Koyunbaba for all their help and advice with this Master's Thesis. I would also like to thank my mother, whom without this would have not been possible. I also respectfully remember and thank my father, whom I sent off to eternity at the beginning of my master's degree. I also appreciate all the support I received from the rest of my family. I would like to thank the Yaşar University for the studentship that allowed me to conduct this thesis. Lastly, I would like to thank my biggest supporter Prof. (PhD) Ahenk Yılmaz for all their help and advice with this Master's Thesis and in my entire education process.

BERKAY NALCAKAN
İzmir, 2024

TEXT OF OATH

I declare and honestly confirm that my study, titled "AN APPROACH FOR ENERGY-EFFICIENT BUILDING FACADES: BIOMIMETIC ENVELOPE DESIGN AND ARCHITECTURAL INTEGRATION PROCESS IN DOHA" and presented as a Master's Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

BERKAY NALCAKAN
09.01.2024

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SYMBOLS AND ABBREVIATIONS

ABBREVIATIONS:

QBTU	Quadrillion British Thermal Units
LPG	Liquefied Petroleum Gas
GHGs	Greenhouse_gases
IEA	International Energy Agency
3D	Three-Dimensional
HVAC	Heating_ventilation_and air conditioning
PV	Photovoltaic
ETFE	Ethylene tetrafluoro ethylene
PCM	Phase Change Material
kWh	Kilowatt hour
GRP	Glass Reinforced Plastic
SUTD	The Singapore University of Technology and Design
DNA	Deoxyribo nucleic acid
EPW	EnergyPlus Weather Data File

SYMBOLS

%	Percentage
º	Angle degree
°C	Centigrade degree
H_2O	Pure water
CO_2	Carbon dioxide
NO_x	Nitrous oxide
CO	Carbon monoxide
CFC	Chlorofluorocarbon
HCFC	Hydrochlorofluorocarbon

CHAPTER 1
INTRODUCTION

The rapid increase in the **world population** has brought with it concerns. According to demologists, the increase in the world population is expected to continue for a few more decades. Spanish researcher Gilles Pison stated that the world population could increase by 2 billion more by the end of the 21st century. (Pison, 2022). According to the United Nations (UN) data, it is stated that the world population will reach 8 billion in 2022. The world population has increased by 1 billion in the last 11 years. According to the United Nations population projections data, the world population, which is predicted to rise to 9 billion levels in 2037, is expected to increase by 2080. John Wilmoth, Director of the United Nations (UN), Population Division, drew attention to the negative effects of world population growth by using the expressions "a great risk for our future" regarding population growth. Shared prospects show that developing countries, which have difficulties in accessing resources due to climate change, will have more difficulties due to the increasing population (United Nations, 2022).

Considering the last half century, the total **energy consumption** in the world is constantly increasing. The increase in the world population and the corresponding changes in the basis of energy consumption are the main reasons for the sharp increase in energy consumption. Changes in the basis of energy consumption, on the other hand, are caused by factors such as technological developments, improving living standards, and climate crisis (Kadoshin et al., 2000). The rapidly increasing energy consumption, the difficulty of energy supply, the gradual depletion of resources and current global problems (depletion of the ozone layer, climate change, global warming, epidemics, etc.) have kept energy-related issues on the agenda (Pérez-Lombard et al., 2008).

Figure 1.1 shows that there is an increase in the amount of energy demand in the world in direct proportion to the increasing world population (National Energy Technology Laboratory, 2011).

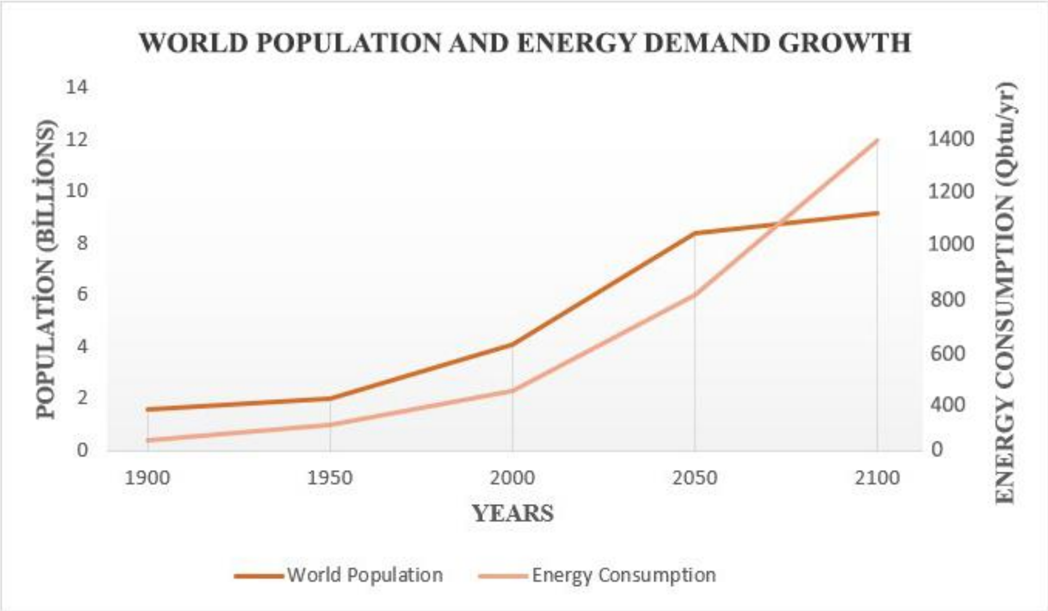


Figure 1.1. World population and energy demand growth by changing years (Adapted from Golpour et al., 2017)

Worrying about energy in the coming years should be considered normal. Because all the vital functions of human beings are dependent on energy. The basic needs of people such as shelter, heating, cooking, production, communication and transportation are realized with energy (Radwan & Osama, 2016). Energy is indispensable in daily life. Every country in the world wants access to reliable, modernized new energy sources in order to develop and grow economically. In affluent economies, existing energy systems serve in relation to population. Countries that have achieved this have improved daily life as much as possible by meeting the energy needs of the growing population (Golpour et al., 2017).

Energy, which is defined as the concept that ensures the realization of any work done, can be found in different types. Energy can exist in forms such as mechanical, electrical, nuclear, and heat. Energy can be transformed from one type to another by preparing a suitable environment. Figure 1.2 shows that the classification of energy sources according to both their "using" and their "convertibility" (Koç & Kaya, 2015). Energy sources are classified as renewable and non-renewable in terms of their using type. Energy sources are divided into two groups as primary and secondary energy sources in terms of their convertibility (Koç & Kaya, 2015). The untreated state of energy is called primary energy. Primary energy sources are natural gas, nuclear, hydraulic, petroleum, coal, biomass, wave-tide, solar and wind. The type of energy obtained by converting primary energy is called secondary energy. Secondary energy sources are electricity, diesel, diesel, gasoline, coke, coal gas, liquefied petroleum gas (LPG), secondary coal and petrocoke (Şenel, 2012).

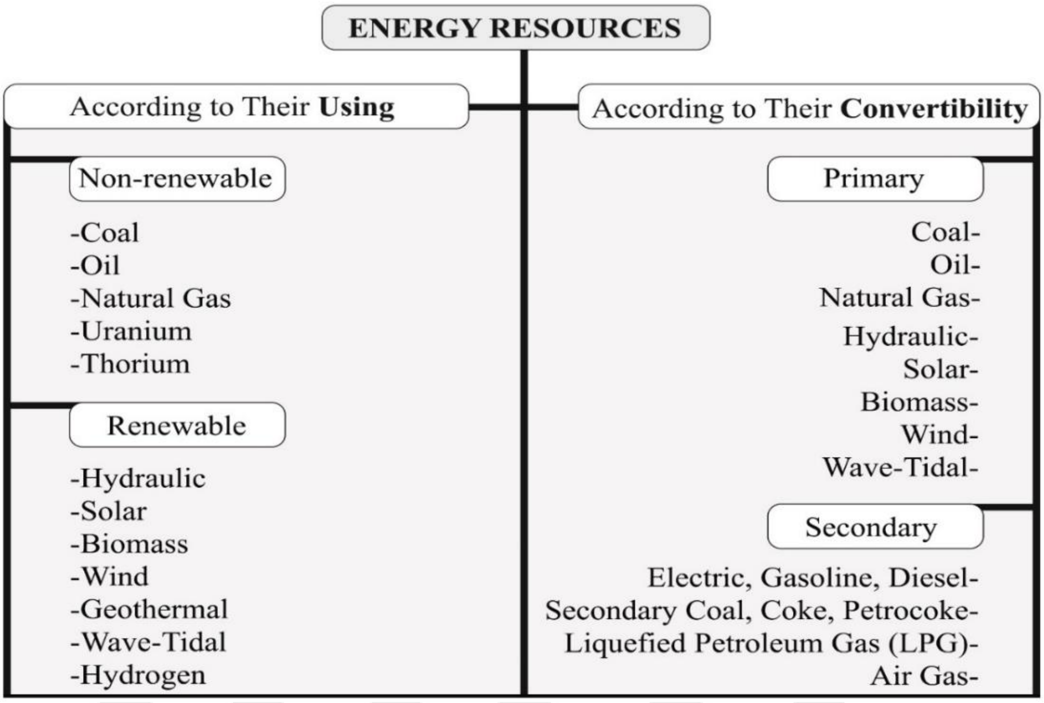
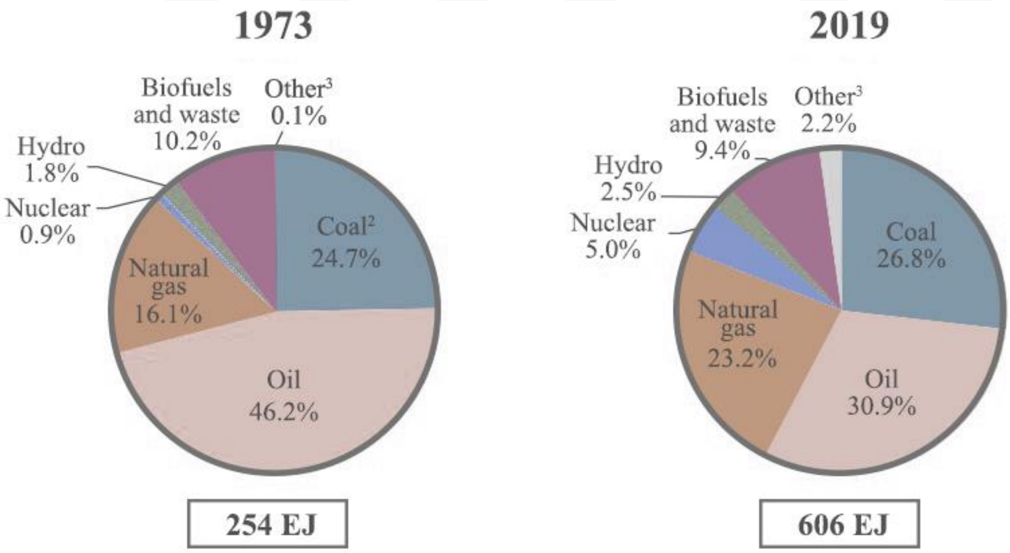


Figure 1.2. Classification of energy sources (Adapted from Koç & Kaya, 2015)

The more widely used classification method today is on whether the energy resources are depleted after they are used. In this type of classification, energy sources that do not run out after being used are called renewable energy sources. The energy sources that are depleted and cannot be renewed after use are called non-renewable energy sources. Coal, oil and natural gas, which are widely used in daily life, are non-renewable energy sources, which are described as fossils. Solar, wind, geothermal, biomass, wave-tide, hydrogen energy sources are examples of renewable energy sources (Koç & Şenel, 2013).

The increasing welfare level as a result of technological developments with the increasing population increases energy consumption day by day. In order to meet this energy need throughout the world, the tendency to non-renewable energy sources is quite high. In order not to run out of resources and to reduce carbon emissions, the use of renewable energy sources should be ensured and the societies related to this should take serious steps (Koç & Kaya, 2015). Most of the energy used in the world is produced from primary energy sources. In this direction, it is observed that societies generally prefer fossil fuels in terms of meeting the demand of the society for energy. Coal, oil and natural gas, which are energy sources for approximately 80% of the global energy demand, are not sustainable energy sources because they cannot be reused. In addition, fossil fuels cause serious damage to the environment as a result of combustion. Greenhouse gases ((H_2O, CO_2) and harmful emissions (NO_x, CO) that seriously harm the environment are produced by the combustion of fossil fuels. The gradual depletion of fossil fuels and their harmful effects push humanity to use alternative renewable energy sources (Golpour et al., 2017). As can be seen in Figure 1.3., when the distribution of primary energy consumed in the world is examined, respectively, oil (30.9%), coal (26.8%), natural gas (23.2%), nuclear energy (5%), biomass energy (9.4%), hydraulic energy (2.5%).) and other renewable energy sources (2.2%). Other renewable energy sources are geothermal, solar, wind, wave-tide, temperature and others (International Energy Agency, 2021).

Figure 1.3. shows the shares of world total energy supply by source, in 1973 and 2019 (International Energy Agency, 2021).



2. Peat and oil shale **3.** Geothermal, solar, wind, tide/wave/ocean and others

Figure 1.3. Worldwide total energy demand by energy sources, 1973 and 2019 (Adapted from Kaskun, 2020)

According to the 2021 report of the International Energy Agency, the buildings and building construction sectors play an important role in the total global final energy consumption. Buildings are not energy sources, but they are a huge potential source of energy efficiency. The buildings and building construction industries are responsible for 30% of total global final energy consumption and have a huge carbon footprint. Figure 1.4. shows the global energy consumption and process emissions from different sectors in 2021, (International Energy Agency, 2022).

Accordingly buildings and building construction are responsible for 27% of the energy sector's total CO_2 emissions. Although the use of fossil fuels is decreasing day by day, it has a large share in the building energy supply. Fossil fuels continued to supply at least 35% of total buildings' energy demand (IEA, 2022). As a result of increasing energy demand with the effect of increasing population, it also affects carbon emissions negatively. When viewed progressively, the increasing population causes the creation of new areas for people to live. New buildings and areas also create energy demand with the developing technology. It is only pos sible to positively influence these interrelated situations by creating building designs that are highly energy efficient, have a zero emission target, and support renewable energy sources. Buildings have a large enough share to have a direct impact on total energy consumption and total carbon emissions (United Nations Environment Programme, 2020).

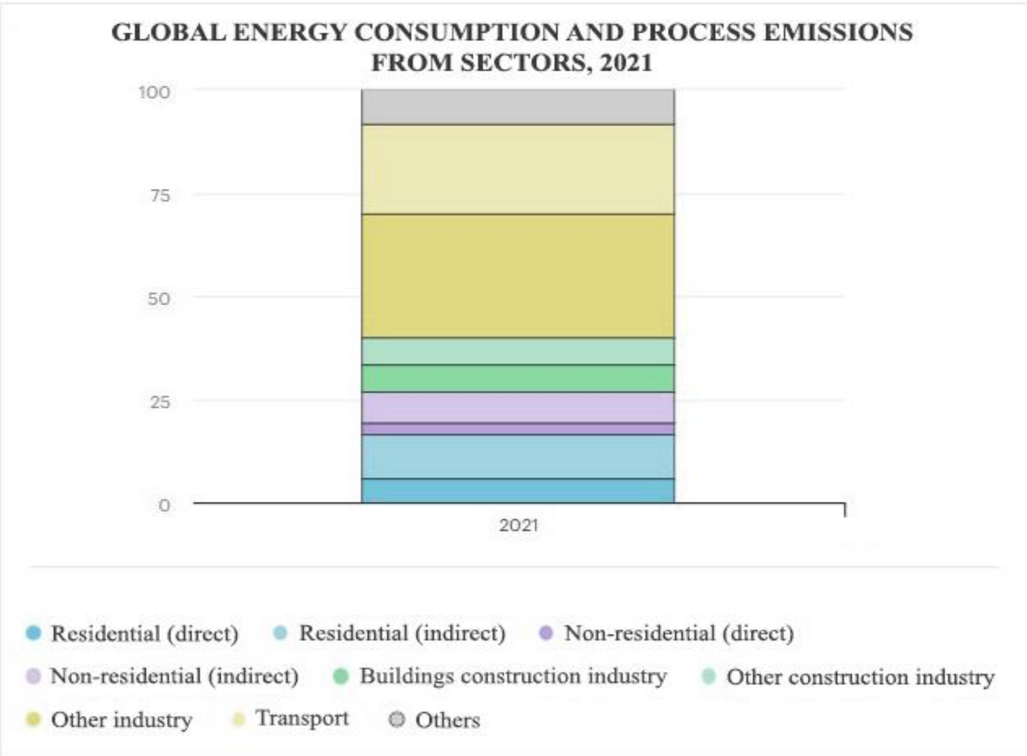


Figure 1.4. Global energy and process emissions from buildings, (Adapted from IEA, 2021)

Since construction and buildings, which are one of the three main sectors in need of energy, have a high share of energy use, more careful designs and applications are required. Buildings account for the vast majority of global energy consumption. For this reason, a significant amount of energy savings can be achieved in buildings designed on the basis of energy efficiency (Chou & Bui, 2014). In recent years, some efforts have been made on the basis of energy efficiency in buildings. The concept of energy efficiency in buildings aims to minimize all energy consumption loads of the building. Buildings are equipped with heating, cooling, ventilation, lighting, etc. to keep the interior comfort stable for the user against changing environmental conditions to activates energy-requiring systems such as. If all systems of a building are designed on the basis of energy efficiency, the energy load of the building is reduced as well (Pacheco et al., 2012). The most important way to save energy in a building is to carefully design the envelope of the building, namely the facade. The function of building facades in architecture is similar to many organs such as skin, membrane, shell, and envelope that play the role of protective layer in nature. As with natural skin, building envelopes are constantly protected from external environmental conditions. Building envelopes, like living organisms, are in constant interaction with the environment. Changing weather conditions and building envelope systems, which directly struggle with the conditions, are very effective on the efficiency of the building. Energy efficient building envelope systems reduce the amount of energy used for the building's heating, lighting, cooling and ventilation needs. (Sandak et al., 2019).

While building envelopes isolate the structures they belong to from the external environment, they also directly affect the energy needs of the building. Regardless of the environmental conditions of the building, building envelopes, which are a bridge between the indoor and outdoor environment, play a major role in energy efficient building designs. Building envelope systems are named according to changing qualities such as purpose, function, material and function. Some of these are kinetic facades, green facades, smart facades, glass facades, biomimetic facades, etc. The discipline of biomimicry, which focuses on the effective solutions of nature, especially on energy efficiency, has a great importance in the creation of energy efficient building envelopes with biomimetic approaches. In general, biomimicry is a discipline that enables the designer to integrate permanent solutions inspired by nature into his projects, unlike the conventional systems and rules used in architectural design. Architects can create sustainable, energy efficient, high performance designs by imitating systems that have proven themselves in nature for centuries and have proven their validity and continuity. As can be understood from all these, biomimicry is a new generation innovation tool that aim to use the superior power of nature (Pawlyn, 2016).

Building envelope systems, which act as a bridge between the inside and outside of the building, support and improve the building interior comfort despite extremely conditions. These regulations are related to the thermal comfort of the building, lighting, ventilation and energy consumption. Living things in nature should be able to adapt to their environment and keep indoor conditions at a stable level, just like in buildings. The outer layers, which are called skin, envelope and shell, which undertake this task, undertake the same tasks as the building facade systems. In the light of these tasks, they protect their vitality by spending energy at a minimum level and by recovering the lost energy in a sustainable way. By making this an approach through biomimicry, it can be aimed that building envelope systems work in an energy efficient and sustainable way like living things. Integrating the strategies used by living organisms to balance their body needs into energy efficient building envelope system designs is important for self-sufficient building designs (Gündoğdu & Arslan, 2020).

As a result of the developments in technology and the increasing world energy crisis in recent years, progress has been made in understanding the biological power of nature and integrating the obtained information into architecture. Research in the field of biomimicry is very effective in finding solutions to today's current problems. Approaches developed by imitating nature are a source of inspiration for façade or envelope systems, which are an indispensable part of energy efficient building designs (Aziz, 2016). In addition, in the light of technological developments in computer-aided design, architects can test more effective strategies in their designs. The most effective solutions can be obtained from the designs created with the biomimetic approaches. Systems inspired by nature create a design process in cooperation with the discipline of biomimicry. All stages of this design process are of particular importance. Thanks to the technological developments in computer-aided modeling and simulation, the decisions taken during the design process and the data obtained can be tested. In the architectural integration process of the design, many analyzes and studies are carried out, and the best result is obtained before the application. In line with the analyzes made, the architect or designer can make changes or improvements during the design process. In line with all these possibilities, the architect can overcome not only aesthetic concerns but also technical concerns before proceeding to the manufacturing process. Architects can also decide the most suitable material and manufacturing process in terms of form and function.

1.1. Research Problem

In recent years, the increase in the world population, industrialization, climate change, increase in technological developments depending on these factors, energy consumption has also increased significantly. Energy use and ease of access to energy are factors that significantly affect our daily lives. Energy is necessary for many basic needs such as heating, shelter, production and transportation. On the other hand, the excessive use of fossil fuels as an energy source increases the carbon emissions released into the atmosphere. This situation brings with it air pollution and indirectly climate change. In addition to all these, energy resources are getting depleted and serious problems are expected in terms of access to energy in the future.

The buildings where we live, work, socialize and receive services constitute the largest share in energy consumption. Building systems that are not designed to provide energy efficiency consume a lot of energy and release greenhouse gases into the atmosphere. For this reason, energy efficient systems should be preferred in the design of all buildings. The façade or envelope systems, where the building is in direct contact with the external environment, is the part that most affects the amount of energy needed by the building. Therefore, it is very important to design façade or envelope systems in an energy efficient manner. Building exterior systems, which act as a buffer between the environment and the interior, have different energy consumption values according to the conditions they are in. Building envelope systems, which can provide effective performance especially in ventilation, lighting, heat and water cycle, should be supported with renewable energy sources that are harmless to nature. In the light of a greener future vision, it should be aimed to minimize or zero energy consumption thanks to developing technology and design methods. Therefore, it is necessary to innovate in building envelope design and integration processes. From this point of view, the design of the exterior systems, which are the most important parts of the buildings that have a great impact on the total energy consumption in the world, is very important.

The main problem addressed in this thesis is the need to understand the impact of envelope systems, which are the parts of buildings that are in direct contact with the external environment, on energy efficiency by designing them with nature-inspired approaches. Within the scope of the study, a literature review was conducted on many biomimetic envelope systems. In the light of these research, a biomimetic envelope system was developed based on energy efficiency and its effects on the building were examined.

1.2. Research Hypothesis

Inspired by nature, the design can guide the energy efficient designs. From this point of view, systems that have proven themselves in nature will be integrated into the building envelope with a biomimetic approach, and effective steps will be taken on energy efficiency. Just as our skin wraps our body and does whatever is necessary for our vitality, the envelope systems developed for the building will do the same for the energy cycle, comfort and requirements of the building. Thanks to technological developments, smart materials and innovative systems, it is easier to imitate nature and to include it in the architectural design process. Building envelope systems, designed with a biomimetic approach based on energy efficiency, are aimed to be integrated into architecture in a way that look like the working mechanism of systems in nature. The systems developed within this scope will meet all the needs of the building within the scope of both the environment and the internal comfort requirements of the energy-efficient building. Briefly, architectural integration process of the biomimetic approach, which is a solution to all the problems of the energy efficient building envelope, can be handled in the most effective way thanks to computer-aided programs.

The main hypothesis addressed in this thesis is a nature-inspired design approach will increase the energy efficiency performance of building envelope designs. Building envelope systems designed with inspiration from many solutions and strategies of nature, can produce sustainable solutions for all vital needs of the building based on energy efficiency. Briefly within the scope of the thesis; designs created with an approach inspired by nature based on energy efficient building envelopes are analyzed through an evaluation criterion in the architectural design process. The design developed in the light of these analyzes is tested with simulation outputs. The developed design process and evaluation criteria will serve as a guide for energy efficient building envelope designs.

1.3. Research Aim

The main aim addressed in this thesis is evaluation of the building envelope system, which is created with a biomimetic approach inspired by nature based on energy efficiency, within the design process and improvement within the architectural integration process. This envelope system will act as a living envelope that provides interior comfort with minimum energy consumption despite the environmental conditions, rather than just a shell surrounding the outside of the building. The design process and evaluation criteria, the design will be tested in the most efficient way in the architectural integration process.

1.4. Research Methodology

In order to reduce energy consumption and the use of fossil fuels within the scope of non-renewable energy, to create more efficient and comfortable buildings, the design and integration processes of biomimetic solutions inspired by nature in building envelope or facade systems are examined. In this direction, the methodology of the study is based on examining the effects of biomimetic approaches on energy efficiency-based envelope designs. In order to observe the effect of nature-inspired solutions on energy efficient design, literature research was conducted. During the literature review, the projects examined were tabulated with a certain method. With this method, the biomimetic approach processes and energy efficiency levels of the projects were correlated and analyzed. Energy efficiency is discussed over the parameters of air, heat, light and water within the scope of the environmental conditions and indoor comfort needs of the projects. This study has been further elaborated and the criteria including the requirements of energy efficient envelope systems within the scope of their duties and responsibilities have been tabulated. The effective parameters on the energy efficiency of the building envelope systems created with the biomimetic approach were analyzed. From this point of view, data that will serve as a guide for the following parts of the study were created and inferences were made. As a result of these inferences and the data obtained, a design process and evaluation criteria were created.

This thesis covers the design process of an energy efficient shading device integrated into the south-facing façade of an imaginary test box belonging to a unit of a high-rise office building in Doha, Qatar. Office buildings are one of the working areas where people spend a lot of time during the day in Doha, which has a hot and dry climate. The energy consumption and interior comfort of these buildings are very important. Especially Doha has difficulties in terms of energy consumption of the building due to climatic conditions. The envelope system was developed in cooperation with the discipline of biomicry, taking into account the environmental conditions and building requirements. This envelope system has been tested through a number of simulation tools in light of the building's improvement in air, heat, water and light, and in the light of the goals of reducing final energy consumption. The building envelope system designed with the biomimetic approach, together with the developed design process and evaluation criteria, was analyzed on the test box. The unit module (test box) of the imaginary high-rise office building was created with the modeling program Rhinoceros 3D Modeling program. The envelope system developed through the Plug-in Grasshopper program was integrated on the created test box. Ladybug-Honeybee tools with Grasshopper add-on were also used in the integration process of the model into the building. Simulation outputs that will affect the energy efficiency of the building have been created and an envelope system has been developed. The biomimetic envelope system, obtained under the guidance of the design process and evaluation criteria, has been analyzed on parameters that vary in its distance to the façade, the amount of opening and closing and the level of transparency. The results were evaluated and compared in the form of a table. It is thought that the study will serve as a guide for future studies on energy efficiency based biomimetic envelope systems designs.

Briefly, the research methodology begins by examining projects inspired by nature, continues by introducing a new biomimetic design process and evaluation criterion to the literature, it ends with the biomimetic envelope system design developed using simulation and computation tools.

CHAPTER 2
LITERATURE REVIEW

One of the most important parameters of associating the building envelope systems created with the **biomimetic approach** with the living nature from which it is inspired is energy efficiency. A building envelope system directly acts as a bridge between the interior and the exterior environment. Many studies are carried out on ensuring the energy efficiency of envelope systems that keep the amount of energy consumed throughout the building at minimum levels and contribute to the energy production required for the building. These studies are called **energy efficient building envelope systems**. In this direction, it is of great importance to investigate biomimetic approaches and technologies developed on building envelope systems in terms of energy efficiency.

2.1. Literature Table: Analytical Study

Biomimicry is a nature-inspired discipline where the strongest and most efficient survive to take advantage of nature's energy efficient solutions. An analytical study has been carried out in line with the assumption that this discipline brings energy efficient solutions for building envelope systems together with technological developments.

The analytical study was shaped according to the main purpose of the thesis. A new criterion has been developed to analyze the project design processes of building envelope systems, which are realized with a biomimetic approach or developed as a concept. Project examples of biomimetic energy efficient envelope systems were analyzed within the scope of project detail tags, biomimetic inspiration processes (architectural integration processes) and building envelope criteria. The table below will serve as a guide to understand the importance of building envelope systems in energy efficiency with a biomimetic approach and to design energy efficient building envelope systems. (see Table 2.1.)

Table 2.1. Literature reviews & analytical study of biomimetic approaches on energy efficiency in building envelope designs

RESEARCH DETAILS				PROJECT DETAILS		BIOMIMETIC INSPIRATION			BUILDING ENVELOPE CRITERIA						
Year	Author(s)	Paper Name	Study Type	Project Name & Project Type	Project Location & Climate	Concept	Level of Biomimetic	Approach to Biomimetic	Envelope Features		Energy Efficiency				
									Material	Technologies Included	Air	Heat	Water	Light	Outcomes
2018	**1.**Abeer Samy Yousef Mohamed	Biomimetic Architecture: Creating a Passive Defense System In Building Skin to Solve Zero Carbon Construction Dilemma	Article & Analytical Study	**The Council House 2** & Office Building	Australia & Oceanic Climate	Trees bark	Organism & Behaviour level	Design to Biology	**1.**Timber **2.**Steel **3.**Concrete	**1.**(PCM) 100 year life-cycle costing model	**1.**Air is 100% filtered **2.**Night time cooling via natural ventilation	**1.**For cooling, automatic night-purge windows **2.**Wavy concrete ceilings **3.**Facade's louvers (powered by photovoltaic cells) that track the sun	**1.**Rainwater pollution management **2.**Rainwater treatment **3.**80% reduction in sewage emissions	**1.**Sensitive to sunlight **2.**Natural daylight **3.**Maxiumum shading	**1.**Minimazing usage of HVAC **2.**Natural lighting and ventilation saved by 65% **3.**HVAC level lowered 20% **4.**Total energy saving 82% **5.**High performance facade design
2018	**1.**Abeer Samy Yousef Mohamed	Biomimetic Architecture: Creating a Passive Defense System In Building Skin to Solve Zero Carbon Construction Dilemma	Article & Analytical Study	**Eastgate Centre** & Shopping and Office Complex	Zimbabwe & Tropical Climate	Termit Mound	Behaviour level	Design to Biology	**1.**Clear glass **2.**Concrete **3.**Double-thick brick	**1.**Utilizing the natural cracking of the rocks, light tech' steel trusses	**1.**Ventilation system uses 10% of the energy needed by a similar buildings. **2.**Air filtered - 100 % **3.** The building got chimneys on both sides for ventilation.	**1.**The use of glass on the north and south facades is limited to 25%. **2**. Solar path simulation is used to minimize solar heat gain	-	**1.** Natural light is restricted	**1.** Thermal comfort is maintained without the HVAC system **2.**The building consumes 90% less energy for ventilation **3.**The building minimizes the heat gain during the day

2016	**1.**Gehan.A.N. Radwan **2.**Nouran Osama	Biomimicry, an Approach, for Energy Effecient Building Skin Design.	Article & Analytical Study	**Water-Cube** & Swimming Centre	China & Monsoon Climate	Soap Bubbles	Organism level	Design to Biology	**1.**Steel **2.**ETFE sheets	**1.**Photovoltaic panels and solar panels – (ETFE)	-	**1.**It provides excellent thermal efficiency, natural heat **2.**90% of the sunlight coming into the building is absorbed	**1.**Cube catches 80% of the water, which is reused and recycled **2.** Rainwater collection, recycling systems.	**1.** The energy used in artificial lighting is reduced by 55% **2.** It takes natural light into the building	**1.**HVAC reduced 30%, Insulation of indoor and outdoor environment, ETFE pads make the building very energy efficient **2.**Energy reduced by 30% **3.**Artificial lighting reduced by 55%
2022	**1.**Azza Elsakksa **2.**Ola Marouf **3.**Mai Madkour	Biomimetic Approach for Thermal Performance Optimization in Sustainable Architecture.	Paper & Case Study	**MMAA Office Building** & Office Building	Qatar & Desert Climate	Cactus	Organism level	Biology to Design	Non recycled material	**1.**The opening and closing of the shading devices takes place according to the cactus sun intensity	**1.**The building can naturally ventilate in a cool way thanks to thorny shading devices **2.** Natural Ventilation	**1.**Shading devices surrounding the building prevent the building from overheating and provide thermal comfort	**1.** Building collects water to cool at night **2.**The building uses different ecological systems to clean the dirty water	**1.** The amount of daylight is controlled **2.** Natural Light	**1.**Energy saving 50% **2.**HVAC level lowered
2017	**1.**Meryem Altınöz **2.**Esma Mıhlayanlar **3.**Seyhan Yardımlı	Analyzing Energy and Biomimesis Concepts in the Context of Sustainability on Building Envelope	Article & Evaluation	**Al Bahar Towers** & Office Building	Abu Dhabi & Desert Climate	Flower	Behaviour level	Design to Biology	**1.**Polytetrafluor oethylene panels	**1.**Movable panels are with the movement of the sun and photovoltaic panels	**1.**Natural ventilation	**1.**Movable panels protect the building from excessive heat in line with the movement of the sun.	-	**1.**Movable panels allow the building to take full advantage of natural light.	**1.**Energy saving 50% **2.**HVAC level lowered **3.**Natural Lighting and ventilation
2022	**1.**Azza Elsakksa **2.**Ola Marouf **3.**Mai Madkour	Biomimetic Approach for Thermal Performance Optimization in Sustainable Architecture.	Paper & Case Study	**The Media TIC Building** & Office Building	Spain & Temperate Climate	Stoma	Behaviour level	Design to Biology	**1.**ETFE	**1.**ETFE balloons, which inflate according to the sun, provide protection.	-	**1.**ETFE balloons, which inflate according to the sun, prevent overheating and provide thermal comfort.	-	-	**1.**Energy saving 95% **2.**HVAC level lowered

2016	**1.**Gehan.A.N. Radwan **2.**Nouran Osama	Biomimicry, an Approach, for Energy Effecient Building Skin Design.	Article & Analytical Study	**Esplanade Theatre** & Theatre and Shopping Centre	Singapore & Tropical Climate	Durian Fruit	Organism and Behaviour	Design to Biology	**1.**Aluminum **2.**Insulated glass **3.**Steel	**1.**The building envelope contains sun shields made of aluminum	-	**1.**Thermal comfort is provided thanks to the sunshade elements on the facades where the sun and heat are high	-	**1.**Durians form provides optimum natural light during the day	**1.**Energy saving 30% **2.**Protection against heat **3.**Natural lighting **4.**Lowered HVAC level 15%
2017	**1.**Pratheek Sudhakaran **2.**Jitendra Singh **3.**Shailendra Kumar **4.**Bhavesh Joshi	Bio-inspired Built Environments For Climate Change: Developing Strategies For Adaptation and Mitigation.	Article & Analysis Study	**Beijing National Stadium** & Stadium	China & Monsoon Climate	Bird Nest	Behaviour level	Design to Biology	**1.**ETFE **2.**Steel	**1.**Very little material was spent to hide the structure	**1.**Facade openings allow natural ventilation by containing ETFE panels	**1.**In accordance with the bird's nest analogy, the façade, the ETFE and the carrier material forming the structure provide shading and prevent overheating.	-	**1.**Panels reduce the dead load supported by the roof and provide sunlight filtration.	**1.**Production cost reduction **2.**Resistant **3.**Recycleable
2017	**1.**Pratheek Sudhakaran **2.**Jitendra Singh **3.**Shailendra Kumar **4.**Bhavesh Joshi	Bio-inspired Built Environments For Climate Change: Developing Strategies For Adaptation and Mitigation.	Article & Analysis Study	**Waterloo International Terminal** & Terminal	England & Oceanic Climate	Pangolin	Organism level	Design to Biology	**1.**Steel **2.**Glass	**1.**Ability to move in response to air pressure forces applied as trains enter and exit	-	-	-	-	**1.**Durable and robust
1996	**1.**Rohlffs K. **2.**Gerber A. **3.**Kamps G. **4.**Disch R.	Energy Characterization of the Rotatable Solar House Heliotrope Trademark in Freiburg, Germany.	Article & Examinatio n	**Heliotrope House** & House	Germany & Temperate Climate	Arctic Popies	Behaviour level	Design to Biology	**1.**Solar panels **2.**Glass **3.**Steel	**1.**Mounted on a pole, the house rotates during the day depending on the direction of sun	-	**1.**Thanks to the solar thermal pipe system, it heats the water and radiators of the house	**1.**Rainwater recycling system and composta system toilet is also designed for this house	**1.**The light in the rooms of the house is constantly changing, as it rotates constantly	**1.**Solar panels located on the roof, producing 6.6 kWH of energy **2.**The Heliotrope House can produce up to five times the energy it consumes

2018	**1.**Nouran M.Ibrahim **2.**Hosam Abd El Aziz	Biological Modeling as a Tool for Promoting Sustainable Construction Technologies and Improving the Energy Efficiency	Article & Comparative Analysis	**Sinosteel International Plaza** & Office and Hotel	China & Monsoon Climate	Honey-comb	Organism level	Design to Biology	**1.**Concrete **2.**Steel **3.**Glass	**1.**Honeycomb structure guarantees minimization of minimum material cost and weight.	-	**1.** The envelope in the hexagonal form prevents the interiors from overheating.	-	**1.** Harmful sun rays are blocked	**1.**Minimum production cost **2.**Maxiumum durability and Stability
2018	**1.**Nouran M.Ibrahim **2.**Hosam Abd El Aziz	Biological Modeling as a Tool for Promoting Sustainable Construction Technologies and Improving the Energy Efficiency	Article & Comparative Analysis	**Gherkin Tower** & Office Building	England & Oceanic Climate	Glass-Sponge	Organism level	Design to Biology	**1.**Steel **2.**Glass	**1.**Aerodynamic, Glazed shape minimizes wind loads	**1** Aerodynamic, Glazed shape minimizes wind loads and maximizes natural ventilation	-	-	**1.**Aerodynamic, Glazed shape minimizes wind loads and maximizes natural light	**1.**Minimum production cost **2.**Maxiumum durability and Stability **3.**Lowered HVAC levels
2020	**1.**Emine Gündoğdu **2.**H. Derya Arslan	Energy-Efficient Facade and Biomimicry in Architecture	Article & Examination	**BIQ Building** & House	Germany & Temperate	Algae	Organism and Behaviour	Design to Biology	**1.**Glass panels with living algae inside	**1.**Bioreactor envelope system	**1.**The algae's absorption of CO, the conversion of light into biomass, provides the structure, Air filtration.	**1.**The algae's absorption of CO, the conversion of light to biomass, provides thermal insulation and gain to the structure.	-	**1.**The algae's absorption of CO, provides the structure with natural lighting and dynamic shading.	**1.**All energy of the building is met. **2.**Carbon emissions fall by 6 tons per year
2020	**1.**Emine Gündoğdu **2.**H. Derya Arslan	Energy-Efficient Facade and Biomimicry in Architecture	Article & Examination	**Flectofin Project** & Central Building	Austria & Transition Climate	Bird of Paradise Flower	Behaviour level	Biology to Design	**1.**Glass **2.**Fiber reinforced plastics (GRP)	**1.**Solar motion system and flexible structure Interactive facade system	-	-	-	**1.**Envelope system provides light control and dynamic shading	**1.**Energy is not consumed while providing light and shading control of the building.

2018	**1.**Shanta Pragyan Dash	Application of Biomimicry in Building Design	Article & Case Study	**HOK Lavasa** & Hill City	India & Monsoon Climate	Fig Leaf	Ecosystem level	Biology to Design	-	**1.**Capillaries carrying excess water protect the city	-	-	**1.**Drains excess water without wasting energy and stores water for use	-	**1.**Foundation stores water. **2.**Drip tip system water to clean its surface **3.**Reacts to seasonal floods. **4.**It carries excess water.
2010	**1.**Ilaria Mazzoleni	Involucri Biomimetici	Article & Student Study	**The Porous Skin Project** -	Desert Climate	Porou	Organism and Behaviour	Biology to Design	**1.**Shading panels	**1.**Dynamic shading system	-	**1.**It provides heat balance. **2.**Prevents overheating	**1.**It has water storage feature.	**1.**Natural lighting **2.**Protection from annoying daylight	**1.** Contributes to the energy saving of the building **2.**Lowered HVAC levels
2015	**1.** Sigurd Carl Sandzén	Biomimicry as design lens for landscape architecture	Article & Case Study	**Milwaukee Art Museum** & Museum	America & Continental Climate	Wings of a Bird	Behaviour level	Design to Biology	**1.**Marble **2.**Steel **3.**Glass	**1.**Computer aided motion shading system	-	-	-	**1.**The movable shading system breaks the excessive sun. **2.**It gets natural and sufficient daylight inside.	**1.**Lowered HVAC levels **2.**Natural lighting
2014	**1.**Rajshekhar Rao	Biomimicry in Architecture	Article & Case Study	**The Habitat 2020** & Residential	China & Monsoon Climate	Stoma	Ecosystem and Organism	Biology to Design	-	**1.**A direct living façade rather than a familiar concrete, steel façade	**1.**Air and wind filtered to provide clean air and natural air conditioned	**1.**Living envelope protects the building from overheating	**1.**Surface absorbs water and converts waste to biogas energy.	**1.**Surface automatically positions itself according to the sunlight and let it in	**1.**The building does not consume energy during the day.

2014	**1.**Rajshekhar Rao	Biomimicry in Architecture	Article & Experimental	**Lily Pad, Floating City** & City	Sea & Conceptual	Water Lily	Ecosystem level	Design to Biology	**1.**Polyethylene foam	**1.**Self-sufficient floating city with zero emissions	**1.**It will be able to clean the polluted air of the environment. **2.**Meeting the need for clean air	**1.**It will adapt to changing climatic conditions. **2.**It will maintain the heat balance.	**1.**It will purify drinking water. **2.**It will store rainwater. **3.**It will reuse wastewater.	**1.**The floating city will benefit from the natural light source.	**1.**100% self-sufficient city. **2.**0 waste, 0 harmful gases, 0 energy
2014	**1.**Rajshekhar Rao	Biomimicry in Architecture	Article & Experimental	**Mangal City** & City	England & Oceanic Climate	Mangro ve Tree	Ecosystem level	Design to Biology	**1.**Ecological system elements Changing modular pod capsules	**1.**Futuristic spiral skyscraper	**1.**Natural ventilation and air filtration	**1.**Thermal confort	**1.**It will store rainwater.	**1.**Natural lighting	**1.**100% self-sufficient highrise building
2020	**1.**Michael Yacubov	Nature does it Better: Biomimicry in Structural and Architectural Design	Article & Theoretical	**Eiffel Tower** & Landmark	France & Oceanic Climate	Femur	Organism level	Biology to Design	**1.**Metal studs and braces	**1.**Heat and expansion resistant steel system	**1.**Withstands bending and shearing effects due to wind. **2.**Ventilation problem solved	**1.**Withstand thermal expansion 70% functionality in design	-	-	**1.**Low cost, high and robust construction
2019	**1.**Michael Pawlyn	Biomimicry in Architecture	Book	**Eden Project** & Agriculture Greenhouse	England & Oceanic Climate	Soap Bubbles	Organism level	Design to Biology	**1.**ETFE	**1.**Maximum utilization of solar energy	-	**1.**Heat gain has been increased.	-	**1.**Maximum use of the sun	**1.**Solar energy was used. **2.**The energy required for the greenhouse was obtained.

2020	**1.**Hala S. Aamer **2.**Ahmed F. Hamza **3.**Mohamed khairy **4.**Islam Ghonimi	Biomimicry as a Sustainable Design Methodology for Building Behaviour	Article & Analysis	**L'arabe Du Monde Institute** & Institute	France & Oceanic Climate	Iris of Eye	Behaviour level	Design to Biology	Steel, glass & Aluminium	**1.**Cladding with screens with automated lens to control light	-	**1.** Controls the amount of sunlight entering the building, keeping it cool.	-	**1.** Controls the amount of sunlight entering the building, flooding room with natural light	**1.**Natural light **2.** Heat balance **3.** Lowered HVAC levels
2017	**1.**Pratheek Sudhakaran **2.**Jitendra Singh **3.**Shailendra Kumar **4.**Bhavesh Joshi	Bio-inspired Built Environments For Climate Change: Developing Strategies For Adaptation and Mitigation.	Article & Analysis Study	**Rafflesia House** & House	Malaysia & Equatorial Climate	Rafflesia Flower flower	Behaviour level	Design to Biology	Tensile environmentally friendly fabric	**1.**Photovoltaic panels	**1.**Ventilation is extremely successful.	**1.**Overheating is prevented	-	-	**1.**92% of all energy expended is produced. **2.**No energy is wasted for ventilation **3.** Lowered HVAC levels
2017	**1.**Pratheek Sudhakaran **2.**Jitendra Singh **3.**Shailendra Kumar **4.**Bhavesh Joshi	Bio-inspired Built Environments For Climate Change: Developing Strategies For Adaptation and Mitigation.	Article & Analysis Study	**Treescraper Tower of Tomorrow** & Office Building	Conceptual	Growing of Tree	Behaviour level	Biology to Design	Steel and Glass	**1.**Photovoltaic panels and aerodynamic shape	**1.**The aerodynamic shape of the building reduces the effect of the wind **2.**It produces oxygen. **3.**Natural ventilation.	**1.**The energy obtained from the sun is used for heat. **2.**Vibrant building design that changes with the seasons.	**1.**It distills water. **2.**It collects rainwater.	**1.**Daylight saving	**1.**It generates and conserves energy **2.**It recycles all the water **3.**It provides natural ventilation
2017	**1.**Pratheek Sudhakaran **2.**Jitendra Singh **3.**Shailendra Kumar **4.**Bhavesh Joshi	Bio-inspired Built Environments For Climate Change: Developing Strategies For Adaptation and Mitigation.	Article & Analysis Study	**Hydrological Centre** & University Center	Namibia & Subtropical Climate	Namibian desert beetle desert beetle, stenocara	Organism level	Biology to Design	Steel and Glass	**1.**The building has a system that traps moisture in the arid desert climate.	-	**1.**It cools the building by capturing the moisture in the air.	**1.**It captures water in the air.	-	**1.** Lowered HVAC levels **2.** Natural cooling

2017	**1.**Gülcan Minsolmaz Yeler **2.**Soner Yeler	Models From Nature for Inovative Building Skins	Article & Case Study	**Q1 Building** & Residential	Germany & Temperate Climate	Feather	Organism level	Design to Biology	**1.**Metal elements	**1.**This building is not just a feathery design element- it also serves as a sophisticated sun shading system.	-	**1.** Keeps the interior cool, reducing the need for air conditioning and climate control.	-	**1.** Blocks excessive sun, supports daylight	**1.**Sophisticated sun shading system **2.**Effective shading systems **3.** Lowered HVAC levels
2017	**1.**Lidia Badarnah	Form Follows Environment: Biomimetic Approaches to Building Envelope Design for Environmental Adaptation	Article & Examination Study	**Kunsthaus Graz** & Cultural Center	Austria & Transition Climate	Water bubble	Organism level	Design to Biology	**1.**Acrylic plastic glass	**1.**Reinforced with biomorphic Screen facade with fluorescent lamp	-	-	-	**1.**Provides controlled daylight	**1.**Effective shading systems **2.** Lowered HVAC levels
2019	**1.**Robin Koontz	Biomimic Building	Book	**National Taichung Theater** & Cultural Conplex	Taiwan & Sub-tropical Climate	Sound Cave	Organism level	Design to Biology	**1.**Concrete **2.**Glass	**1.**Building that stands on its own firmly without supporting pillars or 90-degree walls at all.	**1.**Provides ventilation thanks to the air holes on it	**1.**There are walls that prevent the building from overheating.	-	**1.**Provides controlled light	**1.**Quality sound acoustics is provided. **2.**Natural light **3.**Natural ventilation
2022	**1.**Rania Raouf Awadalla	Biomimicry as an Innovation Behavior in Architecture and Interior Design	Article	**Sagrada Familia** & Basilica	Spain & Temperate Climate	Trunks of trees	Behaviour and Organism	Design to Biology	**1.**Stone **2.**Granite **3.**Glass	**1.**Building with asymmetrical, hyperbolic shapes like tree branches	**1.**Permeable material provides natural ventilation.	-	-	**1.**It takes advantage of daylight in a controlled way.	**1.**A gigantic high and asymmetrical structure with minimal cost

2018	**1.**Ayomi S. **2.**Perera Marc Olivier Coppens	Re-designing Materials for Biomedical Applications: From Biomimicry to Nature Inspired Chemical Engineering	Article & Case Study	**Lotus Temple** & Temple	India & Steppe Climate	Lotus Flower	Behaviour level	Design to Biology	**1.**Marble **2.**Cement **3.**Sand	**1.**The building's twenty seven structures of reinforced concrete in the shape of petals	**1.**Controlled natural ventilation	**1.**Concrete shell prevents overheating	-	**1.**Controlled daylight	**1.**Aesthetically and statically difficult form **2.** Natural Lighting
2009	**1.**Arash Vahedi	Nature as a Source of Inspiration of Architectural Conceptual Design	Article	**Aqua Tower** & Mixed-use	America & Continental Climate	Wave	Organism level	Biology to Design	**1.**Concrete	**1.**Monolithic undulating concrete slab design	-	**1.**Provides very good heat balance.	**1. S**aves water to irrigate	**1.** Long concrete slabs provide shading **2.**Controlled daylight	**1.**Effective shading systems **2.** Lowered HVAC levels
2017	**1.**Seyedehaida Mirniazmandan **2.**Ehsan Rahimianzarif	Biomimicry, an Approach Towered Sustainability of High Rise Buildings	Article & Experimental	**Dragon Fly** & Mixed Building	America & Subtropical Climate	Wings of a Dragon Fly	Behaviour level	Design to Biology	**1.**Conceptual Project	**1.**Solar panels	**1.**Natural ventilation **2.**Evapo-perspiration from the plants **3.**Cooling	**1.**Uses solar energy by accumulating hot air	**1.**Outdoor vertical gardens filters water	**1.**Natural lighting	**1.**100% self-sufficient Project **2.**Natural light **3.**Natural ventilation **4.** Energy production
2022	**1.**Juan Rey-Rey	Nature as a Source of Inspiration for the Structure of the Sydney Opera House	Article	**Sydney Opera House** & Opera Center	Australia & Subtropical Climate	Orange peel	Organism level	Design to Biology	**1.**Concrete **2.**Ceramic tile	**1.**Geometric shell-forms	**1.**Controlled natural ventilation	**1.**Concrete shell prevents overheating	-	**1.**Controlled daylight	**1.**Aesthetically and statically difficult form **2.** Natural Lighting

2017	**1.**Seyedehaida Mirniazmandan **2.**Ehsan Rahimianzarif	Biomimicry an Approach toward Sustainability of High-Rise Buildings	Article & Case Study	**Pearl River Tower** & General Business Center	China & Monsoon Climate	Water sponge	Organism and Behaviour	Design to Biology	**1.**Glass	**1.**Photovoltaic system **2.**Wind turbine	**1.**It takes advantage of the extreme airflow and generates energy.	**1.**The thermal comfort of the building is provided by radiant cooling.	**1.** The pores on the building absorb water.	**1.**Daylight controlled with sun shading system	**1.**The building's energy use will be reduced by 58 to 60 percent.
2017	**1.**Seyedehaida Mirniazmandan **2.**Ehsan Rahimianzarif	Biomimicry an Approach toward Sustainability of High-Rise Buildings	Article & Case Study	**DNA Towers** & Mixed-use Complex	China & Monsoon Climate	DNA helix	Organism level	Design to Biology	**1.**Steel **2.**Glass	**1.**All systems on sustainability	**1.**Natural ventilation **2.**Wind direction design.	**1.**Heat balance	**1.**Water saving	**1.**Design in accordance with the direction of the sun. **2.**Natural daylight	**1.**100% sustainable building
2016	**1.**Firm Brief	Introducing Architectural Tectonics: Exploring the Intersection of Design and Construction	Book	**Loblolly House** & House	United State & Subtropical Climate	Tree	Organism and Behaviour	Design to Biology	**1.**Wood	**1.**Wooden columns	-	-	-	-	**1.**Reflects an environmental ethic, enhance affordability and quality.
2014	**1.**Rajshekhar Rao	Biomimicry in Architecture	Article & Experimental	**Tent Tower** & Multi-Function	Armenia & Continental Climate	Volcano or Tent	Organism level	Design to Biology	**1.**Composite **2.**Concrete	**1.**Resists gravity load resulting from earthquake action	**1.**Cooling indoors in summer **2.**In winter, fresh air will be heated **3.**The principle of displacement ventilation.	**1.**Summer and winter heat balance is maintained	-	**1.**The exteriors will have an adaptable high-performance coating to reduce solar gains during the summer months.	**1.**Optimizing environmental conditions **2.**Minimizing the tower's energy demands

2018	**1.**Shanta Pragyan Dash	Application of Biomimicry in Building Design	Analytical Study	**Shi Ling Bridge** & Bridge	China & Monsoon Climate	Shell	Organism level	Biology to Design	**1.**Sheet material	**1.**Creating highly-efficient and responsive structures with minimum weight and wastage	-	-	-	-	**1.**Form incredibly expressive, unique, economic intuitive bridge
2022	**1.**Rania Raouf Awadalla	Biomimicry as an Innovation Behavior in Architecture and Interior Design	Article	**Guggenheim Museum** & Museum	Spain & Temperat e Climate	Ship	Organism and Behaviour	Design to Biology	**1.**Metal rods	**1.**Random curves of the exterior are designed to catch the light and react to the sun and the weather	**1.**Adequate ventilation	**1.**Prevents overheating and temperature balance is established	-	**1.**Adequate light	**1.**Energy consumption reduced to 60%
2022	**1.**Gamze Satılmış **2.**Özge Yalçıner Ercoşkun	Biophilic Design: Benefits of Biophilic Design Towards Sustainability	Book	**Parkroyal** & Wall Garden	Singapor & Tropical Climate	Garden	Ecosystem level	Biology to Design	**1.**Concrete **2.**Plastic	**1.**Use of Cobiax technology (which uses "void formers" made of recycled plastic to reduce concrete usage)	**1.**Demand-based ventilation systems	**1.**Energy efficient chiller system	**1.** gravitydriven irrigation	**1.** Performance glass to cut solar gain	**1.**Energy and water saving design,
2016	**1.**Nowak A. **2.**Rocicki W.	On Surface Geometry Inspired by Natural Systems in Current Architecture	Article	**SUTD Library Pavilion** & Pavilion	Singapor & Tropical Climate	Timber Shell	Organism level	Design to Biology	**1.**Flat plywood **1.**Galvanized steel sheets	**1.**Canopy forms a lightweight timber shell providing structural stability	-	-	-	**1.**Limited sunlight	**1.**Readly available materials, assembly process at minimal cost

2020	**1.**Bahriye Gülgün **2.**Begüm Altıntaş	The Importance of Biomımicry In Desıgn Studies and Biomimıcry in Aquatic Plants	Book Article	**Kurilpa Bridge** & Bridge	Australia & Oceanic Climate	Spider web	Organism level	Design to Biology	**1.**Steel	**1.**The bridge is a multi-mast, cable-stay structure based on principles of tensegrity	-	-	-	**1.**The energy produced by the panels is used as a light source.	**1.**Provides 75% to 100% of the power required for lighting. **2.**It produces energy. **3.**Robust and durable
2009	**1.**Alan Marshall	Wild Design: Ecofriendly Innovations Inspired by Nature	Book	**Redwood Tree-House** & House	United States & Subtropical	Seed pod	Organism and Behaviour	Design to Biology	**1.**Wood **2.**Glass	**1.**Vertical fins and slats are made from sustainably grown pine and poplar.	-	-	-	-	**1.**Evaluation of sustainable, recyclable materials
2020	**1.**Krystyna Januszkiewicz **2.**Meryem Alagoz	Inspired by Nature: The Sun and Shadow Pavilion, Social Integration and Energy Saving in the Built Environment	Article	**Treepods** & Shading device	United States & Subtropical	Dragon tree	Organism and Behaviour	Biology to Design	**1.**Canopy	**1.**Street-sculpture air-filtering trees Solar panels for energy	**1.**Cleans the polluted air **2.**Produces clean air	**1.**Keeps its surroundings cool	-	**1.**Provides shade, cuts out harmful daylight	**1.**It produces energy. **2.**It produces clean air.
2020	**1.**Krystyna Januszkiewicz **2.**Meryem Alagoz	Inspired by Nature: The Sun and Shadow Pavilion, Social Integration and Energy Saving in the Built Environment	Article	**Epiphyte Pavilion** & Pavilion	Conceptual	Organism	Organism and Behaviour	Biology to Design	-	**1.**Zero carbon emissions Energy production	**1.**Cleans air pollution **2.**Provides ventilation	**1.** Provides cooling	**1.**Collects rainwater **2.**Filters and cleans water	**1.** Blocks ultraviolet harmful rays	**1.**Ecological building system **2.N**atural ventilation **3.**Water purification **4.**Energy generation

2012	**1.**Alessandra Capanna **2.**Mauro Francaviglia **3.**Marcella G. Lorenzi	Architecture, Form, Expression: The Helicoidal Skyscraper's Geometry	Article	**Chicago Tower** & Mixed-use Complex	United States & Subtropical	Nautilus shell	Organism level	Design to Biology	**1.**Glass	**1.**Smart Building and Energy Management System	**1.**Natural ventilation	**1.**The river cools the building by pulling in the water	**1.**Rainwater recycling system **2.**Geothermal system	**1.**Natural lighting	**1.**15% better than energy efficiency standards
2017	**1.**Osama Al-Sehail	A Biomimetic Structural Form: Developing Paradigm to Attain Vital Sustainability in Tall Architecture Architecture	Article	**3TS** & Mixed-use Complex	Canada & Temperate Climate	Palm tree	Organism and Behaviour	Design to Biology	**1.**Steel	**1.**Biomimetic Structural Form and the salient elements of its diagrid system	**1.**Natural ventilation	**1.**Different pressure areas inside and outside the building	**1.**Rainwater collection system	**1.**Minimizes the need for artificial light during the day.	**1.**30% reduction in carbon footprint **2.**Energy saving **3.**Lowered HVAC levels
2019	**1.**Allison Goins **2.**Antonio R. Webb **3.**Josephine B. Allen	Multi-layer approaches to scaffold-based small diameter vessel engineering:A review	Article	**The Vessel** & Staircase	United States & Subtropical	Bee hive	Organism level	Biology to Design	**1.**Steel **2.**Copper **3.**Colored metal sheets	**1.**Scalable structure is composed of 154 stretches of intricately interconnected stairs	-	-	-	-	**1.**Robustness, aesthetics
2022	**1.**May Makarem	Pour contrer la crise climatique, BAD lance sa machine écologique	Article	**The Tower of Life** & Mixed-use	Senegal	Egg shells	Organism level	Design to Biology	**1.**Local soil **2.**Additive printing.	**1.**Photovoltaic glass Bioreactor	**1.**Creates a microclimate **2.**Natural ventilation **3.**Air quality	**1.**Solar energy is used for heating **2.**Used in hand energy cooling with bioreactor	**1.**Rainwater collection system	**1.**Natural lighting	**1.**Energy production **2.**Lowered HVAC levels

2022	**1.**Aslıhan Fedakar **2.**Ruşen Yamaçlı	Energy Efficent Facade Design With in The Context of Sustainable Architectural Design: Biomimetic Facades	Article	**Davies Alpine House** & Greenhouse	UK & Oceanic Climate	Peacock ant mounds	Organism and Behaviour	Biology to Design	**1.**Iron **2.**Glass	**1.**Shell system made of glass and iron	**1.**Natural ventilation	**1.**Cooling without using energy **2.**Heat gain	-	**1.**Natural lighting **2.**Lets 95% of daylight in	**1.**Passive cooling system **2.**Lowered HVAC levels
2022	**1.**Aslıhan Fedakar **2.**Ruşen Yamaçlı	Energy Efficent Facade Design With in The Context of Sustainable Architectural Design: Biomimetic Facades	Article	**FB Elytra I Research Pavilion** & Pavilion	UK & Oceanic Climate	Elytra beetle	Organism level	Design to Biology	**1.**Clear glass **2.**Fiber **3.**Black carbon fiber	**1.**Biological fiber systems	-	-	-	**1.**Controlled light **2.**Dynamic shading	1.Lowered HVAC levels
2022	**1.**Aslıhan Fedakar **2.**Ruşen Yamaçlı	Energy Efficent Facade Design With in The Context of Sustainable Architectural Design: Biomimetic Facades	Article	**Hygroskin** & Pavilion	France & Temperate Climate	Pinecone	Behaviour level	Biology to Design	**1.**Wood	**1.**Hygroscopicity	**1.**Natural ventilation	-	**1.**Humidity control	**1.**Natural lighting	**1.**Passive cooling system **2.**Lowered HVAC levels
2022	**1.**Aslıhan Fedakar **2.**Ruşen Yamaçlı	Energy Efficent Facade Design With in The Context of Sustainable Architectural Design: Biomimetic Facades	Article	**Snow Leopard's Small Pocket Project** & Shelter	Conceptual	Snow leopard	Organism and Behaviour	Design to Biology	-	**1.**Pocket system consisting of body, telescopic frame, rods and membrane	**1.**Natural ventilation	-	**1.**Humidity control	**1.**Natural lighting	**1.**Heat balance **2.**Lowered HVAC levels

2.2. Evaluation Of Analytical Study

Building envelopes inspired by the strategies developed by nature have been extensively researched with research resources. These projects, either in concept or in existence, have been analyzed and tabulated on their basic information, biomimetic inspiration processes, features and energy efficiency. How the biomimetic envelope system integrated into the projects affects the building's air, water, light and heat parameters has been examined. The result output of each project was arranged. In the light of all this, the following findings were reached:

Biomimetic Level

As the biomimicry level of the analyzed projects, it has been seen that the solutions developed by living things at the level of organisms and behaviors are mostly used. Based on the analysis of the samples, it was concluded that behavioral and organism levels play a more active role in energy efficient building design. It has been determined that the ecological level can produce more comprehensive results than the behavior and organism levels, depending on the building and climatic conditions.

Biomimetic Approach

When considered as a biomimetic approach, it has been seen that the approach from biology to design is mostly preferred in conceptual and more detailed projects. It has been observed that this approach can be applied with a comprehensive knowledge of biology and research. It has been observed that the other approach type, the design to biology approach, is preferred more in innovative design proposals with high energy efficiency. Innovative systems inspired by organisms are used in accordance with energy efficient building design requirements such as water efficiency, natural ventilation, natural lighting, energy production and heat balance.

Material

Environmentally friendly, recyclable, self-renewing, local, smart and cost-effective materials play an active role in the energy efficient design of the building. Material selection of systems inspired by nature is an important part of biomimetic design. The determined materials directly affect the function, energy efficiency, sustainability and cost of the system to which it will be applied. It has been observed that generally recyclable and environmentally friendly materials are preferred in the examined projects.

Technologies

It has been observed that the natural strategies developed by the organisms in the projects are combined with the technological systems in the design process. With this cooperation, it has been observed that biomimetic envelope systems can produce sustainable solutions to current problems. In envelope systems, where the technological equivalents of solutions inspired by nature are applied, gains are higher in terms of efficiency. The developed systems appear as systems that wrap the building completely like envelope in some projects, and as a secondary façade that is integrated into the building later in some projects.

When viewed as a whole, it is seen that wind turbines, active facade systems, living facade systems, smart systems are applied. When you go down to a lower level, many technological solutions such as dynamic shading elements, facade panels, sensitive sunshades, bioreactor panels, ventilation ducts are seen. Sensors that respond to daylight, photovoltaic panels, climate and environmental sensitive systems have also been integrated into the works.

Energy Efficiency

In most of the evaluated projects, it has been observed that the strategies developed by systems or organisms that have proven themselves in nature (air, light, heat, water) are transferred to energy efficient facade systems. It has been observed that sustainable and energy efficient solutions brought by nature bring more efficient results together with technological developments.

Outcome

In the examined projects, it has been observed that the building envelope systems created with the biomimetic approach improve the building they belong to in terms of energy efficiency. It has been analyzed that the design ideas inspired by nature have been transferred to the projects by considering the technological developments. Thanks to today's architectural possibilities and innovative technological inventions, it has been understood that biomimetic approaches are more effectively integrated into buildings. Especially with the developments in computer-aided modeling and simulation programs, the proposed designs can be tested before going to the implementation phase. Thus, it is possible to see and improve the effects of the developed biomimetic envelope system on the building to which it will be integrated.

In conclusion; It has been seen that existing or concept projects developed with a biomimetic approach are successful in energy saving, natural lighting and natural ventilation, creating heat balance, thermal comfort, water efficiency and less HVAC load consumption.

2.3. Sample Analysis

In the light of intensive analyzes on the applicability of biomimicry in energy efficient building envelope design, a more detailed review was created on the examined projects. The following table has been created as a continuation of the previous table in order to create a new evaluation criterion and design process for the architectural integration of energy efficient based biomimetic approaches. In the light of this table, the findings will be converted into a graph. (see Table 2.2.)

Table 2.2. Classification of biomimetic building envelope systems according to various parameters

	Project Name	Functionality or Aesthetic	Recycled Material	Renewable Enery Usage	Cost Effective or Technology	Natural Ventilation	Natural Lighting	Heat Balance	Water Efficiency	Energy Saving or Production	Energy efficient?
1.	The Council House 2	O	O	O	O	O	O	O	O	O	O
2.	Eastgate Centre	O	O	O	O	O	O	O		O	O
3.	Water-Cube	O	O	O	O	O	O	O	O	O	O
4.	MMAA Office Building	O		O	O	O	O	O	O	O	O
5.	Al Bahar Towers	O	O	O	O	O	O		O	O	O
6.	The Media TIC Building	O	O		O			O		O	O
7.	Esplanade Theatre	O	O		O		O	O		O	O
8.	Beijing National Stadium	O	O		O	O	O	O		O	O
9.	Waterloo International Terminal	O	O		O					O	O
10.	Heliotrope House	O	O	O	O		O	O	O	O	O
11.	Sinosteel International Plaza	O	O		O		O	O		O	O
12.	Gherkin Tower	O	O		O	O	O			O	O
13.	BIQ Bilding	O		O	O	O	O	O		O	O

	Project Name	Functionality or Aesthetic	Recycled Material	Renewable Enery Usage	Cost Effective or Technology	Natural Ventilation	Natural Lighting	Heat Balance	Water Efficiency	Energy Saving or Production	Energy efficient?
14.	Flectofin Project	O	O	O	O		O			O	O
15.	HOK Lavasa	O			O				O	O	O
16.	The Porous Skin Project	O			O		O	O	O	O	O
17.	Milwaukee Art Museum	O	O		O		O			O	O
18.	The Habitat 2020	O		O	O	O	O	O	O	O	O
19.	Lily Pad, Floating City	O	O	O	O	O	O	O	O	O	O
20.	Mangal City	O	O	O	O	O	O	O	O	O	O
21.	Eiffel Tower	O	O		O	O		O		O	O
22.	Eden Project	O	O	O	O		O	O		O	O
23.	L'arabe du monde institute	O	O	O	O		O	O		O	O
24.	Rafflesia House	O	O	O	O	O		O		O	O
25.	Treescraper Tower of Tomorrow	O	O	O	O	O	O	O	O	O	O
26.	Hydrological Centre	O	O		O			O	O	O	

	Project Name	Functionality or Aesthetic	Recycled Material	Renewable Enery Usage	Cost Effective or Technology	Natural Ventilation	Natural Lighting	Heat Balance	Water Efficiency	Energy Saving or Production	Energy efficient?
27.	Q1 Building	O	O		O		O	O		O	O
28.	Kunsthaus Graz	O			O				O	O	O
29.	National Taichung Theater	O	O		O	O	O	O		O	O
30.	Sagrada Familia	O	O		O	O	O			O	O
31.	Lotus Temple	O	O	O	O	O	O	O		O	O
32.	Aqua Tower	O	O	O	O		O	O	O	O	O
33.	Dragon Fly	O	O	O	O	O	O	O	O	O	O
34.	Sydney Opera House	O	O		O	O	O	O		O	O
35.	Pearl River Tower	O	O	O	O	O	O	O	O	O	O
36.	DNA Towers	O	O	O	O	O	O	O	O	O	O
37.	Loblolly House	O	O		O					O	O
38.	Tent Tower	O	O	O	O	O	O	O		O	O
39.	Shi Ling Bridge	O	O		O					O	O

	Project Name	Functionality or Aesthetic	Recycled Material	Renewable Enery Usage	Cost Effective or Technology	Natural Ventilation	Natural Lighting	Heat Balance	Water Efficiency	Energy Saving or Production	Energy efficient?
40.	Guggenheim Museum	O	O		O	O	O	O		O	O
41.	Parkroyal	O	O	O	O	O	O	O	O	O	O
42.	SUTD Library Pavilion	O	O		O		O			O	O
43.	Kurilpa Bridge	O	O		O		O			O	O
44.	Redwood Tree-House	O	O		O					O	O
45.	Treepods	O	O	O	O	O	O	O		O	O
46.	Epiphyte Pavilion	O	O	O	O	O	O	O	O	O	O
47.	Chicago Tower	O	O	O	O	O	O	O	O	O	O
48.	3TS	O	O	O	O	O	O	O	O	O	O
49.	The Vessel	O	O		O						
50.	The Tower of Life	O	O	O	O	O	O	O	O	O	O
51.	Davies Alpine House	O	O		O	O	O	O		O	O
52.	FB Elytra I Research Pavilion	O			O				O	O	O

	Project Name	Functionality or Aesthetic	Recycled Material	Renewable Enery Usage	Cost Effective or Technology	Natural Ventilation	Natural Lighting	Heat Balance	Water Efficiency	Energy Saving or Production	Energy efficient?
53.	Hygroskin	O	O		O	O	O		O	O	O
54.	Snow Leopard's Small Pocket Project	O			O	O	O		O	O	O

2.4. Evaluation Of Sample Analysis

A detailed sample analysis was carried out in order to reach a new evaluation criterion based on energy efficiency design principles. Percentage calculations were made on the graph below, which was created in the light of these analyses. (see Figure 2.1.)

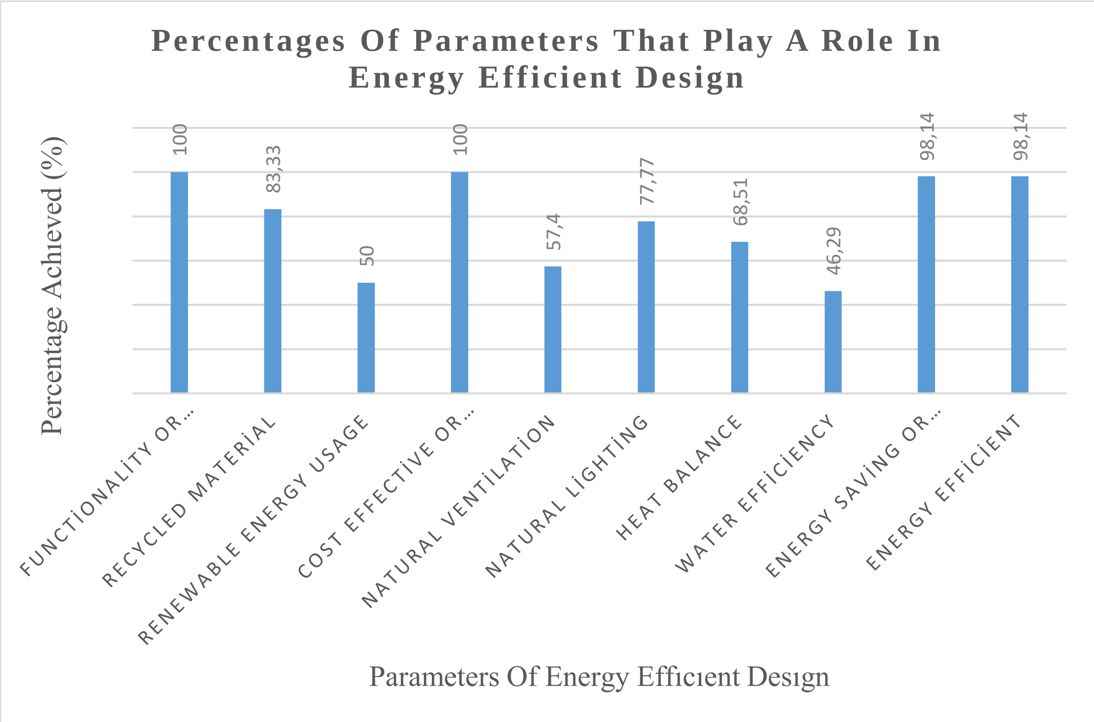


Figure 2.1. Percentages Of Parameters That Play A Role In Energy Efficient Design

Sequencing the parameters based on the maximum percentage of energy efficiently design achieved through various parameters:

- Functionality or Aesthetic – 100%
- Recycled Material – 83,33%
- Renewable Energy Usage – 50%
- Cost Effective or Technology – 100%
- Natural Ventilation – 57,4%
- Natural Lighting – 77,77%
- Heat Balance – 68,51%
- Water Efficiency – 46,29%
- Energy Saving or Production – 98,14%
- Energy Efficient? – 98,14%

In the light of the findings, it is seen that the building envelope systems created with the biomimetic approach are mostly successful in design parameters that support energy efficiency. The data show that water efficiency should be emphasized more in designs inspired by nature. It can be said that approaches and technologies that support renewable energy sources should be used today, where natural resources are increasingly depleted. In general, biomimicry seems to be an effective approach for energy efficient building envelope designs.

In order to ensure energy efficiency in building envelope design, feasibility should be established in terms of cost, technology, material and all parameters that consume energy. In the light of these parameters, the targeted energy efficient building designs are achieved more effectively. Many environmental and energy problems have been solved with architectural interventions made with the biomimetic approach. Biomimetic envelope systems were created with a functional and solution-oriented strategy rather than aesthetic concern. Any building envelope design based on energy efficiency should establish a strong association for architectural integration.

2.5. Biomimetic Design Process With New Criterion

The most important intersection cluster in associating biomimetic approaches with nature's powerful systems is energy efficiency. The most important part of a building between the interior and exterior is the envelope systems. From this point of view, a building envelope design should meet with the right technology and systems with a biomimetic approach.

In the light of all analyzes and evaluations, a new design process and evaluation criteria have been developed to focus on energy efficient building envelope designs for the purposes of the biomimicry discipline. Evaluated projects show that the developed biomimetic envelope systems act in common with the basic principles of energy efficiency. In this context, parameters that directly or indirectly affect energy efficiency should be evaluated and developed during the design process in order for designs to yield more effective results.

A new design process has been developed in the light of the analyzes and data. It was aimed to develop the design obtained in this process based on the basic principles of energy efficiency. On the other hand, it was possible to evaluate the design in the architectural integration process. The steps related to this design process and evaluation criteria are given below.

Problem Statement

Focusing on the causes of the problem, deciding how the design should result, both functionally and aesthetically. In line with this decision, it is also determined which issues the design will struggle with.

Discovery

After the problem has been determined, how nature will struggle with this problem should be considered and systems that have proven itself in nature should be discovered. Systems that will best respond to the designated design problem should be investigated. In doing so, it is necessary to cooperate with the science of biology.

Comparison and Selection

Among the systems presented by nature should be compared and the system to respond best to the determined problem should be selected. It should be considered that the created biomimetic approach will affect all parameters of the building. In addition to the main problem, the developed design should be taken into consideration in other parameters such as the needs and comfort level of the building.

Abstraction

The process of transforming the possibilities and principles offered by nature into technologies and systems to be used in design. This stage can be called the transition from nature to architectural design. It acts as a bridge between nature and design.

Imitation

The stage of copying the systems developed by nature using the data obtained after the abstraction stage. With this stage, systems that have proven themselves in nature turn into design with current technological developments.

Evaluation

In the light of the data obtained, some inquiries and analyzes should be made in order to be sure how much of a solution the design produces. Through an evaluation criterion, the performance of the building envelope system realized in the design process in terms of energy efficiency can be measured. This evaluation criterion will serve as a guide for the evaluation of the energy efficient building envelope design before implementation and for the development afterwards. (see Table 2.3.)

Simulation Analysis

Architectural integration processes of designs developed with a biomimetic approach are a difficult process in terms of both cost and time. Before starting the implementation process, the design must be optimized. Different combinations of the biomimetic approach created within the scope of the developed design process and evaluation criteria should be created. These combinations should be developed on the variable parameters of the design. As an example, parameters such as the distance and angle between the developed building envelope system and the existing building can be given. These options should be tested with computer aided modeling and simulation tools. The most version of the design developed in the light of the test data should be determined according to the current conditions and needs. Since this varies depending on the design problem, the accuracy of the other stages in the design process is very important.

Development

After the evaluation criteria process, the aspects of the design that need improvement should be focused on. The shortcomings of the design are developed before the implementation process is started.

(see Table 2.3.) shows that a new Criterion: Evaluation of the biomimetic envelope system in the design process based on energy efficiency and design principles.

Table 2.3. Criterion: Evaluation of the biomimetic envelope system in the design process based on energy efficiency and design principles.

Biomimicry							Envelope Features									Energy Efficiency												Energy Efficient Envelope Design Principles
Concept		Level of Biomimetic			Approach to Biomimetic		Envelope Materials					Envelope Technology			Envelope Integration	Air		Heat			Water		Light	Energy		
Yes	No	Organism	Behaviour	Ecosystem	Design to Biology	Biology to Design	Recycled	Self-Cleaning	Self-Renewing	Accessible	Smart	Environmently	Renewable Enegy Usage	Innovative	Adaptive	Natural Ventilation	Air Filtration	Heat Balance	Heat Isolation	Heat Storage	Water Filtration	Water Storage	Natural Lighting	Energy Saving or Production	Lowered HVAC Usage	
																										Sustainability
																										Responsibility
																										Functionality
																										Recyclability
																										Renewability
																										Sensitivity
																										Indoor Quality

Energy efficiency in building envelope systems created with a biomimetic approach can be achieved with a single parameter or systematically. In line with the analyzed studies, it is aimed to reduce the energy consumption of the building envelope system and to preserve the interior quality. On the other hand, the building's struggle with external environmental conditions is supported. In the light of all these, the building envelope system should be in cooperation with all other systems for all the conditions that the building is struggling with. At this point, the building envelope system should be designed in a way that will directly affect the energy consumption by working in cooperation with the building construction systems and the environment.

Systems inspired by nature guide the designs. Architectural designers have to cooperate with many disciplines in order to integrate these systems into their designs architecturally. Thus, biological solutions are transferred to designs in a logical and rational way. These systems, abstracted on the basis of energy efficiency, play a major role in the creation of sustainable, responsible, functional, recyclable, reusable, sensitive envelope systems that care about interior quality. For this, while designing energy efficient building envelope systems, the systems, conditions, difficulties and problems presented by nature should be well analyzed and integrated into the building.

In this literature study, energy efficiency based analyzes were made on building envelope systems developed with a biomimetic approach. These analyzes have been further expanded and a new design process and evaluation criteria have been established for energy efficient biomimetic building envelope designs. It has been determined that this design process and evaluation criteria should be supported and tested with energy simulation programs, modeling tools and computer aided computational methods.

CHAPTER 3
NATURE-INSPIRED DESIGN

Thanks to today's technological developments and design approaches, it is possible to produce self-sufficient designs with high energy efficiency. In the architectural design process, it is necessary to use new methods against the problems that are being tackled. These methods are of great importance for a world where there is no dependence on more livable and non-renewable energy sources. Nature, which has been producing solution methods for architectural design problems and problems for years, has been used many times with applicable approaches. Imitating systems that have proven themselves in nature offers countless options to respond to today's energy problems. The natural models that have survived to the present day by fighting for the right life under the most difficult conditions for years produce the most appropriate solutions for the problems we face. Nature, which we have indirectly benefited from throughout history, still gives an idea to repair the damage done to it. The discipline of biomimicry emerges at the point of transferring technological developments and accurate solutions of nature to designs. It acts as a bridge at the point of transferring permanent solutions of nature to designs against today's energy crisis and accompanying environmental problems (Fedakar & Yamaçlı, 2022). Within the scope of this thesis, the concept of biomimicry or biomimetic approach refers to a design method that aims to produce energy efficient building systems.

3.1. Biomimicry

Nature has managed to survive with the organisms it has housed for billions of years. Many problems that human beings try to solve in nature have already been solved, the important thing is that people look to nature for the solution they are looking for (Benyus, 1997). In fact, imitating the solutions and methods that nature has brought to the present day for billions of years is as old as the history of humanity. From the existence of humanity to the present, the proven systems and methods of nature have been applied. When examining the historical remains of civilizations that lived millions of years ago, it is understood that people living in that period observed nature in order to adapt to the difficulties of the environment. It is seen that they make shelters and nests just like animals in order to protect themselves. Sometimes they were inspired by the animals living underground and sometimes by the animals that took shelter in the cave. Sometimes they built their own nests with the wastes of bushes and twigs, as in bird nests (Gündoğdu & Arslan, 2020). The following images can be shown as examples. (see Figure 3.1. and Figure 3.2.)

Figure 3.1. People inspired by the bird's nest

Figure 3.2. People inspired by the cave life

Technological developments in recent years have made 'biomimicry' a branch of science thanks to the changes and developments in our learning methods from nature (Öztoprak, 2020). Especially with the industrial revolution, the opportunity to examine nature in a more comprehensive and detailed way has arisen. Unlike the imitation of nature by simply observing, it is possible to examine the millions of organisms it contains at the atomic level and to use the solutions produced by these organisms against the problems in our daily life. From this point of view, innovative inventions were realized with approaches inspired by nature (Fıstıkcı & Gunduz, 2021).

The following images are examples of technological solutions inspired by nature. (see Figure 3.3. and Figure 3.4.)

Figure 3.3. Airplane inspired by bird

Figure 3.4. Solar Panels inspired by sunflower

Different names have been given to approaches inspired by nature in different disciplines and teachings. These approaches inspired by nature are named in the literature with names such as biotechnics, biophilia, bio-interaction, biomimesis, biomimicry and biomorphism. However, all of them believed that nature is a great inventor and adopted that every information obtained from nature will produce sustainable and definite solutions (Steadman, 2008). Biomimicry can be defined as a formation that brings solutions to the current problems and problems of humanity by examining and imitating organisms, tissues, methods, actions, strategies found in nature (Radwan & Osama, 2016). Biomimicry can be used not only to produce a solution to any problem or difficulty, but also as a design method used for the goal of aesthetic anxiety. As it is known, biomimicry does not mean biology or technology, it refers to the technology of biology (Ozen, 2016). Biomimicry actually reminds us that humanity is a part of nature and should not be distanced from it. As a part of this extraordinary system, it should develop biomimetic solutions inspired by nature to the problems that exist within the framework of the rules of nature.

3.1.1. History of Biomimicry

The term "biomimicry" is a combination of two different words. It is formed by combining the Greek words 'bios' meaning life and 'mimesis' meaning imitation in Greek. Imitating and being inspired by nature has evolved from ancient times to the present (Pawlyn, 2016). The important developments that played a role in this development can be listed in chronological order as follows:

- Inspired by nature, ornaments inspired by palm trees and lotus plants were used in column capitals in ancient Egyptian civilization in 3100 BC (Elsakksa et al., 2022). (see Figure 3.5.)

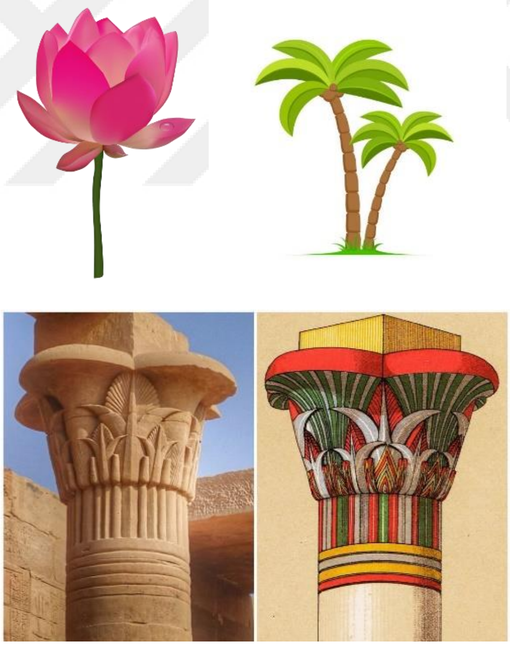


Figure 3.5. Ancient Egyptian column capitals inspired from palm trees and lotus plants

- Around 500 BC, natural organisms were used by Greek philosophers as models for harmony, balance, and proportion in their designs (Radwan & Osama, 2016).

- In 1482, Leonardo Da Vinci was inspired by birds to be able to invent a flying machine. It paved the way for Wright to develop the brothers' aircraft prototype (Kenny et al., 2012). (see Figure 3.6.)

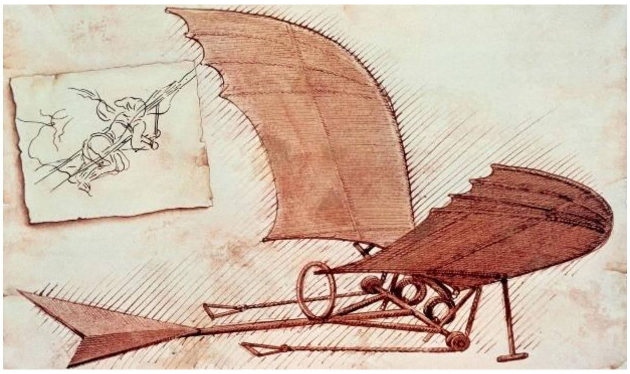


Figure 3.6. Leonardo Da Vinci's dream of flying

- In the 1950s, an American biophysicist, Otto Schmitt, first used the word "biomimetic". Otto Schmitt interpreted the concept of 'biomimetics' as the transfer of analogs and ideas from biology to technology (Vincent, 2006). (see Figure 3.7.)

Figure 3.7. Francis Otto Schmitt, Ph.D. (1903-1995)

- The term "Bionic" was coined by engineer Jack Steele in 1960 (Vincent, 2001)

- In 1974, the term "Biomimetics" entered the Webster Dictionary. The dictionary defined this term as the study of the formation, structure or function of biologically produced substances and materials (Scobey-Thal, 2014). (see Figure 3.8.)

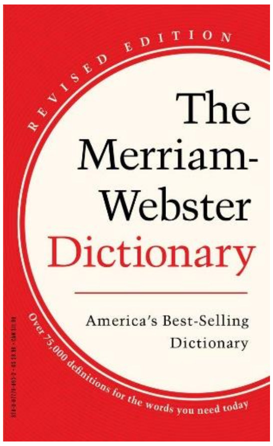


Figure 3.8. Webster's Dictionary

- The term "biomimicry" was first coined in 1982. It was popularized in Janine Benyus' work "Biomimicry: Innovation Inspired by Nature" in 1997. Janine Benyus introduced the concept of "biomimicry" to the literature with her book "Biomimicry: Innovation Inspired by Nature" published in 1997 (see Figure 3.9.). Benyus used biomimicry to solve a problem. He stated that instead of benefiting from a specific plant or animal species, she could benefit from all organisms (bacteria, fungi, plants and animals) (Benyus, 1997).

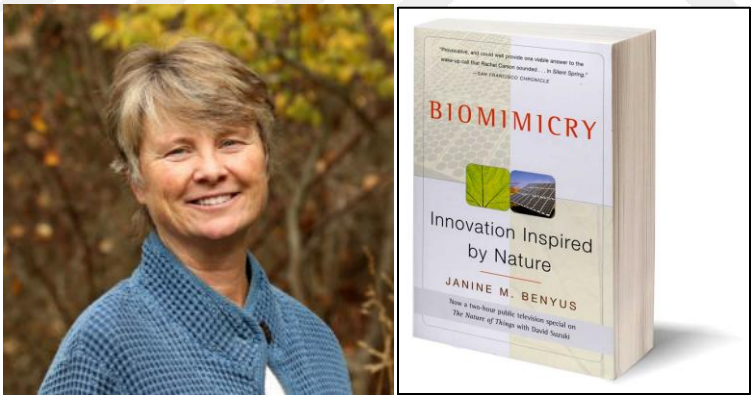


Figure 3.9. Janine M. Benyus and her book: “Biomimicry: Innovation Inspired by Nature”

- In 2005, Bryony Schwan and Janine Benyus co-founded the Biomimicry Institute (Peters, 2011).

- In 2007, Chris Allen created the database "AskNature", the world's first digital library (see Figure 3.10.). This is a biomimicry database of nature-inspired design strategies (Winters, 2009).

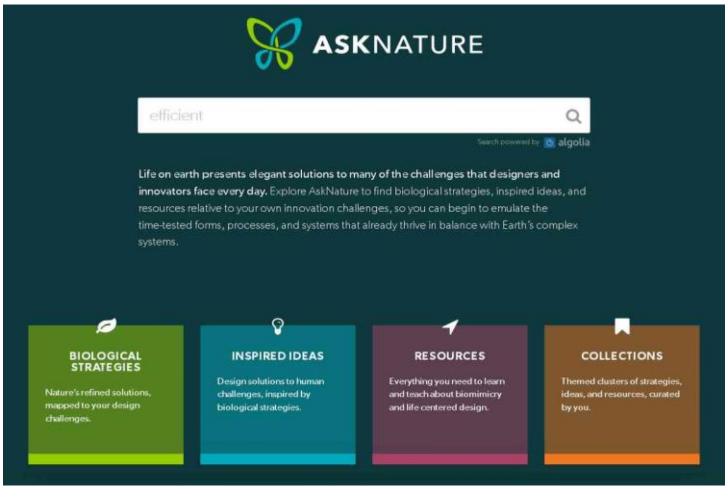


Figure 3.10. The World's first digital library, AskNature

- In 2016, Michael Pawlyn published the book "Biomimicry in Architecture". Architect Micheal Pawylyn has an architectural office where he works inspired by nature (Pawlyn, 2016). (see Figure 3.11.)

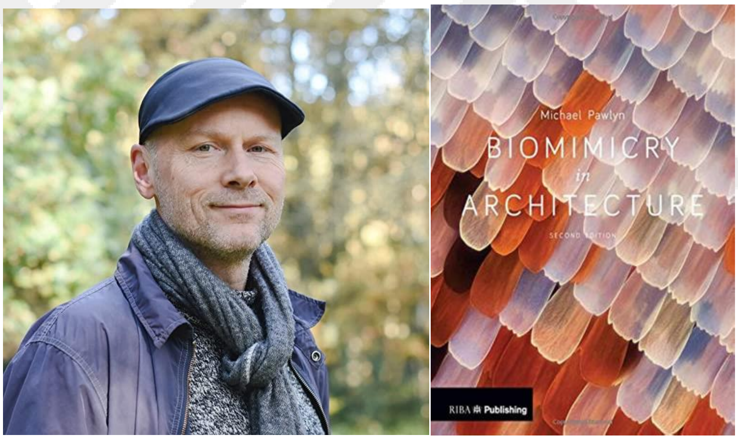


Figure 3.11. Michael Pawlyn and his book: "Biomimicry In Architecture"

3.1.2. Biomimicry and Architecture

The concept of biomimicry and biomimetic approach in architecture is to understand the relationship of all organisms living on Earth with nature and to benefit from nature, which is a guide and inspiration to find solutions to current problems. Nature offers the systems it has developed for billions of years to architects free of charge. Inspiration, interpretation, abstraction from something inherent in the design was used in the times when the concept of biomimicry did not exist (Benyus, 1997). It is understood that thousands of years ago, human beings continued their existence thanks to the inferences they gained by observing the nature in which they lived, and were able to struggle with the conditions and problems of that day. It is seen that people living in that period were inspired by the places where animals took shelter, living in caves, in shelters similar to bird nests, and underground like most reptiles. An example of this is the underground cities of Cappadocia, whose history dates back to the fourth century BC (see Figure 3.12.). The mysterious underground cities, some of which were large enough to accommodate thirty thousand people, were created to protect themselves from the dangers of that period. According to the German Martin Urban, who conducted the most serious research in this region between 1960 and 1970, the existence of underground cities dates back to ancient times (Çiner & Aydar, 2019). As a result of the ancient excavations obtained, it is seen that nature has affected human life for thousands of years. It is obvious that in ancient times, people were able to survive and make their lives easier by imitating nature, unaware of biomimicry, which served to better understand nature and apply the systems it developed (Pathak, 2019).

Figure 3.12. Cappadocia underground cities

Considered the first biomimetic building in architecture, 'Crystal Palace' was designed by Joseph Paxton in 1851, inspired by the leaves of the lotus flower (see Figure 3.13.). Designed by Gustave Eiffel in the late 1880s, the Eiffel Tower was inspired by the structure and strength of the thigh bone (see Figure 3.14.). Architect Antoni Gaudi was inspired by many organisms when designing the Sagrada Familia Cathedral, where he died before its construction was completed. Combining medieval architecture with modern architecture, Gauidi believed that nature was superior for design inspiration. It is thought that the Sagrada Familia work, whose construction continued after Gaudi's death, was inspired by animal skeletons, crustaceans and plants (Vincent, 2019).

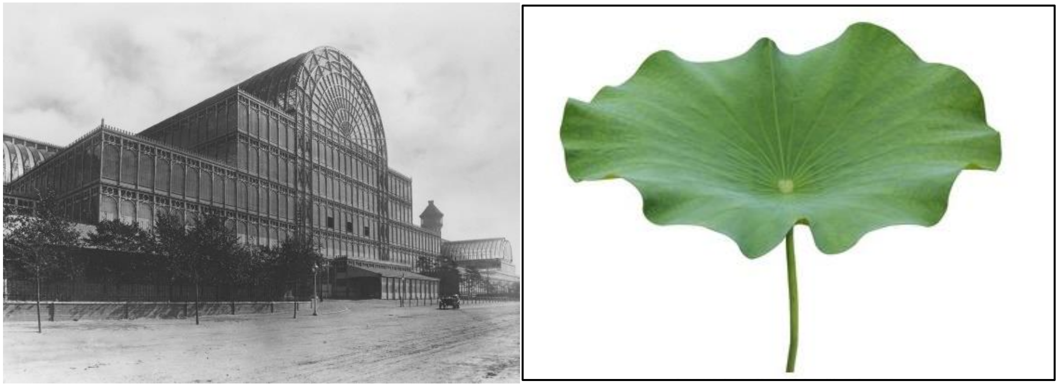


Figure 3.13. Crystal Palace and leaves of the lotus flower

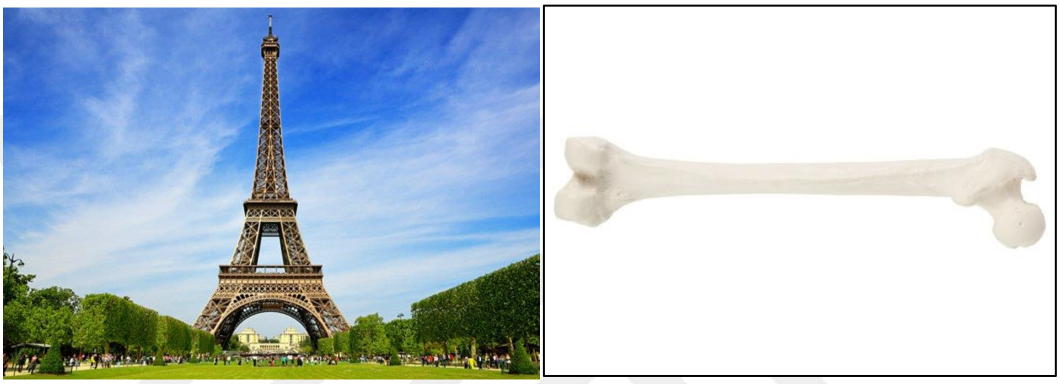


Figure 3.14. Eiffel Tower and thigh bone

Today, biomimetic architecture emerges as a new contemporary architectural style that will revolutionize all aspects of the world's problems and building users, from the materials used by architects in the buildings to the development of technologies that will direct the building's energy consumption. The idea that architecture does not have much effect in our daily lives is destroyed by the fact that the buildings we live in constitute a significant amount of total energy consumption and fossil fuel use. Due to the developing technological developments, current problems and the energy crisis we are in, today's architects believe that biomimicry is more than just the use of decorations or aesthetic improvement of buildings (Pathak, 2019).

Biomimicry in architecture is the beginning of the approach that allows a building design to be considered as a whole. The architect, together with biomimicry, goes beyond traditional design methods, examines that organisms that exist in nature produce sustainable solutions to existing and potential problems and difficulties, and carries out his designs by considering all concerns. In other words, when faced with the architectural design problem, the solution should be sought in an ecological order as in nature. Thus, it is ensured that the designed structure or system is efficient and in harmony with the entire environment. Michael Pawlyn thinks that human-made systems are designed for a single purpose, while ecosystems in nature evolve towards an optimized overall system (Chayaamor, 2023).

The task of biomimetic architecture is not only to give form and shape to the space in question, but also to develop a relationship between the built structure, environmental conditions and problems. An example is the 'CH2' Office Building ('CH2' Council House), designed as an extension of an existing office building in Australia (see Figure 3.15.). Thermite mounds were inspired by the building's heating and cooling system. This system, which regulates the temperature of the building, reduces the use of HVAC systems. Biomimicry has been used in situ for all problems of the building, both internal and environmental. Ventilation chimneys are placed on the north façade, which is most exposed to the sun. These air holes are inspired by the bronchi of the tree. It is balanced with the cold air coming from the south vents. Inspired by the epidermis structure of the tree on the western front, the external climate is combated. The eastern façade also acts as a protective layer as it is inspired by the bark of the tree. It acts as a filter for air and light. From this point of view, it is proof that biomimetic approaches can meet the needs of a building and fight environmental conditions at the same time (Gündoğdu & Arslan, 2020).

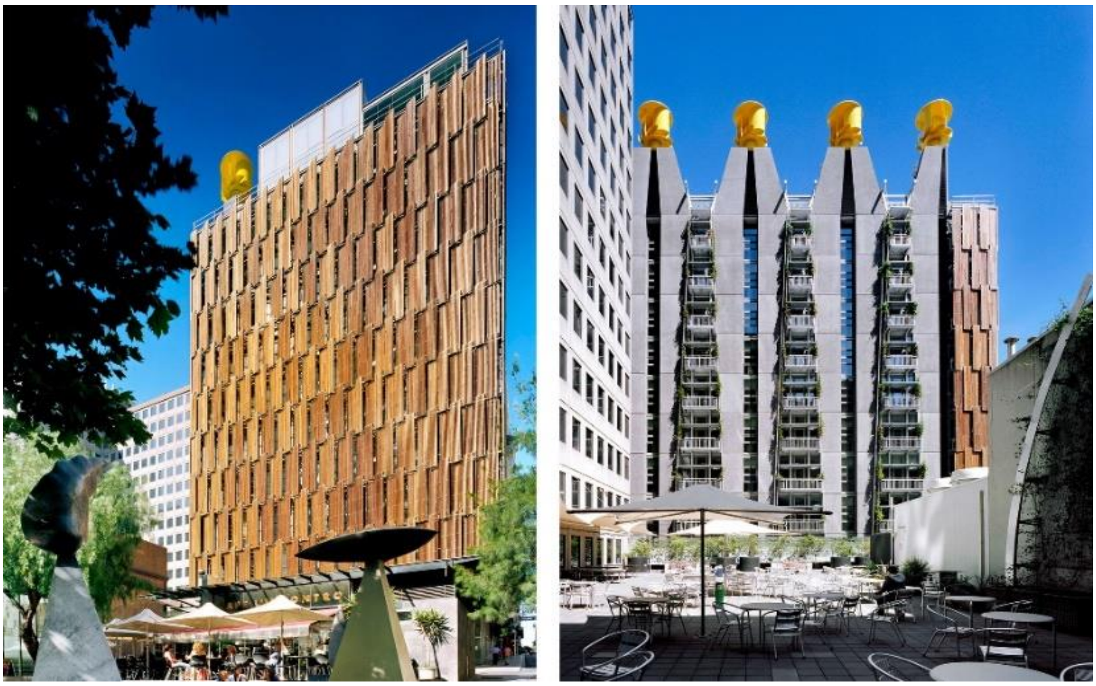


Figure 3.15. City of Melbourne Council House 2

To date, biomimetic approaches and biomimicry appear more in academic and research studies than in architectural practices and construction practices. Biomimicry applications need to be implemented and produce solutions to today's problems. Biomimicry acts as a bridge between architect and design to create self-sufficient building designs that are energy efficient, less costly, sustainable, environmentally compatible, encouraging renewable energy sources. Architects and designers need to combine the ideas of nature with technology in order to produce designs that provide thermal comfort and water efficiency, as well as natural ventilation and lighting systems in buildings.

By collaborating with biomimicry technology, it will help overcome environmental problems such as the greenhouse effect, global warming and energy crisis. Biomimetic approaches that have the potential to affect many parameters such as the quality of the material used in the construction of the buildings and the use of technological equipment that will alleviate the energy load of the building should be realized. As a result, for millions of years, nature has produced solutions to people's architectural problems. In the light of today's technological developments, the strategies offered by nature are more easily integrated into architectural designs.

3.1.3. Biomimetic Approaches

In the process of applying biomimicry to design, the researchers divided the developed biomimetic approaches into two different groups. As the design process, biomimetic approaches are divided into two: from **'design to biology'** and from **'biology to design'**.

3.1.3.1. Design to Biology

In this type of approach, the steps are dynamically guided by inspiration from biology. In the design-to-biology approach, the designer's task is to correctly identify problems and issues. Existing or probable problems in the target design should be determined beforehand. In the light of these problems, the needs of the design are determined. After this stage, the basic idea is to determine how nature struggles with similar conditions and problems. Thus, it helps the designer or architect to set the initial goals for the design. The architect or designer, who is in search of a solution from the problem-centered nature in the design process, easily determines the parameters that will affect the process. This type of problem-based approach allows objectives and design limitations to be defined. In the next stages, the solution inspired by nature is imitated and the architectural integration process is started. This approach method provides feedback as well as improvement in the design process (Badarnah, 2012). The development cycle of this type of approach, also called the top-down approach, consists of 6 stages (Peters, 2011). (see Figure 3.16.)

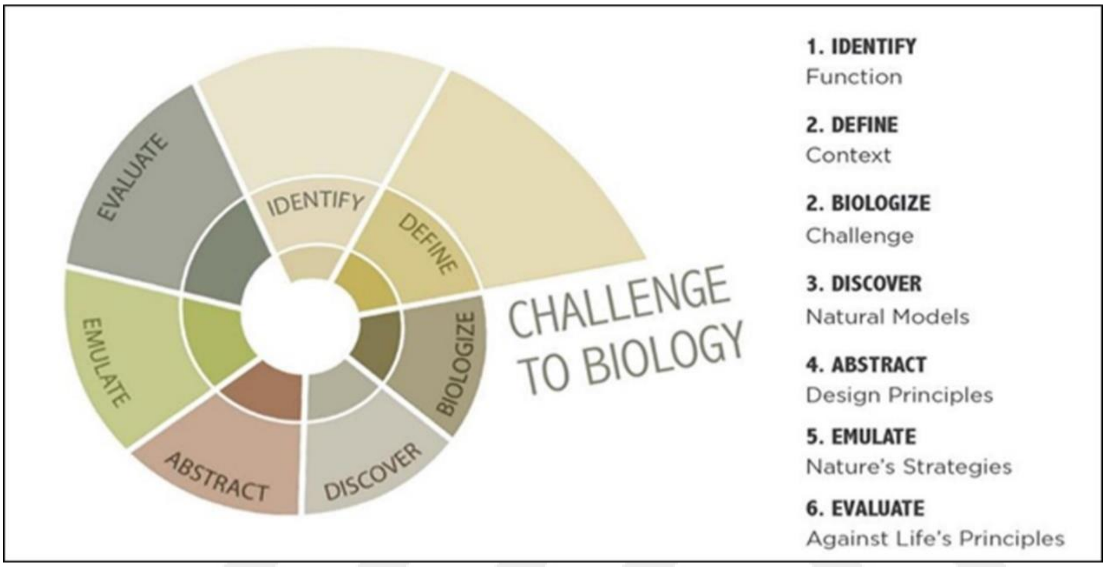


Figure 3.16. The spiral of approach from design to biology, (Lotfi, 2014)

3.1.3.2. Biology to Design

In this type of approach, it initially focuses on the scientific findings of biologists and scientists rather than design problems. In the type of approach from biology to design, the task of the architect or designer is to access relevant biological information rather than having knowledge of what the design problem is. It is necessary to focus on the behavior, functioning or characteristic of any organism or ecosystem. In this type of approach, biology presents the stages of producing a solution to a design problem. It is of great importance that a biological research is done with care. Care is taken to ensure that these studies include methods that can be used in the context of design. Therefore, it can be said that this approach type has limitations in terms of design (Dash, 2018). The design cycle of this type of approach, also known as bottom-up approach and solution-oriented approach, consists of 5 stages (Peters, 2011). (see Figure 3.17.)

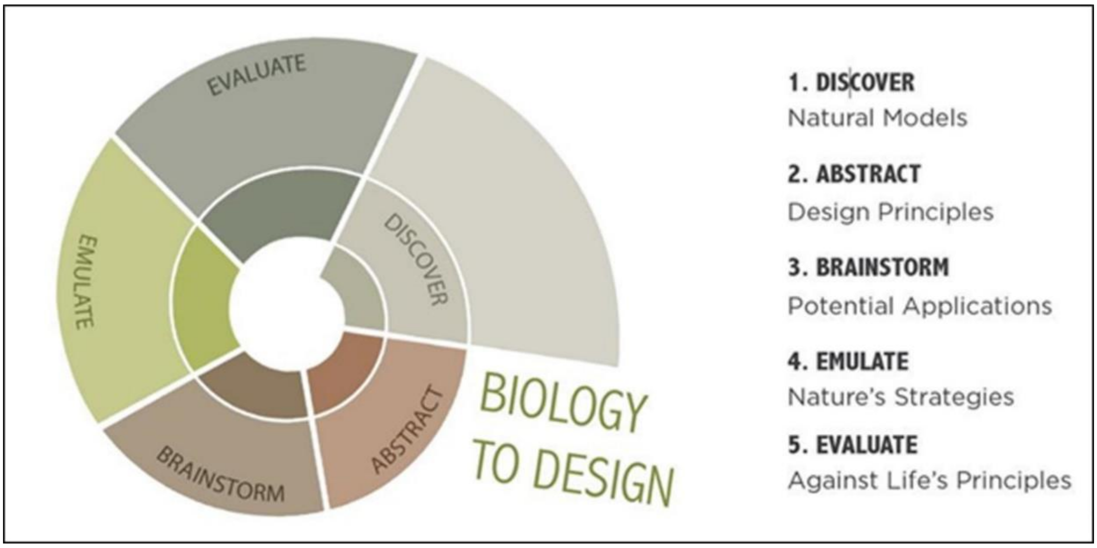


Figure 3.17. The spiral of approach from biology to design, (Lotfi, 2014)

3.1.4. Levels of Biomimicry

In biomimicry, organisms are in a hierarchical order according to their characteristics and abilities. Therefore, the process needs to be further elaborated in order to understand in which subject a particular organism is sufficient or successful. The fact that nature has an opinion on every subject, but these ideas should be separated makes it easier to reach solutions more effectively. In summary, organisms should be handled at certain levels in order to produce designs inspired by nature and to understand the solutions offered by nature more easily (Vincent, 2006).

For the solution of design problems, nature is imitated at three different levels and transferred to designs. These; organism, behavior and ecosystem levels. The names given inform the designer about which aspect or level of nature is being imitated. The organism level requires the designer to analyze how a particular organism, such as a plant or animal, works. All or part of the organism can be mimicked. At the behavioral level, the interaction or adaptation of a particular organism with its environment is imitated. It is often used to produce fully harmonious designs that do not resist its surroundings. The third level, the ecosystem level, mimics how an organism interacts with the environment along with other components. This level gives effective results in urban scale or designs with more than one component (Zari, 2018).

In addition, at each biomimicry level, there are five different dimensions that determine the extent to which mimicry occurs. A design is differentiated by how it looks (form), what it is made of (material), how it is made (construction), how it works (process) and its capacity (function) (Othmani et al., 2018). The table below was created by Zari (2018) to better understand the levels of biomimicry. (see Table 3.1.)

Table 3.1. A framework for understanding levels of biomimetic design (Zari, 2018)

Biomimicry Levels		A building that mimics termites
Organism Level (Mimicry of a particular organism)	Form	The building looks like a termite.
	Material	The building is made of the same material as a termite; for example, a material that mimics the termite's outer shell.
	Construction	Building is done in the same way as a termite; for example, it goes through various growth cycles.
	Process	The building works the same as the termite; produces hydrogen efficiently, for example, through metagenomics.
	Function	The building functions like a termite; It recycles cellulose waste and creates compost, for example.
Behaviour Level (Mimicry of an organism's behavior or relationship to its environment)	Form	The building looks like it was built by a termite; such as a termite mound
	Material	The building is made of materials used by a termite; for example using digested fine soil as primary material.
	Construction	The building is made the way a termite would build; for example, to be positioned on a certain number of land in certain places.
	Process	The building works like a termite mound; carefully, the shape, material selection and natural ventilation or mimics how termites work together.
	Function	The building functions as if it were built by termites; for example, internal conditions are arranged to be optimal and thermally stable.
Ecosystem Level (Extensive emulation of an ecosystem)	Form	The building resembles the ecosystem in which a termite lives.
	Material	The building is made of the same materials as a termite ecosystem; for example using naturally occurring ingredients.
	Construction	The building is created as in a termite ecosystem; for example, the principles of increasing complexity and succession over time are used.
	Process	The building works in the same way as the ecosystem in which a termite lives; for example, it captures and converts energy and stores water.
	Function	The building can work just as the ecosystem does and forms part of a complex system using relationships between processes; for example hydrological, carbon, nitrogen cycles etc. can join.

3.1.4.1. Organism Level

The organism level, which is the first level of biomimicry, aims to be inspired by a certain part or all of an organism found in nature. The systems, methods and actions that organisms have developed in nature for millions of years have survived to the present day. These solutions developed by organisms shed light on the problems of humans today. Organisms are able to produce many solutions for the energy problem that has been increasing in the world in recent years (Zari, 2018).

Solutions obtained by imitating only the form, shape or a certain part of organisms may not exhibit the performance of the organism as a whole. Therefore, imitating only the form of the organism constitutes the first steps of the biomimetic approach. Inspired by the form of the living thing, together with the solutions it develops as an organism, creates more sustainable designs. Today, it is observed that biomimicry at the organism level brings productive ideas with the developing technology. But these generative design ideas often communicate indirectly with the inspired organism. Solutions developed at this design level may not directly point to the living thing (Öztoprak, 2020).

At the organism level biomimicry practices are often inspired by a particular feature or part of the inspired organism rather than the whole. The approach developed at this level is an add on solution for the improvement of the built environment, rather than reconstructing the whole system. It appears as an innovative approach that will contribute to and influence the functioning of the system. With this level, sustainable and energy efficient designs can be produced by producing environmentally friendly, recyclable, smart solutions, especially in terms of material technology. For innovative and permanent solutions in energy efficient building designs, which are critical today, nature should be inspired at the organism level (Gündoğdu & Arslan, 2020).

3.1.4.2. Behaviour Level

The second of the levels, which is of great importance in the formation of biomimetic approaches in order to get more efficiency from nature, is the behavior level. This level, which plays an active role in making nature more understandable, focuses on the behavior of organisms rather than their form. At the behavioral level, the focus is on how any organism copes with the problems it encounters in nature and how it relates to its environment. Organisms living in nature are struggling with the problems they encounter within their means. Organisms engage in various behaviors for needs such as adaptation with the environment, energy needs, protection. Biomimimetic designs developed at the behavioral level are complementary to the organism level (Badarnah, 2012).

The application of biomimicry at the behavioral level brings with it important considerations. It is not possible to directly copy some behaviors developed by organisms to struggle with the harsh conditions of nature. Because the environment in which the inspired organism lives and its needs are very different from those of people. For this reason, it is necessary to be selective in the process of integrating solutions developed at the behavioral level into human life. To give an example, the living spaces that ants build underground can offer cool, safe and comfortable areas, but it would not be right to integrate this behavior exhibited by the bellies into human life. In other words, biomimetic analyzes developed at the behavioral level should be made suitable for human life (Öztoprak, 2020).

3.1.4.3. Ecosystem Level

The third level is the ecosystem and the imitation of all the systems that make up it. It is mostly used in urban scale designs. With this level, sustainable and energy efficient solutions are targeted. Biomimetic approaches developed at the ecosystem level are more complex than other levels. Because it is aimed to imitate the holistic system that coordinates each other. The ecosystem level also includes other biomimicry levels. Other levels are also used in developed designs. Another advantage of biomimicria at the ecosystem level is that it can be used on multiple scale. This level is quite suitable for creating a self -sufficient urban designs of a place. It plays an important role in serving designs for human needs and problems. Since the designs at the ecosystem level cover many systems and parameters, performance is achieved in the general context. In this context, cities should be designed more comprehensively with this level. With the biomimetic approaches developed at the ecosystem level, it should be aimed to create more sustainable, energy -effective cities by inspiring ecosystems that have existed in nature for millions of years (Benyus, 1997).

3.2. Energy Efficient Building and Envelope Design

As a result of the energy crisis in the 1970s, many of the countries dependent on foreign energy took measures on energy efficiency. Among these measures, it is aimed to reduce the current energy consumption amount as much as possible and to increase the use of renewable energy sources. The share of buildings in energy consumption is quite large. It is possible to talk about energy consumption in the design, construction, use, renewal, repair, demolition and similar life cycle of buildings. Buildings are responsible for both depleting energy resources and greenhouse gases released into the environment. It is seen that there is a huge amount of energy consumption and environmental pollution in all buildings that are not designed in an energy efficient way. For this reason, buildings should be designed in accordance with the principles of environmentally friendly, supporting renewable energy sources and energy efficiency (Çakmanus , 2004).

The most distinctive feature that distinguishes energy efficient building designs from other designs is that all components of the building are designed to minimize energy consumption. From the selection of the materials used in the building to the ventilation, lighting and heating systems to be used in the building, energy efficiency is taken as a basis. On the other hand, the building is supported by technologies that support renewable energy sources. As the amount of deviation between the environmental conditions of the building and the interior comfort expectation increases, the amount of energy required to be used also increases. In this context, the building is supported by systems that will meet its needs without much need for energy. The façades, which are like the envelope of the building, are the parts that affect the energy use the most. In order to prevent the depletion of energy resources and the increase in environmental pollution, energy-saving envelope designs are developed within the scope of energy efficiency of buildings. At this point, the design of the building envelope aims to reduce the total energy consumption of the building, generate energy, store energy and improve the level of interior comfort. In summary, based on the energy efficiency of a building, technological developments and other related disciplines should be cooperated for the design of building envelope systems, which play an important role in the efficient use of energy (Fedakar & Yamaçlı, 2022).

3.2.1. Building Envelope Design

The facades, which are the parts of the buildings in direct contact with the external environment, can be named in different ways. Concepts such as shell, sheath, membrane, skin, leather characterize the part of the building where it communicates with the interior and exterior environment. While explaining the concept of facade, different names are given for its meaning, but all of them have similar responsibilities and purposes. Building envelopes should be handled with the solutions offered by nature in line with these purposes and responsibilities (Sandak et al., 2019).

Buildings, which are formed by the combination of various parts and systems, work as a whole. This situation can be likened to the functioning of all organs and systems in a certain harmony, as in the body of animals. When examined, the similarity of animal skin and building facade system can be seen. (see Figure 3.18.) Buildings also need many systems to maintain their vital activities and meet their internal comfort needs (Sandak et al., 2019). Building envelope systems, which are in direct communication with all of these systems and with the external environment, are more important than all other systems. These systems, which have similar responsibilities with the part in the role of the outermost layer of many living things in nature, directly affect all the needs of the buildings. Building envelopes can be defined as a separate whole system that provides all the necessary features for the building by acting as a bridge between the external environment of the building and the internal environment of the building. It contributes to the improvement of the building in many aspects such as ventilation, lighting, heat and water regulation. Building envelope systems act as a carrier or as a protective layer, depending on the needs of the building. While all these are provided, they meet all demands in terms of aesthetics (Aldemir, 2014).

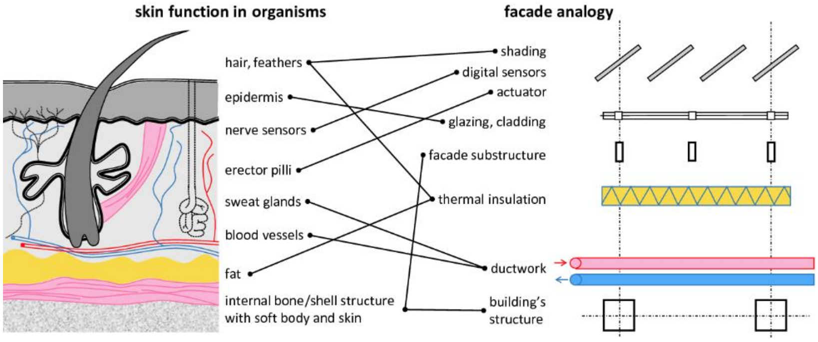


Figure 3.18. Analogy between animal skin and building facade
(A. Sandak et al., 2019)

From the beginning of a building design, its entire relationship with the building envelope system should be considered. Although the primary duty of building envelope systems is to surround and protect the building they belong to, they have many responsibilities and duties to fulfill. Today, with technological developments, it is possible to develop building envelope systems that cover all requirements. Building envelope systems meet the demands in terms of energy efficiency as well as aesthetic concerns and static requirements. When considered in a general context, facade systems should be created by considering all other systems that make up the building. During the building envelope design, solutions should be produced within the holistic needs of the building and the parameters that affect these needs. In summary, building envelope systems are a separate holistic system that differentiates according to the needs and environmental conditions of the building they belong to, and serves different functions according to the building they belong to (Knaack et al., 2007).

3.2.1.1. Factors in Building Envelope Design

Arranging all systems in relation to each other while creating the building design makes it easier for the building to reach the targeted criteria. The building is a mechanism that consists of many systems working together. The most important of these systems is the building envelope systems. Building envelope systems are in direct communication with all other systems that make up the building. In order to produce more effective and inclusive solutions, the factors affecting the design process should be well analyzed. If these factors can be resolved correctly, the contribution of the envelope system to the building will increase (Sandak et al., 2019).

The determination of the external environment-related factors of the building will bring the determination of the conditions that the envelope system must struggle with. The designs of the building envelope systems, which are the parts of the buildings that communicate directly with the external environment, are shaped according to climatic factors. Factors such as outdoor temperature, wind, humidity, and sun level are important for the building envelope system to provide a smooth transition between the external environment and the indoor environment. On the other hand, technological solutions such as solar panels, wind turbines, ventilation shafts and similar developed depending on the climate of the building's location show that the building has turned the external environmental conditions in its favor. Thus, envelope systems create environmentally compatible and sustainable solutions that support the use of renewable energy. On the other hand, factors such as air pollution and noise level may vary depending on the external environment. These factors make it difficult to meet the ventilation need of the building. As a result, all factors related to the external environment directly affect the indoor comfort of the building. The positive realization of this effect is the responsibility of the building envelope systems (Çakmanus, 2004).

Determining the factors related to the indoor environment of the building will allow the joint solution of the outdoor conditions and indoor environment requirements. In particular, ensuring the indoor heat and humidity balance, benefiting from the maximum level of daylight, and providing natural ventilation systems are the main factors that create indoor comfort. Regardless of the outdoor conditions, these factors are directly related to the building envelope system. Building envelope systems act as a bridge between interior spaces where factors such as external environmental pollution and noise are minimized as much as possible (Ricci et al., 2019).

The general purpose of all the factors that are effective in the design and application of building envelope systems is to reach the maximum level of indoor comfort despite the outdoor conditions of the building they belong to. In addition, another factor that is generally effective in the design of building envelope systems today is energy efficiency. It is aimed to minimize the amount of energy consumed in all stages, from the production of the material constituting the building envelope system to the application method, and to create energy generating systems in addition to this. In the light of developing technological developments, building envelope systems are shaped in accordance with the outdoor and indoor conditions; It should be handled with factors that directly affect the design, such as ensuring energy efficiency, protecting natural resources, supporting alternative energy sources, reducing waste and pollution, using recyclable smart materials, and producing sustainable solutions with a long service life (Dikmen, 2011).

3.2.1.2. Function of Building Envelope

A building envelope has functions to fulfill. The building envelopes, which are responsible for the building they belong to, have a wide area of influence on the building. All the parameters that they affect on the building are interrelated. Building envelope systems can negatively affect other parameters while performing any function. For example, if more gaps are opened on the surface in order for the building to benefit from natural light sufficiently, the thermal balance of the building may be disturbed. Depending on the conditions of its location, the building may either get colder or warmer during the day. For this reason, the building increases the HVAC load, allowing the building to be heated or cooled more than it needs. As a result, building envelope systems should be designed on the basis of energy efficiency in line with their functions.

In this context, the functions that the building envelope should fulfill can be listed as follows (Schittich, 2001):

- Ventilation,

- Lighting,

- Insulation (against weather conditions)

- Protection against glare,

- Privacy,

- Aesthetic,

- Security,

- Protection (against fire, mechanical damage, etc.),

- Sound control,

- Energy efficiency,

- Cost.

In addition to these, it is very important for the continuity of humanity in new functions that are a solution to today's problems such as the gradual depletion of natural resources, environmental pollution and climate change. With the developing technological developments, systems that support renewable energy sources will reduce the fossil fuel needs of buildings. Building envelope systems that can produce the energy they need, are self-sufficient, have zero carbon emissions, are environmentally friendly and sustainable should be preferred. The materials that make up the building envelope system must be recyclable and harmless to the environment. In summary, nature-sensitive building envelopes that the world offers without any compensation should be developed. These envelope systems can also be created with biomimetic approaches, inspired by nature.

3.2.1.3. Elements of the Building Envelope System

The building is a whole formed by the combination of many systems. The structure of the building, its spatial planning, technical setups, roof, façade etc. are some of the subsystems that make up a building. Of these systems, roof and facade systems are the primary parts of the building that directly struggle with the environmental conditions. These systems are very important both in the creation of the interior comfort balance and in the efficiency of the building. The envelope systems of the building have a great impact on issues such as ventilation, lighting, heat balance, water efficiency and energy efficiency. For this reason, the envelope system design of a building should be considered holistically in line with its functions, taking into account the environmental conditions it belongs to (Karamanlıoğlu, 2011).

Designing the envelope as a system provides the opportunity to construct all the components that make it up separately. The energy-efficient, high-performance building envelope design aims to bring together all the sub-components that make it up in the most efficient way. These subcomponents come together to serve the functions that the building is supposed to fulfill. Examples include windows that allow the building to benefit from daylight, doors that provide entrance and exit control, and shading elements that prevent overheating. Material selection and technological methods involved in the formation of these facade elements are also very important. Parameters such as the quality of the glass forming a window, the laths required for its assembly, insulation materials, color and shape directly affect the energy efficiency and performance of the building. All the components in the building envelope system and the decision of the materials that make them up are interrelated. Changes made in any one of them can affect the operation of the entire system. For this reason, all components must be designed in harmony with each other in the design process (Gündoğdu, 2020).

In summary, the building envelope design should be designed as a system. All components in this system should be organized according to the needs and comfort expectations of the building. Envelope systems require functionally holistic design of the components, parts and materials that make up them.

3.2.2. Energy Efficient Building Design

Energy efficient smart buildings are designed to minimize the need for natural energy resources. Instead of mechanical and electrical electronic systems, systems working with energy obtained from solar, wind and the like are preferred. In general, it is aimed to reduce the dependence on energy resources in the construction of the building, material selection, manufacturing process and in the process of its operation. In order for energy efficient buildings to be self-sufficient, it is ensured that they get more efficiency from renewable energy sources adapted to nature. The design is made by minimizing the environmental effects that will affect the energy used by the building. Steps are taken to achieve energy efficiency by developing systems that produce auxiliary formulas for tasks such as heating, ventilation and lighting, which passive systems undertake in buildings (Yılmaz, 2016). In the report prepared by the Ministry of Environment and Urbanization (Yöntem & Kılınç, 2016), the principles to be considered in energy efficient building designs are listed below:

- Positioning and shaping the building according to the sun, arranging the openings accordingly, and effective use of natural light,

- Efficiency in the use of energy and natural resources,

- Passive and active heating / cooling systems integrated into the building,

- Low CO_2 emission targets,

- Application of low carbon energy sources,

- Collecting and producing energy in the field,

- Using recycled materials,

- Sourcing materials from sustainable sources,

- Predominant use of local and natural materials,

- Minimizing waste in the construction process,

- Not using materials that cause CFC, HCFC and ozone corrosion,

- Minimal interference with natural resources,

- Indoor air quality and the use of materials that do not contain volatile organic compounds,

- Accessibility, safety and proximity to social services,

- Ecological landscape design.

When these principles are not fulfilled adequately, the building cannot be said to be successful in terms of energy efficiency.

3.2.3. Parameters For Energy Efficient Building Design

In order to talk about energy efficiency in buildings, many parameters need to be included in the design process. Paying attention to these parameters in the building design process allows the building to produce energy efficient and sustainable solutions. Thus, the design process is created on the basis of energy efficiency by considering the needs, environmental conditions and physical possibilities of the building. Within the scope of energy efficient building designs, effective parameters are examined in three different categories. These are: parameters depending on indoor needs, environmental parameters, building dependent parameters.

3.2.3.1. Parameters Depending On Indoor Needs

Whether the interior needs of a building are provided or not directly affects the quality of the environment that that building offers to the user. Regardless of the purpose of use and environmental conditions of a building, it must provide the comfort of the user. For this purpose, buildings should be created by taking into account the interior needs. During this whole process, it should be aimed that the building supports energy conservation. The energy load used for heating in the winter and cooling in the summer should be reduced to a minimum. The building should save energy by performing natural lighting and natural ventilation tasks. Considering these parameters, every design decision directly affects the energy consumption of the building. Every wrong decision taken in this process can double or triple the energy consumption of the building. Because as the amount of deviation from the comfort limits aimed by the building increases, the energy to be spent to improve the comfort level will also increase (Çakmanus, 2004). For this reason, in the design processes based on energy efficient building design, the needs of the building to improve the interior comfort should be determined in the first stages. In general, parameters such as ventilation, lighting, thermal balance and water efficiency represent the basic interior needs of the building. In the light of these parameters, the design process is developed on the basis of energy efficiency, taking into account the current conditions of the building. To summarize, energy efficiency should be considered together with the interior needs of a building. While providing interior comfort of the building, minimum energy consumption should be aimed at the same time (Šujanová et al., 2019).

3.2.3.2. Environmental Parameters

It has been previously stated that as the amount of deviation between indoor conditions and comfort requirement increases, the energy expenditure of the building will increase in direct proportion. The other parameter that affects the change in the amount of deviation in between is environmental factors. The climate and vegetation of the location of the building will greatly affect the amount of energy consumed in the building. In general, depending on the location of the building, the cooling load will increase in hot and dry climates and the heating load will increase in cold and rainy climates. For this reason, it should be aimed to absorb all conditions that will disrupt indoor comfort with minimum energy use. Other environmental factors that will directly affect the building's energy consumption are the topography of the building's location, the location of the building, the environmental landscaping of the building, and the construction texture around the building. Regardless of the outdoor conditions, the building should provide energy savings with the right air conditioning and mechanical systems. Thanks to the systems developed in the light of technological developments, it should benefit from alternative energy sources such as sun and wind according to the environmental conditions of the building. The transition of external climate and weather conditions to the interior should be softened. Areas that will act as a buffer between the building and the outside environment should be created. Facade systems that can prevent overheating caused by the sun and also support natural ventilation and lighting should be preferred. Solutions such as sunshade systems that can move according to the sun at different times of the day should be developed. In summary, the effect of environmental factors brought by the location of the building on the building should be minimized. In addition, it should be ensured that these environmental factors serve both the purpose of use and indoor comfort of the building. Thus, the amount of energy that the building needs to use will also decrease (Annunziata et al., 2016).

3.2.3.3. Building Dependent Parameters

Building dependent parameters that affect the energy efficiency of a building depend on the building's direction, shape, location, form, shell, height, spatial organization, and the like. The variability of these parameters will greatly change the total energy consumption of the building. For this reason, it should be aimed to make the existing parameters energy efficient in line with the decisions taken during the building design process. For example, let's assume that we take a unit most affected by daylight in a high-rise office building as an example. In addition to making efficient use of daylight, this office unit should also prevent the sun from overheating the building. The cooling load should be met with alternative energy sources as much as possible. In short, various solutions on energy efficiency should be brought against factors such as the spatial organization of a building, its length, for what purpose it is used, and which facade it faces. These solutions can sometimes be realized by changing the building form, and sometimes with sunshade systems that can be integrated into the building later. Along with the entire design of the existing building, simultaneous steps should be taken on energy efficiency. In this way, the building can not only fulfill its duties and responsibilities, but also save energy consumption (Gündoğdu, 2020).

3.3. Biomimetic Approach to Energy Efficient Envelope Design

The outermost layer of the buildings, where they interact directly with the external environment, is called by different names. These names generally describe the facade system that surrounds the building. In this thesis, as in the previous chapters, the term envelope is used for the facade of the building. The place of the facade or envelope of buildings in architecture and the function of the skins that cover the bodies of living things are similar to each other. The most important layer that protects the living things in nature from external conditions is their skin system. Just like living things, buildings are protected from outdoor conditions with their envelope systems and keep their interior comfort levels stable (Sandak et al., 2019). (see Figure 3.19.)

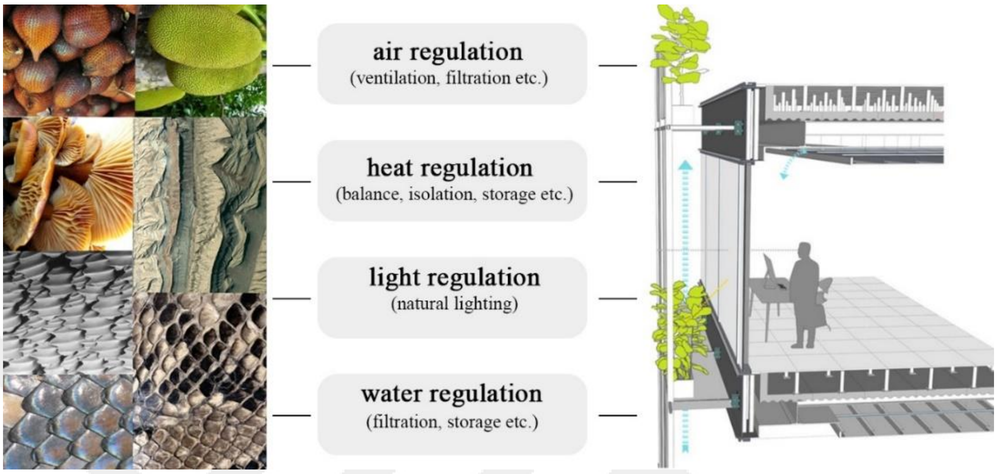


Figure 3.19. Similarity of building façade and living envelope (Adapted from A. Sandak et al., 2019)

Design processes are very important when it comes to the energy efficiency of building envelope systems. Energy efficient building envelope systems are designed with biomimetic approaches developed by nature within both environmental conditions and indoor needs. By imitating nature, various solutions are produced regarding energy consumption, as well as improving the air, heat, light and water factors depending on the interior comfort conditions of the building. The systems developed by living things that have managed to survive under difficult conditions in nature with minimum energy consumption are adapted to the building envelope systems, and it is aimed that the buildings operate in an energy efficient and sustainable way. Thus, the strategies that living things possess and develop according to conditions find an architectural response thanks to the discipline of biomimicry. In the light of these strategies, in this section, the basic principles that play an effective role in the energy efficient building envelope design are determined and examined together with the parameters that directly affect these principles (Gündoğdu, 2020).

3.3.1. Envelope Features

Architects, engineers and designers should develop building envelope systems that are versatile and environmentally friendly. Building envelope systems, which are the parts of a building that are in direct contact with the environment, should positively affect all the functions that the building needs. Like the skin systems of living things, it should both protect the building from the external environment and act as a filter. With technological developments, the most creative ideas about how building envelope systems should behave can be obtained from nature. Innovative façade systems that work like a natural skin system play a vital role in the functioning of buildings.

The design process should be detailed in order to increase the efficiency of the building envelope systems and to expand the functional area. Decisions taken on issues such as the selection of materials that make up the envelope of the building, the determination of the technological solutions developed, and the process of integration into the building contribute to the building's providing a sustainable interior comfort area and achieving energy efficiency. Generally, it should be aimed that the building envelope is compatible with nature, consists of environmentally friendly materials, contains technological add-ons that support renewable energy sources, consumes minimum energy while serving the interior comfort needs of the building, easily integrated into the building (Mohamed, 2018).

3.3.1.1. Envelope Materials

Materials developed based on biomimetic approach play a very active role especially in energy efficient building designs. These materials, which have various application areas in many disciplines, adapt to the order of nature. The materials preferred in the creation of building envelope systems, especially within the scope of architecture and engineering, are effective in improving the different aspects of the system they belong to (Al-Obaidi et al., 2017).

Smart materials are materials that can instantly react to a certain stimulus and develop different solutions to changing conditions, as in organisms and all similar living things. These smart materials ensure that the building envelope they create fulfills all of its responsibilities in a sustainable way. The ability of organisms that survive in nature to change certain properties in response to physical, chemical and environmental conditions, and to produce instant solutions according to changing conditions, inspires smart materials developed with a biomimetic approach. Smart material selections that can react to effects such as temperature change, amount of light, sun direction, wind speed, humidity and so on are one of the most basic needs of energy efficient building exterior designs. Intelligent material innovations inspired by nature are divided into two groups, physical stimuli and chemical stimuli, according to the type of stimulus. In addition, smart materials enable adaptive technologies to be included in the design according to the variability of certain parameters (Ritter, 2006).

Another feature that enables living things in nature to continue their vital functions uninterruptedly is the continuous self-renewal and improvement of the units that compose them. Just like living things, building envelope systems can renew and heal themselves without harming the environment, thanks to the choice of renewable and recyclable materials. The fact that these materials can be used repeatedly not only prevents the consumption of natural resources, but also reduces carbon emissions. Thus, energy savings are achieved in the production and renewal of the materials that make up the building envelope systems. It achieves energy efficiency not only during the operation phase of the building, but also during the construction and restoration phases. Building envelope systems can behave in the same way with recyclable and renewable material choices, just as organisms living in nature can reuse and renew the units that compose them (Radwan & Osama, 2016).

It contributes to the creation of the building envelope system, which is under construction or repair, in a way that is fast, easy and with minimum energy consumption, with the selection of accessible materials. Choosing the most logical one for the existing building and design among the local materials for the construction of the developed building envelope system positively affects the energy efficiency of the target building. For example, the use of wood material in a settlement where forestry is common saves time, cost and energy. The availability of the material is very advantageous (Herzog et al., 2012).

Finally, the selection of self-cleaning materials allows the existing building envelope to be self-cleaned in the next stages without the need for any external solutions and energy. Envelope must be self-cleaning, as are mechanisms found in nature, such as the wing of a cicada, rice leaf, and lotus leaf. The fact that the building envelopes are self-cleaning in line with the decisions taken during the design process will directly affect the energy consumption of the existing building (Liu & Jiang, 2012).

As a result, material selection of building envelope systems developed with a biomimetic approach based on energy efficiency is critical. The material decisions taken during the design process contribute to the target building's being energy efficient, sustainable and environmentally friendly both during and after the construction phase. In today's conditions, where natural resources are being depleted and carbon emissions are increasing day by day, designers, architects and engineers need to be more careful about material selection.

3.3.1.2. Envelope Techonology

In today's conditions, where natural resources are gradually depleted and carbon emissions and environmental pollution are increasing day by day, it is necessary to support building envelope designs that both produce energy and clean the air, such as photosynthesizing plants in nature. Technological developments in different fields have made building envelope systems created with a biomimetic approach more applicable (Lurie-Luke, 2014).

In the pre-design process, it is possible to examine the targeted building envelope design, to identify its deficiencies and to analyze it according to environmental conditions, with computer-aided modeling and simulation programs. Technological developments in these computer-aided programs enable the most efficient state of the building envelope system to be tested before the architectural integration and application process. In this way, the contribution of the designed biomimetic envelope system to the building will be determined beforehand. Thus, the envelope system will help the building to both meet the interior comfort needs and adapt to the external environmental conditions (Kalaycıoğlu & Yılmaz, 2019).

Technological developments, especially in materials, application techniques and smart systems, enable the targeted building envelope design to be implemented faster with lower costs. Increasing energy costs and carbon emissions can be avoided in the application and architectural integration processes of a building envelope, and more appropriate and efficient decisions can be taken. It is aimed that the building will act like a living organism with smart, innovative technologies that are sensitive to its environment and make it easier to adapt to changing conditions in the next phase of the design. Building envelope systems, especially created with a biomimetic approach, are like living organisms, in which current technological developments can be easily integrated (Al-Obaidi et al., 2017).

The fact that plants living in nature can produce energy by utilizing the sun inspires the creation and more widespread use of renewable energy sources. Biomimetic building envelope systems, designed on the basis of energy efficiency, support renewable energy systems. Within the scope of technological developments for energy production in building envelope systems, it is aimed to integrate mechanical and electronic systems that convert solar and wind energy into various types of energy into the existing design. Thanks to innovative inventions such as photovoltaic systems, solar collectors and wind turbines, the building is able to produce energy on its own without harming the environment and consuming natural resources. Equipped with innovative technological developments, biomimetic envelope systems produce sustainable solutions for the building both in terms of energy efficiency and benefits to the environment (Karamanlıoğlu, 2011).

3.3.1.3. Envelope Integration (Adaptivity)

Energy efficient building envelope systems are an important part that requires the control of parameters such as light, heat, air and water, as well as other systems in the building. The adaptive design of building envelope systems aims to adapt the existing building system to changes in environmental and interior conditions through sensors, software and smart systems. Associating technological developments with the harmony of living things in nature with their environment contributes to the creation of sustainable, adaptive building envelope systems. It is expected that the designed building envelope system will adapt to both the existing building and its surroundings.

Building envelope systems should adapt to the interior comfort needs, function, and static and mechanical systems of the building to which they will be applied. The condition of the existing building should be evaluated and the design process of the building envelope system should be carried out in that way. It should not be forgotten that the envelope system is one of the most important parts that surrounds that building. If the design process is continued by considering the building and the building envelope together, full efficiency will be achieved in terms of energy savings and interior comfort level. In summary, the envelope systems in question should be created according to all the conditions of the building where they will be applied. An efficient envelope system should be created between the building and the environment by developing easy and applicable solutions in the architectural integration process. On the other hand, adaptive building envelope systems also express the relationship of the existing building with its environment. Envelope systems, in which the building interacts directly with its environment, are of great importance in terms of adaptation. The building envelope system developed with the integration process should also have an adaptive approach towards its environment. With this approach, building envelope systems turn into a system that produces solutions for many parameters instead of only responding to building needs. Adaptable building envelopes aim to create minimum waste and consume energy depending on the changing conditions (weather conditions, temperature changes, daylight differences, humidity changes, wind direction, etc.) outside the building and the changing conditions (occupancy rate, changes in building usage, different comfort demands of users at different times of the day, etc.) inside the building. As a result, the designed building envelope system must exhibit an adaptive stance during and after the integration process. Thus, energy efficient, environmentally sensitive and sustainable solutions can be developed (Al-Obaidi et al., 2017).

3.3.2. Energy Efficiency

In general, energy efficiency aims to reduce energy consumption without affecting the interior comfort level of building users. It can be defined as minimizing the energy consumed without compromising the performance level, quality and comfort areas (Knapp & Wagner, 2009).

The energy efficient approach helps to protect natural resources by making maximum use of renewable energy resources. This approach supports the use of renewable energy resources by preventing the natural resources that are being depleted day by day in today's conditions and the harmful gases that arise as a result of the energy obtained from these resources. In this way, buildings that are self-sufficient and meet their energy needs without harming the nature can be obtained (Tokuç et al., 2018).

On the other hand, energy efficiency is encountered during the construction phase as well as the general functioning of the buildings. It aims to minimize energy consumption in all other stages, such as the production and assembly of materials to be used in buildings, and not to harm the environment as much as possible. In summary, it is possible to talk about energy efficiency in all vital phases of the building such as construction, operation and repair (Zigenfus, 2008).

In the light of this information, energy efficiency can be defined as the ability to minimize energy consumption for everything that requires energy. Evaluating the envelope systems, which have the most responsibility for energy consumption in buildings, on the air, heat, water, light and energy parameters directly related to energy consumption will contribute to the development of energy efficient building envelope.

3.3.2.1. Air

Ventilation systems used in buildings in recent years aim to increase indoor air quality and comfort with minimum energy consumption. Air quality in buildings is very important. The indoor air quality expectation may change depending on the purpose for which the building is used. In general, mechanical systems or natural ventilation solutions are used to improve indoor air quality. Although natural ventilation solutions are lucrative in terms of energy efficiency, they have some challenges. In buildings that are naturally ventilated by utilizing the pressure and wind difference between the outdoor and indoor environment, the incoming air must be constantly filtered and kept under control (Badarnah, 2012).

In today's conditions, ventilation is generally provided by the windows on the facade of the building. In addition to ventilation, these window openings make it easier for the building to heat up by making more use of sunlight in winter and to cool down in summer thanks to the air flow. Airtight systems that prevent air flow are used in building envelope systems designed on the basis of energy efficiency in order to keep the indoor air quality stable and to consume less energy. Thus, mechanical ventilation systems are used inside the building, since the air passage between the indoor and outdoor spaces is cut off. With mixed systems in which mechanical systems and natural ventilation solutions are used together, the ventilation need of the building is handled more efficiently without affecting other parameters (Liddament, 1996).

Buildings have to breathe just like living things in nature. As important as air is for living things, it is indispensable in buildings. Just as most organisms in nature can continue their vital functions by needing air, they need air for the air needs and comfort of their users in buildings. For this reason, energy efficiency-based ventilation strategies are created, especially in the envelope systems of buildings. These strategies can be made more effective with hybrid solutions, inspired by living things that meet their air needs by developing both passive and active systems in nature (Gündoğdu, 2020).

3.3.2.2. Heat

Building envelope systems aim to create a heat balance by acting as a buffer between the indoor and outdoor environment. Building envelope systems developed within the scope of energy efficient building designs reduce the heating and cooling costs used in the interior. Physical changes such as air temperature, exposure time to the sun, wind and humidity directly affect the thermal comfort of the building. Depending on the change in outdoor conditions, the energy costs of the building also change. Generally, mechanical systems that consume a lot of energy are used in buildings to create thermal balance for the comfort of users. These include air conditioners, radiators, etc. systems are examples. From this point of view, it is understood that a building envelope system should be a system that creates a balance between the external environment and the interior environment and produces solutions, rather than a layer that protects the building from the external environment (Kingma & Lichtenbelt, 2015).

Living things in nature have developed many strategies to keep their body temperature in balance in response to the conditions in which they live. Heat regulation and balancing solutions that will inspire building envelope systems should be inspired by these living things. While some living things develop strategies to keep more heat, some living things have developed strategies to cool off. To give an example, the fat layer and blood circulation mechanisms under the penguins' skin enable them to live in harsh cold climate conditions. On the other hand, camels protect their vital organs from the desert heat by absorbing the excess heat in the fat stores they keep in their bodies. From this point of view, regardless of the environmental conditions, the building can be kept in thermal equilibrium thanks to the solutions to be produced by the building envelope systems. In this way, the need for mechanical systems that require energy consumption is also reduced (Mazzoleni, 2013).

3.3.2.3. Water

In today's conditions, water efficiency is very important. Accessibility to water is decreasing due to factors such as global warming and the increase in the world's population day by day. For this reason, in addition to the efficient use of water in building designs, various systems such as water supply, wastewater treatment, rainwater collection should be developed. In general, new strategies should be created in order to use water efficiently in building designs.

All organisms found in nature are composed of water. Water is very important for the continuity of life. Living things have developed many systems related to water in order to continue their lives. First of all, organisms that develop very sustainable strategies for the supply of water and the protection of the water obtained afterwards, provide inspiration for the use of water in buildings created within the scope of energy efficient building design. Although 70% of the world is covered with water, it is necessary to be very careful at the point of supply of drinkable fresh water (Mazzoleni, 2013).

3.3.2.4. Light

Buildings are exposed to different amounts of sunlight during the day. This causes the buildings to both overheat and receive uncomfortable daylight. In order to prevent this, buildings have to consume more energy both for lighting and to provide thermal comfort. For this reason, regardless of the environmental conditions in which the building is located, it should be illuminated naturally without being exposed to excessive daylight. The amount of energy consumption of the building should be reduced by making maximum use of sunlight and realizing minimum energy consumption (Badarnah, 2012).

Light, which is very important in terms of indoor comfort in buildings, can be controlled by systems developed during the design of the building. Sustainable strategies can be developed at the point of natural lighting, both with the shading and sunshade systems developed outside the building, and by changing the parameters such as the size, material, angle, transparency and reflectivity of the glasses used on the facade of the building. Living things in nature also produce many solutions such as collecting, reflecting, focusing, refracting and so on in order to benefit from the light in the most efficient way. Depending on the location of the building and its position relative to the sun, inspiration should be drawn from the solutions developed by living things in nature. In building designs developed within the scope of energy efficient building design, it should be aimed to use light efficiently. For this purpose, sustainable solutions should be developed. Thus, the energy consumed by buildings for lighting during the day should be reduced (Gündoğdu, 2020).

3.3.3. Energy Efficient Envelope Design Principles

With regard to the building envelope systems developed within the scope of energy efficient building designs, the targeted efficiency is achieved with the biomimetic approach, together with the strategies and technological developments obtained from nature. The discipline of biomimicry, which makes imitating nature a teaching, provides various opportunities for architects and designs to direct their designs. With the biomimetic approach, organisms that have managed to survive in harsh conditions for millions of years are of great importance in terms of integrating the accumulation they have acquired into today's building designs. All analyzes and tests of the building envelope system, which is designed with computer-aided modeling and simulation software, are seen before the implementation phase. Both the wisdom of nature and the developments in technology have facilitated the design process of energy efficient building designs. In this way, architects and designers can create a envelope design that protects and supports the building with certain principles, rather than a shell that surrounds only the exterior of the building. While increasing the efficiency and comfort of the building on light, air, heat, water and energy parameters, it also aims to work on the following principles:

-Sustainability

-Responsibility

-Functionality

-Recyclability

-Renewability

-Sensitivity

-Indoor Quality

Building envelope systems, created with a biomimetic approach inspired by nature, enable the building to live like a living thing in the company of these principles. Just as a living thing can adapt to the difficulties in its own habitat, the building becomes adaptable to its environment thanks to its biomimetic envelope. As a result, buildings are improving in terms of comfort, energy efficiency and working principle (Mohamed, 2018).

CHAPTER 4
METHODOLOGY

In this chapter, the methodology of the study, the general configuration of the study, the test box, the design approach, the envelope system (shading device) and the tools used in this study are explained. Briefly, the study begins with a test box generative model simulation. It continues with the simulation of the envelope system (shading device), which was developed with a biomimetic approach and can be integrated into the building later. Production continues until the solution set consisting of various variations of the developed biomimetic system is created. Then, the models in the solution set are evaluated separately. The flow chart of the study in detail is shown below in Figure 4.1.

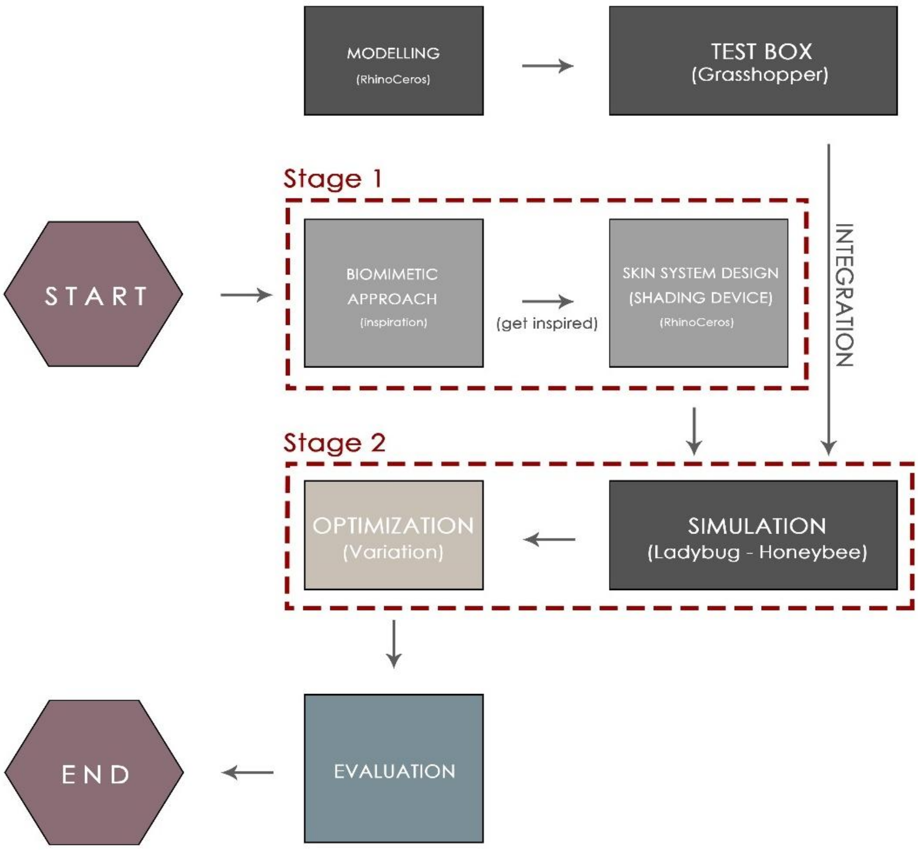


Figure 4.1. Flow chart about the methodology

In this study, a test box with features that will be explained later is used. This test box is an office space in Doha, Qatar, located east of the Arabian Peninsula in the Asian continent. According to Köppen Geiger Climate Classification seen in Figure 4.2. the climates are divided in 5 groups which are A(temperate), B(arid), C(temperate), D(cold) and E(polar). Doha's climate type is BWh which is hot desert climate according to Köppen Geiger Climate Classification. The hot desert climate is dominant in Doha, where summers are dry and humid, and winters are mild and less rainy (Beck et al., 2018). While summers in the Doha region are long, sultry and hot, winters are comfortably dry and windy. The temperature normally varies between 14°C and 42°C throughout the year.

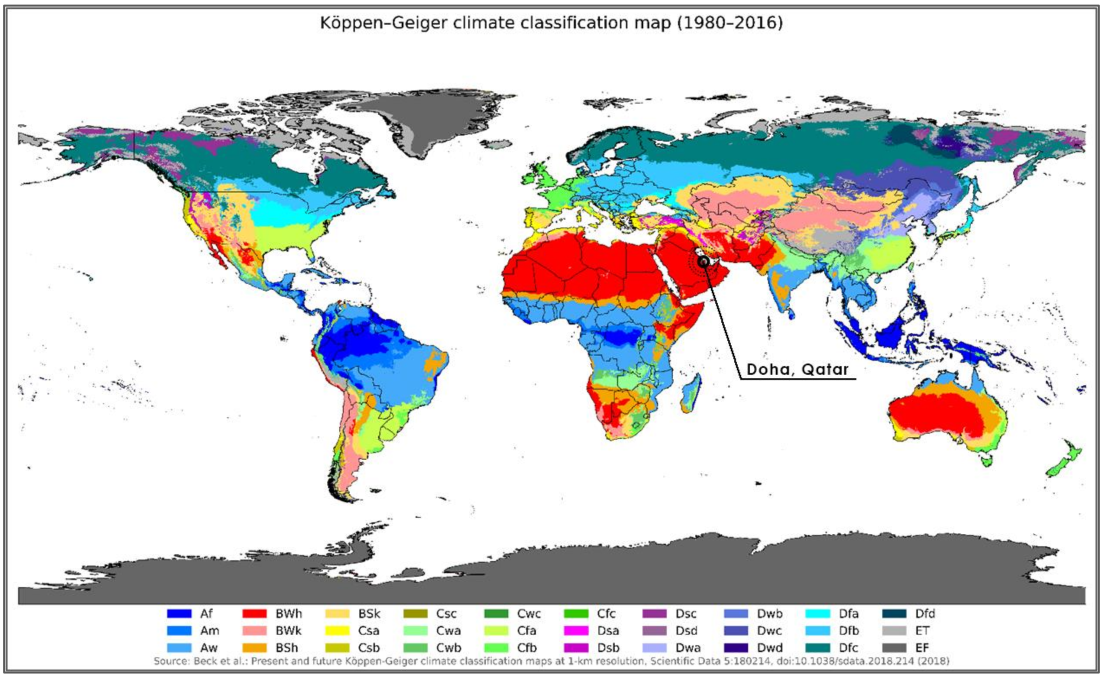


Figure 4.2. Global Köppen-Geiger Climate Classification (1980-2016)

The test box is rectangular, with a width of 10 meters, a depth of 5 meters and a height of 5 meters. The south-facing test box has a large window opening for maximum daylight. The test box has a window size of 4.7 meters high and 9.6 meters long. On the other hand, the need for protection from excessively hot. Because Doha, Qatar has scorching heat and uncomfortable sunshine. Thus, the developed envelope (shading device) will be tested under the most difficult conditions. The simple simulation view of the test box is given below in Figure 4.3.

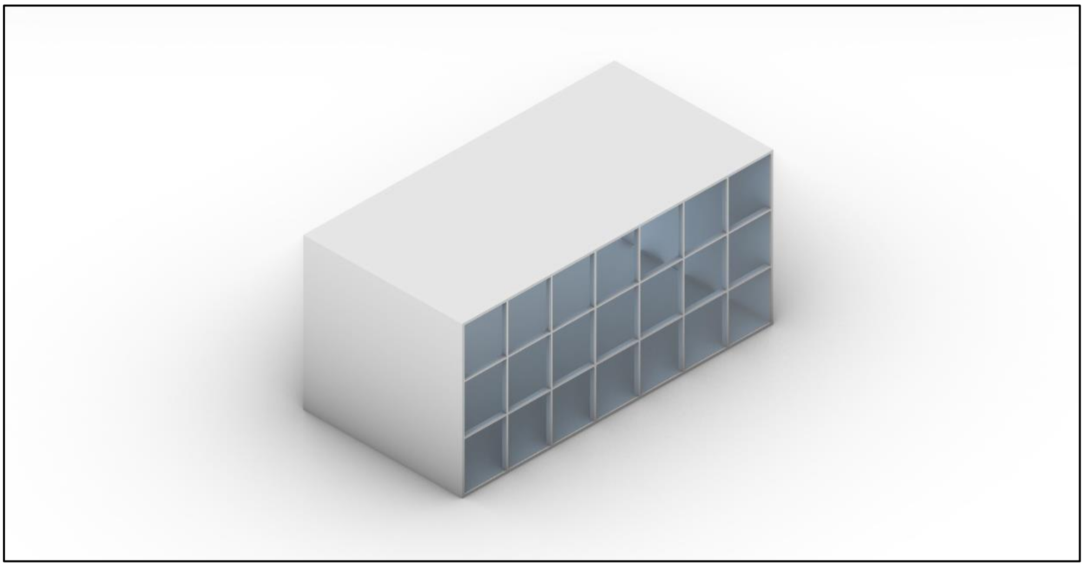


Figure 4.3. Test Box

After determining the direction, dimensions and location of the test box, it was decided for what purpose the test box would be used. The zone program was chosen as an open office because many people spend their time at work during the day. In summary, the office unit located on the south-facing facade of a high-rise office building was accepted as the test box. Some measures are taken to protect the comfort of both employees and other users in office spaces. However, due to the location, orientation and function of the test box, two important factors that affect indoor comfort in a good way are in conflict with each other. Office spaces must be adequately illuminated. In order to reduce the amount of energy consumed by the building for lighting, it should benefit from daylight as much as possible and stay away from artificial lighting sources. On the other hand, in Doha, which has an extremely hot climate, the sun indirectly heats the interior of the building. For this reason, the building has to consume more cooling energy. The challenge here is to efficiently naturally illuminate the test box, the office unit, while at the same time minimizing the cooling load.

An environment that can be analyzed can be created by transferring the weather data of any region to the simulation tools. With the hourly air temperature and sky data of the region, a measurable model simulation close to reality can be provided. Grasshopper is an EnergyPlus based program, the weather data of Doha in EnergyPlus is used as the input climate data for the simulations. According to ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers), Doha's climate zone is 3D.

EPW data were used in this study. The EPW file is a saved weather data file in the standard format used by EnergyPlus energy simulation software. EPW data is regulated by the World Meteorological Organization. EPW weather data of Doha, Qatar was integrated into the simulation and a realistic environment was created on the computer.

The most important component of the building on energy efficiency is its facades and the shading systems integrated into these facades. These systems, which directly affect the energy consumed for both lighting and cooling, also keep the energy consumption of the building in balance. This study aims to find the most efficient form of the biomimetic envelope system inspired by nature in order to improve the indoor comfort and balance the energy consumption against the extreme environmental conditions of the building. This shading system, which was developed by being inspired by living things with habitats similar to the environmental conditions in which the building is located, has decision variables such as the opening angle and the number of layers. For this reason, a solution set was created from the combinations of these decisions with each other within the limits. All variations within the solution set will be evaluated and analyzed, and the most efficient one will be determined.

In the later parts of the study, a total of six different variations were created as a result of crossing three different opening angles (30, 60 and 90 degrees) and two different ETFE layer numbers (single and double layer) options in the envelope system (shading device) developed with a biomimetic approach. These variations were compared among themselves. In addition, the test box was evaluated without any envelope system. The effectiveness of the biomimetic envelope system (shading device) developed from this point of view was also determined. The details, design process and variations of the energy efficient envelope system created with the biomimetic approach will be explained in the following sections. All biomimetic envelope design variations and test box Doha, Qatar are simulated using EPW data. The skeletal structure of the envelope system, which has different variations as a result of variable decisions, the way it is attached to the test box, and the geometry of the test box it is integrated into do not change. The general structure of the simulation and the data used are preserved in all variations.

The geometry and variations of the biomimetic envelope system are evaluated after they are created. This evaluation is about examining the contribution of all types in the created solution set to the building in terms of daylight efficiency and cooling load. As a result of these examinations, the most efficient one among all compared types is determined and interpreted. It should be noted that each type of building envelope system differs from each other with the changes in the opening rate and the number of ETFE layers.

The methodology of this study is described in detail below. This methodology is divided into five main sections, namely tools, test box, biomimetic envelope system (shading device), simulation settings and simulation outputs, respectively.

4.1. Tools

Increasing building energy efficiency has become one of the important issues in recent years. The common goal of architects, designers, researchers, developers and engineers is to minimize the amount of energy consumed in buildings. For this purpose, many simulation and evaluation tools are being developed with technological advances. Thanks to these tools, buildings can be designed energy efficient with certain tests and analyzes.

In order for the simulation programs to work properly and produce the desired results, the building or test model must be carefully created in the program. A lot of data is needed to create the building model. These data completely determine how detailed and realistic the simulation will be. Many data such as the form of the building, materials used, climate and weather conditions, lighting products, furniture, user profile and so on can be mentioned. However, the desired data for the targeted simulation is selected (Kalaycıoğlu & Yılmaz, 2019).

In this study, first of all, the basic structure and form of the test box was created with the computer aided modeling and design program Rhinoceros 3D and the Grasshopper software, which is an add-on. According to the studies in the literature, Grasshopper is one of the energy simulation tools with the highest potential in terms of compatibility with other programs and ease of creating various geometries (Dal et al., 2023). Grasshopper is an algorithmic design tool for the Rhinoceros 3D modeling program. With Grasshopper software, it can simulate user models more effectively. Thanks to the handy interface it offers, it makes it easier for the models to reach the desired target.

Secondly, the simulation of the envelope system (shading device) integrated into the south façade of the test box was also done in Rhinoceros 3D via Grasshopper. Ladybug-Honeybee tools, a Grasshopper add-on, provide energy simulations for models of various purposes. Ladybug-Honeybee plugins are compatible with many simulation programs such as EnergyPlus, OpenStudio, Daysim, Radiance. With the EPW data transferred into Ladybug-Honeybee vehicles, the test box and its surroundings bear the regional characteristics of Doha, Qatar. In addition, the simulation tools are adjusted according to the office function of the test box. Thus, simulation outputs give results close to reality. All programs and software used in the simulation design process are given in detail in the chart below in Figure 4.4.

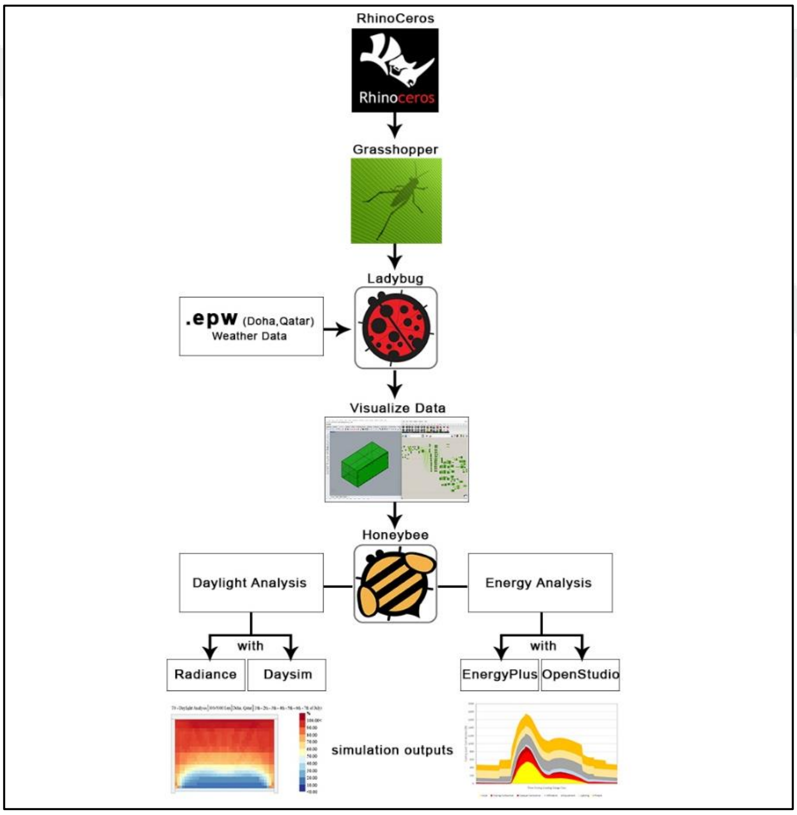


Figure 4.4. Simulation Tools Chart (Adapted from Xu et al., 2020)

Finally, the analysis outputs of the simulations obtained are converted into graphics by the Microsoft Excel program, which is a spreadsheet program. In this way, the results can be compared and interpreted through graphics. Thus, all the tools that are preferred and used from the beginning to the end of the simulation help the targeted analyzes and tests to give accurate results. A sample image of the interfaces of Rhinoceros and Grasshopper programs in the development process of this study (simulation model) is given below in Figure 4.5.

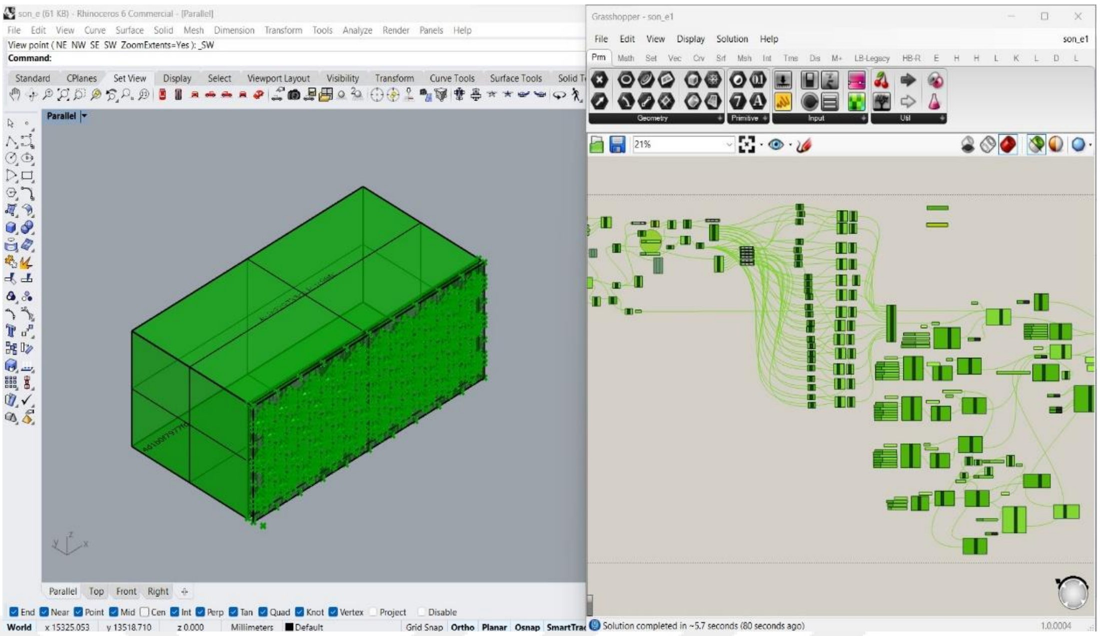


Figure 4.5. Sample Image of the Simulation Model Process

4.2. Test Box

The test box has a length of 10 meters, a depth of 5 meters and a height of 5 meters. This test box has 50m^2 of office space and is located in Doha, Qatar. During the study period, glass facade material and other wall, floor and roof materials on the south side of the test box will not be considered a research priority for the test box. The priority of this research is to examine the potential of the building envelope developed for the south façade of the test box on test box simulation (energy/daylight). The focus will be on the inspiration, material selections, design process and variable decisions of the envelope design being developed. Therefore, the materials used in the test box are not included in the solution set creation and development process, depending on the scope and limitations of the research. For this reason, the building materials were selected from the ASHRAE 2005HOF Materials in the EnergyPlus building materials library.

The glass façade, located on the south side of the test box that receives the most light, is very important for analyzing the potential of the developed envelope system. It should be noted that the test box receives daylight only through this glass facade. In the light of all these, double-clear glass facades, which are generally used in office buildings, were preferred. In addition, this glass material has been used in many types of research and all its values are available for simulation. Detailed information of the glass material used on the south façade of the test box is given below in Table 4.1.

Table 4.1. Test Box Specifications – Window (EnergyPlus Library)

Material Type	Thickness (mm)	U Value	SGHC Value	TSOL Value	TVIS Value	Simulation
Window (Double Clear)	3mm Clear 13mm Air 3mm Clear	2.556	0.764	0.705	0.812	Energy & Daylight

The other construction materials used were selected in accordance with the climate zone where the test box is located so that the envelope system produced can be simulated and analyzed effectively. These materials are walls, roof and floor. The detailed information of the construction materials used in the test box is given below in Table 4.2.

Table 4.2. Test Box Specifications – Construction Materials (EnergyPlus Library)

Material Type	Thickness (cm)	Orientation	Material Name For Energy Simulation	Material Name For Daylight Simulation	Simulation
Wall	20	South-North West-East	ASHRAE 189.1-2009 Extwall Clımate zone 3	Exterior_Wall	Energy & Daylight
Floor	15	Down	ASHRAE 90.1-2010 Attıcfloor Clımate zone 3 Semiheated	Interior_Floor	Energy & Daylight
Roof	15	Up	ASHRAE 90.1-2007 Extroof Clımate zone 3 Semiheated	Interior_Ceiling	Energy & Daylight

There are some points to be considered in the modeling and simulation processes of the test box. In order for Grasshopper and the software in it to work effectively, some requirements must be fulfilled. Ladybug-Honeybee requires a closed zone to analyze the energy performance of the simulations. For this reason, the geometry of the test box is created with the Grasshopper box component. In general, a large part of the southern façade of the test box is the glass façade. The other sides of the test box is wall material, the lower part is the floor, and the upper part is the roof. In addition, there are RAD materials that use a color picker program to calculate the reflections and give the physical properties of each color used. RAD Materials show the color of surfaces using RGB Reflectance values. These RAD Materials, which are important for daylight simulation, affect the accuracy of the analysis. For the test box, the walls are white and the floor and roof are cream colored. Since Doha, Qatar has an extremely hot climate, light colors are preferred. A sample image of this color selection tool is given below in Figure 4.6.

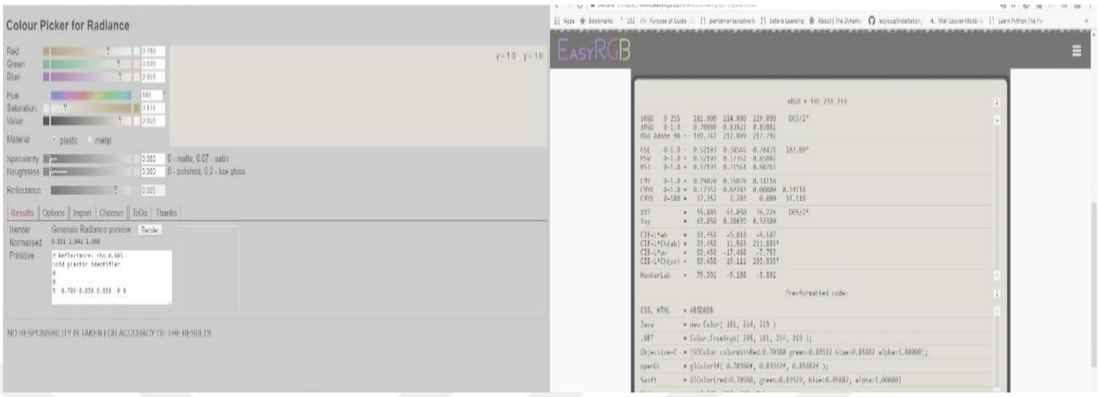


Figure 4.6. Color Picker Tool For Construction Radiance Materials

4.3. T0 - Base Geometry

The test box described in detail above is named T0. The test box is simulated as closed so that energy and daylight analyzes can be made. It has a flat and clear rectangular geometry. In the next stages of the study, the test box will be referred to as T0 in the analysis outputs and comparative evaluations. T0 is the non-integrated variation of the developed biomimetic envelope system. It will be effective in analyzing the performance of the developed biomimetic envelope system (shading device). The T0 state of the test box is shown below in see Figure 4.7.

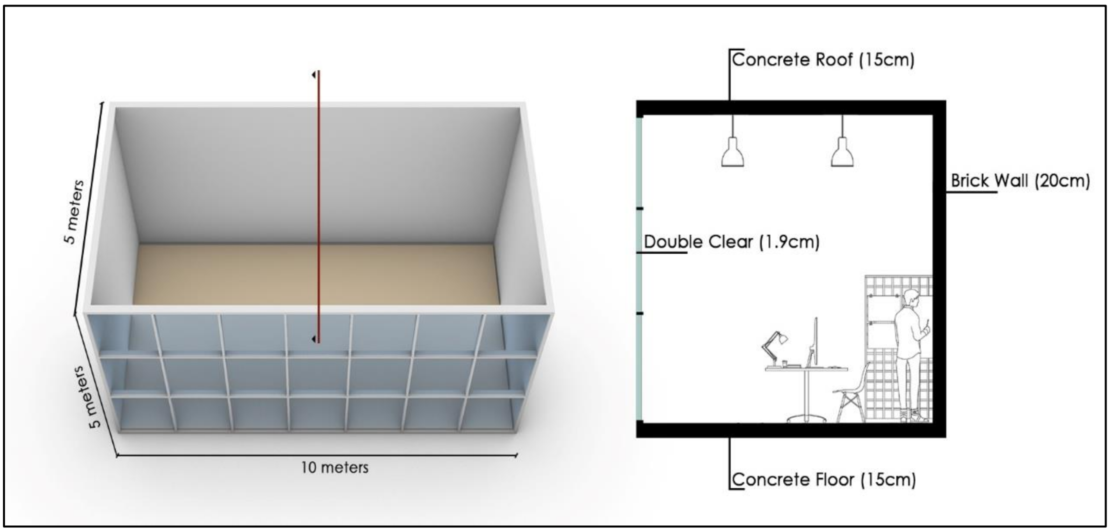


Figure 4.7. T0 – This is the simplest version of the test box.

4.4. Building Envelope System (Shading Device)

At this stage of the study, an envelope system (shading device) suitable for the south facade of the test box was developed. This envelope is the focus of the study, as stated in the previous sections. For this reason, a design process that comprehensively addresses the development of the envelope system is proposed. This design process consists of two stages. The first stage is on the design proposal developed with the biomimetic approach in a general context. At this stage, a biomimetic envelope system (shading device) was developed, inspired by nature, that is energy efficient, comfortable for the user, sustainable and will contribute to the building performance. The second stage is a continuation of the first stage. At this stage, the ground was prepared in order to analyze the effect of the envelope system (shading device) developed in the general context on the test box. It aims to test the design with various simulation and computation tools in the computer environment within the scope of the architectural integration process. The envelope system (shading device) developed for this purpose was diversified and a solution set was created to determine the most optimized state of the design comparatively.

4.4.1. First Stage – Design Process with Biomimetic Approach

The first stage of the design process is the discipline of biomimicry which is instrumental in drawing inspiration from the systems of organisms that have proven their existence and vitality despite the harsh conditions in nature in order to produce more sustainable and efficient solutions. Organisms living in nature develop permanent methods for the difficulties and problems they encounter with minimum energy consumption without harming their environment in their struggle for vitality. Biomimicry offers many opportunities to transfer these methods to our daily lives. Basically, if any organism living in nature can maintain its vital functions and make it a principle to use energy resources efficiently, this systematic cycle can be integrated into building designs. With the discipline of biomimicry, systems and methods in nature can be imitated on form, material, construction, process and function issues for the design of envelope or facade systems, which are the most important structural elements of buildings. The steps to be taken in the first stage within the said design process are given in detail in the flow chart below in Figure 4.8.

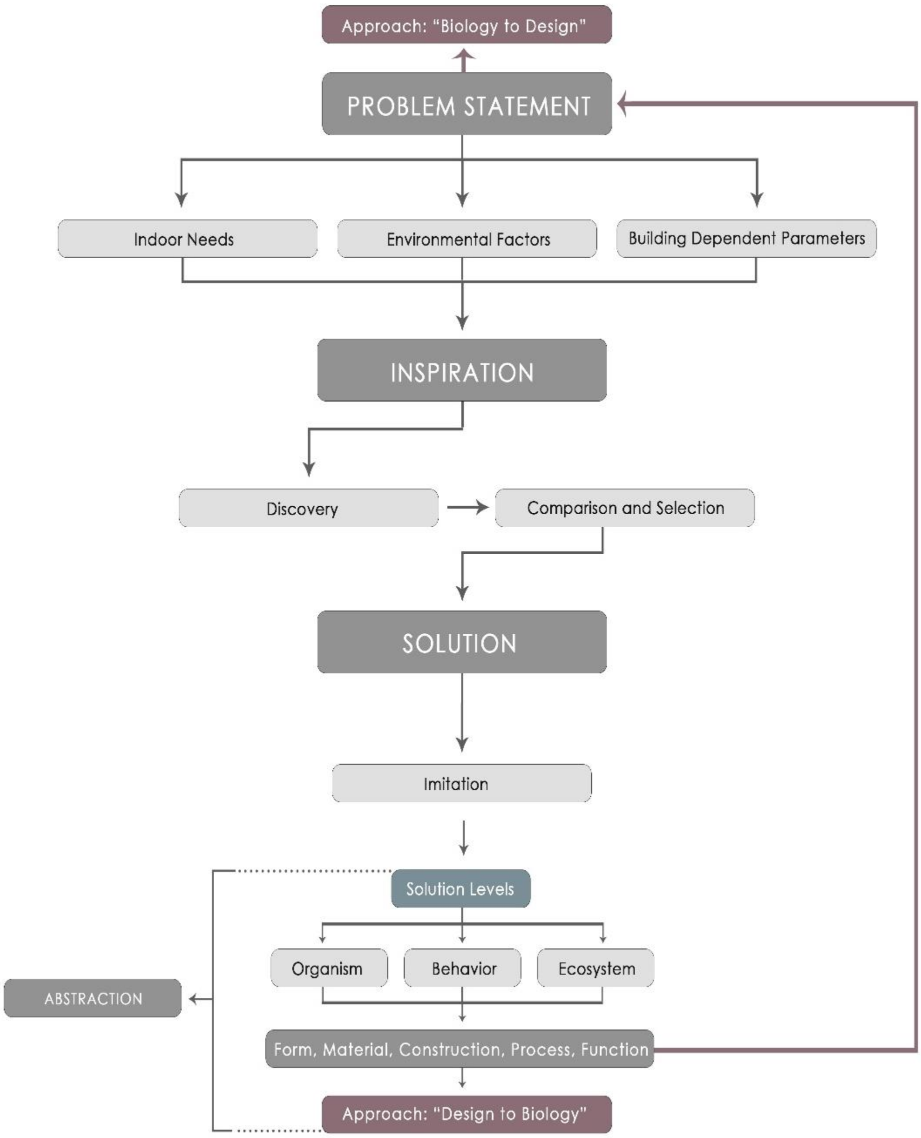


Figure 4.8. Flow chart about the first stage

4.4.1.1. Problem Statement

Meeting the indoor needs of the office unit (test box) located on the south façade of a fictional high-rise office building in Doha, Qatar is very important for user comfort. In general, the interior requirements of office spaces are about users being able to move efficiently and comfortably while performing their work. In order to increase work efficiency and satisfaction in offices, there is a need for an office design that can meet the needs of users. Because nowadays, people spend most of the day in work areas such as offices. For this reason, office spaces should offer comfortable indoor environments that are suitable for work ergonomics and human health, regardless of the outdoor conditions.

One of the most important indoor comfort needs in office spaces is lighting. Lighting is an indispensable requirement for office workers, customers, visitors and all users in general. For this reason, there are more glass surfaces in office function buildings in order to benefit more from the natural light source, the sun. Meeting the need for natural lighting in extremely hot regions such as Doha, Qatar also brings other problems. In particular, the fact that the test box is located on the south side of the office building makes the situation extremely difficult. Because uncontrolled excessive daylight and large glass facades cause problems such as unbalanced heat, light, shade, humidity and humidity in the space. To summarize, daylight must be taken into the office unit (test box) in a controlled manner. (see Figure 4.9.)

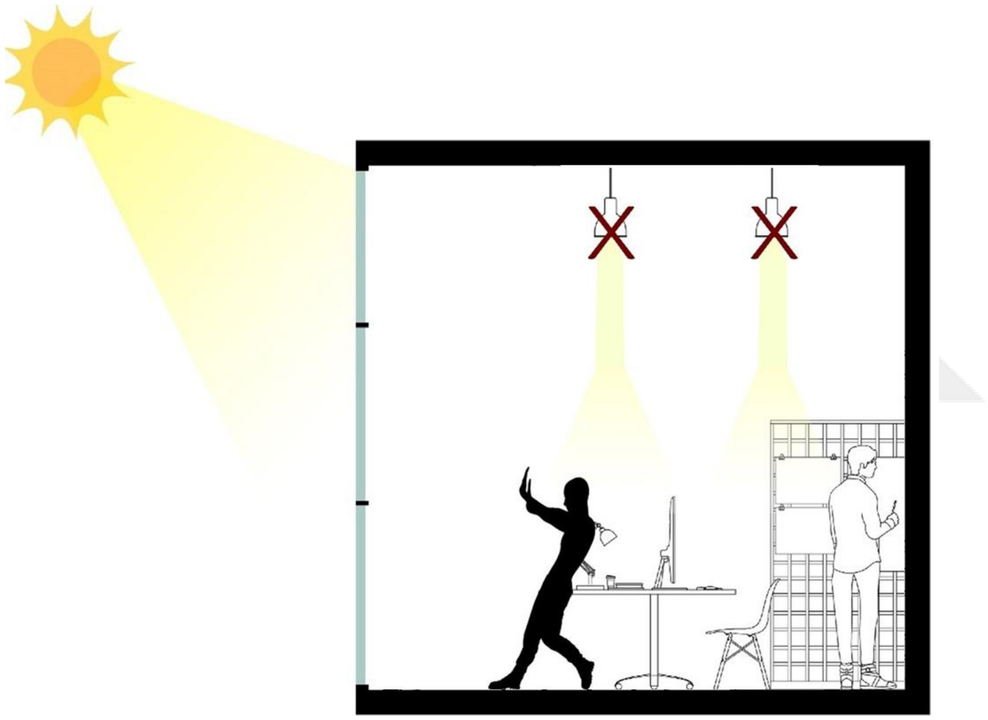


Figure 4.9. The importance of controlled natural lighting

Another parameter affecting the indoor comfort of the test box in Doha, Qatar, within the scope of the research is heat. Office units located in extremely hot climate regions such as Doha, Qatar become uncomfortably hot when exposed to intense sun during the day. For this reason, the indoor temperature is tried to be brought to a normal level with mechanical cooling systems. The greater the difference between the outdoor temperature and the indoor temperature suitable for working conditions under normal conditions, the building consumes energy in direct proportion. This is also true in cold climates. For this reason, based on the test box, in office buildings located in extremely hot climates, some systems should be developed apart from the existing building systems in order to ensure that the users have an efficient indoor temperature. In summary, the test box located on the south façade of the office building in Doha, Qatar should not be exposed to excessive solar radiation. (see Figure 4.10.)

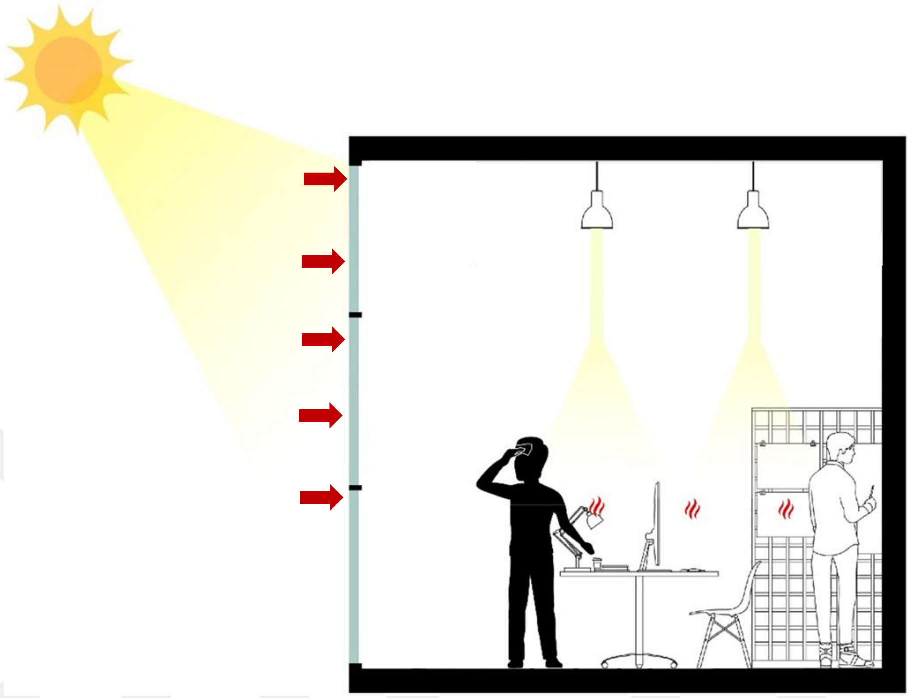


Figure 4.10. The importance of controlled solar radiation

Another important indoor comfort requirement in office spaces is ventilation. Users need fresh air in order to feel comfortable and to get efficiency from their work. The decrease in oxygen, which is one of the essential needs for life, in the environment causes a decrease in the health of the users, and on the other hand, the working efficiency. Although this need is met with mechanical ventilation systems in high-rise office buildings, natural ventilation is more efficient. Mechanical systems both increase the energy consumption of the building and the desired air quality cannot be achieved. Considering the test box, natural ventilation of buildings in residential areas with high humidity and temperature levels such as Doha, Qatar brings other problems. If ventilation is not done in a controlled manner, indoor temperature and humidity may increase. For this reason, controlled ventilation is of great importance. (see Figure 4.11.)

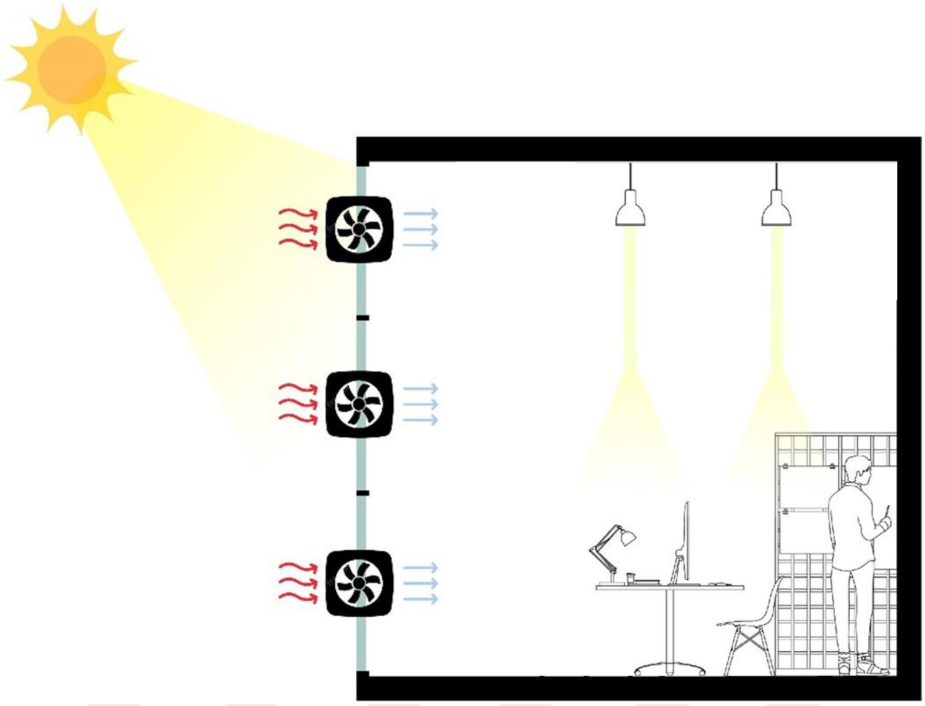


Figure 4.11. The importance of natural ventilation

In today's conditions, besides lighting, ventilation and heat parameters in buildings, water is also very important. Fresh water resources are depleted due to increasing environmental pollution and global warming. This makes it difficult for living things to access water, which is their basic need for life. This situation becomes very important in regions such as Doha, Qatar which are extremely hot and have low annual rainfall. This situation can be improved with systems such as recycling of waste water used in the building and collection of rain water, albeit a little. On the other hand, the humidity rate is quite high in Doha, Qatar. In the light of this situation, the possibility of using the humidity in the air to cool the building can be considered, apart from the traditional methods taken for the efficiency of water.

As a result, meeting the indoor environment needs of a building directly affects the indoor environment quality offered by that building for its users. In particular, the office building, which is located in an extremely hot climate such as Doha,Qatar needs to provide indoor environment quality to its users despite the hot climate conditions. Within the scope of this whole process, the energy saving of the existing office building should be taken into account. The energy used for cooling during most of the year should be kept to a minimum. The test box, that is, the office unit, has to fulfill the duties of natural lighting and natural ventilation. Considering all these, it should not be forgotten that every decision taken affects the amount of energy consumption of the building. In the light of all these, the interior needs of the building were determined in advance within the scope of the process developed on the basis of energy efficiency in this study. In the next stages, the biomimetic envelope system (shading device) developed on the basis of energy efficiency is aimed to improve the interior comfort of the imaginary office building in Doha, Qatar as well as to reduce the energy consumption of the building. In general, the focus will be on lighting and cooling, where the building consumes the most energy. Considering the location, function, environmental conditions and physical characteristics of the building where the test box is located, the report outputs of the problem statement phase, which is the first step in the design process, are shared below in Figure 4.12.

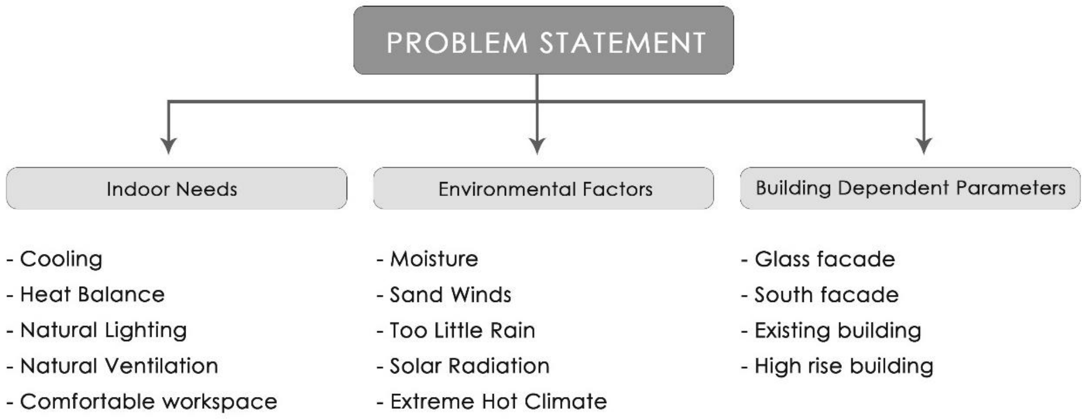


Figure 4.12. Parameters of problem statement phase

4.4.1.2. Inspiration

The development of nature for millions of years has brought many effective and sustainable biological solutions to the present day. Since its existence, human beings have developed with what they have learned from nature. Imitating nature can lead to the development of efficient and effective solutions to improve the spaces, systems, products and many more used in life. Especially in recent years, with the technological developments, the effort to imitate the solutions used by nature against any problem has become easier. At this stage of the study, an discove will be made in nature in order to produce solutions that will shed light on the parameters determined in the previous stage. In the light of the data obtained as a result of this discovery, the organism with the most effective solution potential for the problems, properties and environmental conditions of the existing test box will be selected.

4.4.1.2.1. Discovery

In this part, the first step was taken for the envelope system (shading device) to be developed as the focus of the study, to reach its goal by being inspired by nature. The decisions taken in this section will directly affect the next process of the study. Despite similar problems and situations identified in the previous parts of the study, the potentials of organisms that have proven themselves in nature, which can be an inspiration for producing effective and sustainable solutions, were analyzed. In order for this process to give faster and more efficient results, ecological sorting was used. In this way, millions of living species were filtered and the desired goal was achieved. The flow chart, which includes the whole process, accompanied by ecological ranking, is given below in Figure 4.13.

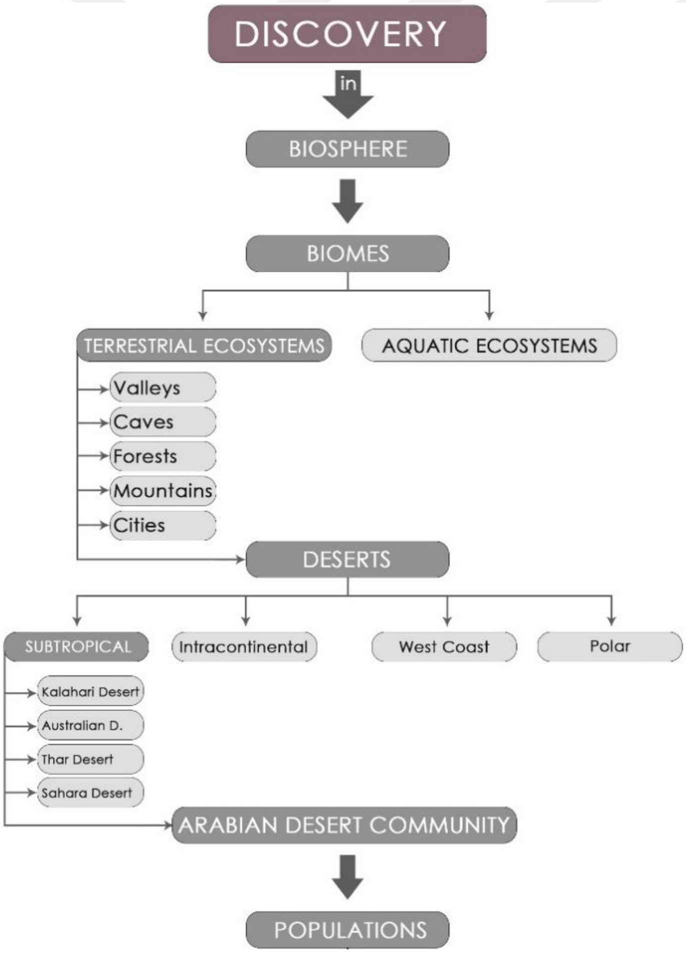


Figure 4.13. Flow chart about the discovery phase

As can be seen in the flow chart above, the discovery process of the living thing that will inspire the biomimetic envelope system (shading device) is detailed. In order for the envelope design to be developed to adapt to the conditions of the targeted location, a discovery process has been developed, starting from the general and leading to the target, for the detection of living things that have survived despite challenging conditions similar to Doha. During the process, parameters such as the needs, problems and environmental conditions of the test box were taken into account.

This discovery process begins with the biosphere, which characterizes the layer where all living things live on Earth. Biosphere is a term that encompasses all living things on earth in general context. The process continues with the term biome, which represents large areas that contain many ecosystems and are dominated by the same climate and environmental conditions. Biomes are divided into aquatic biomes and terrestrial biomes. Based on the geographical features of Doha, Qatar, where the test box is located, the discovery continued based on desert ecosystems within terrestrial biomes. The only common point of all desert ecosystems in the world is the limited access to water. Deserts can differ from each other in terms of other characteristics such as climatic conditions, humidity and temperature level. In general, discovery research continued with subtropical desert ecosystems among the desert ecosystems divided into four different groups. These very hot subtropical deserts can be found in both the Northern and Southern hemispheres. Located in the Northern hemisphere where the test box is located, the Arabian Desert is very similar to Doha in terms of community characteristics and conditions. Below is a comparative graph showing the similar conditions under which populations living in the Arabian Desert community and in the Doha community live. (see Figure 4.14.)

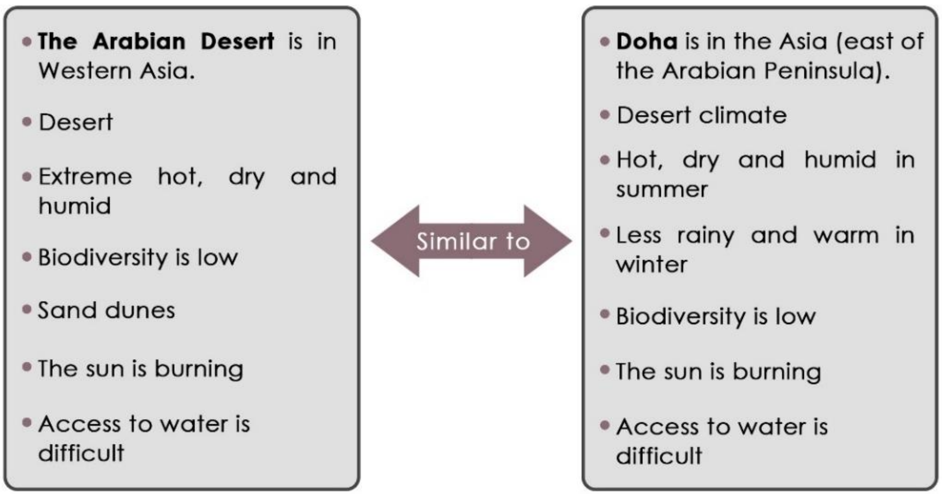


Figure 4.14. Chart about the similarities of Arabian Desert and Doha

Thanks to this discovery, which was reduced to the population level based on the interrelationships of all the levels that cover each other under ecology, an important step was taken to identify the organisms that would most efficiently contribute to the targeted biomimetic design among millions of living things. At this point, it has been observed that the Arabian Desert directly coincides with the conditions of the location where the test box is located. The Arabian Desert was determined as the most suitable community for the selection of the living thing that will inspire the biomimetic envelope design, which is the focus of the study. In the next part, populations that have adapted to the Arabian Desert, developed systems against difficult conditions and managed to survive for years thanks to these systems will be compared among themselves and the most efficient one will be selected for the targeted design.

4.4.1.2.2. Comparison and Selection

The Arabian Desert, which is among the subtropical deserts, is a very hot desert. It covers most of the Arabian Peninsula. It contains very little biodiversity. Many species, such as the striped hyena, the jackal, and the honey badger, became extinct here. Living conditions are quite harsh for living things. It contains red sand dunes and deadly swamps. Figure 4.15. is an informative graphic about the Arabian Desert (Edgell, 2006).

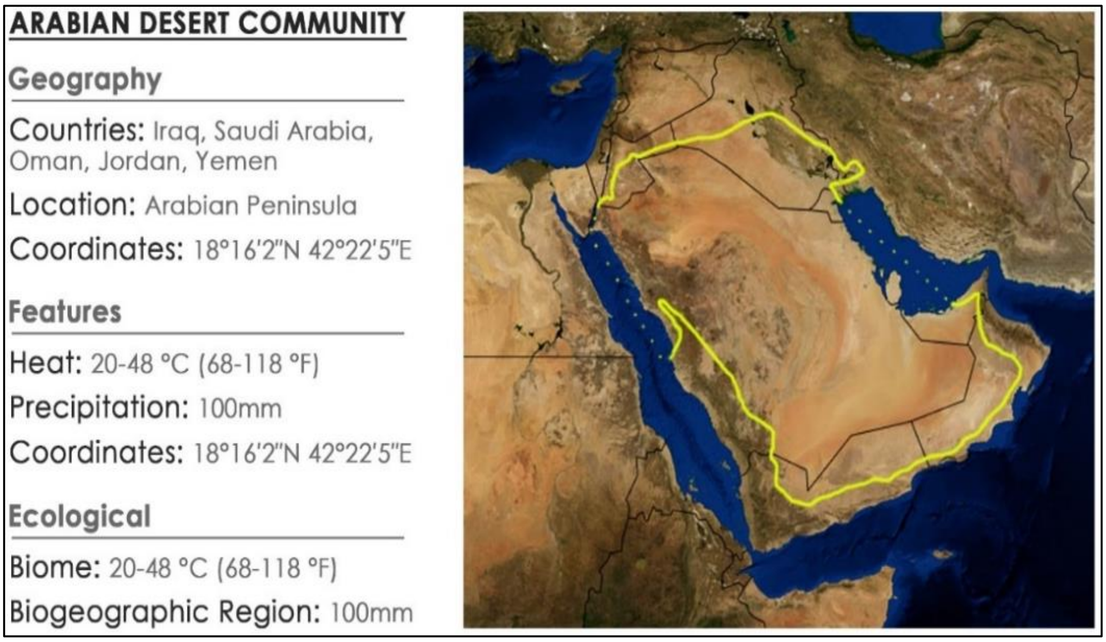


Figure 4.15. Informative tag about the Arabian Desert and map image (https://upload.wikimedia.org/wikipedia/commons/5/51/Arabian_Desert.jpg)

It covers most of the Arabian Peninsula. It has spread to many countries such as Iraq, Saudi Arabia, Oman, Jordan, Yemen. The temperature in the Arabian Desert ranges from 20 degrees Celsius to 48 degrees Celsius. It receives very little precipitation. It is unfavorable enough for life and is difficult. There are also living species that have managed to survive in this harsh desert environment.

At this part of the study, the focus was on the species that have survived for many years in the Arabian Desert. The living things here are protected from the heat as much as possible and continue their lives with minimum water and energy consumption. Living things are able to survive in this harsh Arabian Desert, thanks to the many different strategies they have developed. Some species hunt at night, and some species maintain their lives in a hot desert environment by storing water in their bodies. In general, the living things living here struggle with extreme heat and drought. The living things adapted to the Arabian Desert habitat and the strategies they developed were analyzed and compared. The life strategies developed by living things and the effects of these strategies on air, light, water and heat parameters are examined with the illustrated charts below in Figure 4.16. and Figure 4.17.

In the Arabian Desert, which has similar conditions to the test box created in the previous parts of the study, ten different species that have been living for years were examined. It has been seen that these living species continue their lives with various strategies and solutions. It was analyzed how the strategies and solutions developed by living things for harsh desert conditions contribute to the parameters of air, light, water and heat. At the same time, the biomimetic approach and biomimetic levels of these strategies and solutions were determined. As a result of all analyzes and inferences, it has been noticed that the thorny devil lizard was more efficient than other living things in adapting to the desert. (see Figure 4.17.) The thorny devil lizard has solutions and strategies that will affect all four different parameters (air, light, water, heat) analyzed in terms of energy efficiency. Therefore, it was chosen as the living being that would inspire the biomimetic envelope system, which is the focus of the study. In the next stages, the thorny devil lizard will be imitated and transferred to the targeted design. Building envelope will be developed with a biomimetic approach.

GAZELLE	Biomimicry Levels	
Mammal - animal	Organism Level	✓
Life Strategy:	Behaviour Level	✓
-Colors are bright earthy colors.	Ecosystem Level	
-They are water resistant.	**Biomimicry Approach**	
-Hunting hours are after the sun.	Design to Biology	✓
	Biology to Design	
Energy Efficiency		
Air:		
Light: Thanks to their bright colors, they reflect sunlight		✓
Water: Although they consume a lot of salt during the day, they do not need much water.		✓
Heat:		

CAMEL	Biomimicry Levels	
Mammal - animal	Organism Level	✓
Life Strategy:	Behaviour Level	
-They can change their body temperature	Ecosystem Level	
-Reduces sweating thanks to their skin	**Biomimicry Approach**	
-Stores fat in their humps	Design to Biology	✓
-One-time drinking capacity is high	Biology to Design	
Energy Efficiency		
Air:		
Light: Thanks to their bright colors, they reflect sunlight		✓
Water: They obtain water when they cannot reach water by burning the fat they store in their humps.		✓
Heat: They increase body temperature according to the increasing temperature and prevent sweating.		✓

GOLDEN MOLE	Biomimicry Levels	
Mammal - animal	Organism Level	
Life Strategy:	Behaviour Level	✓
-They live underground	Ecosystem Level	
	Biomimicry Approach	
	Design to Biology	✓
	Biology to Design	
Energy Efficiency		
Air:		
Light:		
Water:		
Heat: By digging deep burrows underground, it escapes the burning sun and stays cool.		✓

FENNEC FOX	Biomimicry Levels	
Mammal - animal	Organism Level	✓
Life Strategy:	Behaviour Level	✓
-They have long ears.	Ecosystem Level	
-They store fat in their body	**Biomimicry Approach**	
-Their fur is light colored (white & cream).	Design to Biology	✓
-They hunt at night	Biology to Design	✓
Energy Efficiency		
Air:		
Light: Thanks to their light-colored fur, they reflect the sun's rays		✓
Water: They meet their water needs thanks to the fat they store in their bodies.		✓
Heat: Thanks to their long ears, they keep their body temperature in balance.		✓

DARKLING BEETLES	Biomimicry Levels	
Arthropod - animal	Organism Level	✓
Life Strategy:	Behaviour Level	✓
-They catch water in the air.	Ecosystem Level	
-They change color.	**Biomimicry Approach**	
-They have long legs	Design to Biology	✓
-Shell structures prevent water loss	Biology to Design	✓
Energy Efficiency		
Air:		
Light: They are protected from the irritating rays of the sun by fading the color of the bark.		✓
Water: Thanks to the special tissue on their backs, they hold the water drops in the air.		✓
Heat: Thanks to their long legs and shell structure, they do not overheat.		✓

Figure 4.16. Evaluation chart 1 about living things in the African Desert

DESERT PARTRIDGE	Biomimicry Levels	
Birds - animal	Organism Level	✓
Life Strategy:	Behaviour Level	✓
-They are camouflaged by their colors.	Ecosystem Level	☐
-They can carry water in their breasts	**Biomimicry Approach**	
-They can live for a long time without water.	Design to Biology	✓
	Biology to Design	☐

Energy Efficiency	
Air:	☐
Light:	☐
Water: They can use the water they have accumulated in their breasts.	✓
Heat: Thanks to the water they accumulate in their chests, they cool off in the desert environment.	✓

THORNY DEVIL LIZARD	Biomimicry Levels	
Reptile - animal	Organism Level	✓
Life Strategy:	Behaviour Level	✓
-They regulate body temperature	Ecosystem Level	☐
-They can camouflage themselves	**Biomimicry Approach**	
-They can absorb moisture from the environment.	Design to Biology	✓
-They cool off by keeping the water on the body surface	Biology to Design	✓

Energy Efficiency	
Air: Thanks to their prickly and scaly skin, they cool by providing air flow on the body surface.	✓
Light: They are protected from the sun's rays thanks to their barbed skin systems. They also adjust the standing positions according to the sun.	✓
Water: Thanks to the scales on their prickly skin, they can absorb the fog, humidity and water drops in the environment as water.	✓
Heat: They cool down by keeping the humidity, fog and water drops on the prickly skin surface. Thanks to their prickly skin, they balance their body temperature.	✓

CORNULACA ARABICA	Biomimicry Levels	
Desert Bush - plant	Organism Level	✓
Life Strategy:	Behaviour Level	☐
-Conserves water	Ecosystem Level	☐
-Wind resistant	**Biomimicry Approach**	
-Prevents water loss	Design to Biology	✓
	Biology to Design	☐

Energy Efficiency	
Air:	☐
Light:	☐
Water: The general structure of the plant is to conserve water.	✓
Heat: They do not have broad leaves and stems, they are protected from overheating.	✓

PANICUM TURGIDUM	Biomimicry Levels	
Desert Bush - plant	Organism Level	✓
Life Strategy:	Behaviour Level	✓
-They reach water with their long roots.	Ecosystem Level	☐
-They are drought resistant.	**Biomimicry Approach**	
	Design to Biology	✓
	Biology to Design	☐

Energy Efficiency	
Air:	☐
Light:	☐
Water: Thanks to their long roots, they can reach groundwater.	✓
Heat: With their durable and stunted structure, they prevent overheating and are resistant to drought.	✓

DESERT CACTUS	Biomimicry Levels	
Cactiaceae - plant	Organism Level	✓
Life Strategy:	Behaviour Level	✓
-They hold water by opening their pores at night	Ecosystem Level	☐
-They close their pores during the day	**Biomimicry Approach**	
-Their roots are very long	Design to Biology	✓
-They are resistant to heat and sunlight.	Biology to Design	✓

Energy Efficiency	
Air:	☐
Light:	☐
Water: They hold and store water in the air by opening their pores at night.	✓
Heat: They prevent excessive wear and water loss by closing the pores during the day.	✓

Figure 4.17. Evaluation chart 2 about living things in the African Desert

4.4.1.3. Solution

In this part of the study, a biomimetic envelope system (shading device) was developed for the office unit (T0) located on the south façade of the fictional high-rise office building in Doha, Qatar. The process worked as a continuation of the previous parts of the study in the light of all the data and findings obtained during the study. Inspired by the thorny devil lizard, considering the problems identified for the targeted energy efficiency-based biomimetic envelope design and the environmental conditions in which the test box is located. In particular, considering the criterion table (Table 2.3.) developed in the light of the literature reviews of this thesis, energy efficiency, envelope features and envelope design principles were taken into account in the design process of the envelope system in question. This part, which is a solution for the design of the biomimetic envelope, which is the focus of the study, consists of two stages. The first phase focused on the thorny devil lizard that inspired the envelope design. It was analyzed which features of the thorny devil lizard that facilitate its adaptation to harsh conditions can be imitated. In the second stage, the strategy and features of the thorny devil lizard were abstracted and transferred to the architecture. In summary, in this section, which is the end of the biomimetic design process created within the scope of the study, the transfer from nature to architecture was carried out.

4.4.1.3.1. Imitation – Thorny Devil Lizard

Living things under extreme conditions such as high heat and cold need various strategies and adaptations to survive in these environments. Thorny devil lizards are also a type of reptile that survives in extremely hot and dry environments. These lizards have been able to adapt extremely successfully to extreme desert conditions. The thorny devil lizards, struggling to survive under the scorching sun throughout the day, almost challenge the desert environment in many ways.

Research and observations show that thorny devil lizards try different posture techniques to regulate their body temperature in harsh desert conditions. For example, the lizard minimizes its contact with the ground when the surface temperature it comes into contact with rises (Withers & Dickman, 1995). (see Figure 4.18.)

Figure 4.18. Thorny Devil Lizard - *(Moloch horridus)*
Photo by David Nelson

Another feature of the thorny devil lizard in its fight against hot desert conditions is its ability to protect itself from the scorching sun rays. The skin of the lizard, consisting of sharp thorns, not only protects it from other living things, but also prevents the burning sun rays like a shading apparatus. In addition, it is protected from the burning sun rays by changing its color during the hottest times of the day. Thus, with these methods, the lizard prevents the steep rays of the sun from increasing its body temperature in the desert environment (Withers & Dickman, 1995). (see Figure 4.19.)

Figure 4.19. Thorny Devil Lizard - *(Moloch horridus)*
Photo by Eduard Galoyan

These living things, which have almost completely adapted to the arid and hot desert environment, can absorb water from the moist air and soil through their skin. The scales of the thorny devil lizard are protruding like sharp thorns. Thanks to these sharp thorns that cover its entire body, the lizard can simply collect water droplets in the environment it comes into contact with. In addition, the lizard can catch dew and moisture in the air thanks to its protruding scales like thorns. Research shows that the capillary channels on the surface of the lizard's thorny skin are connected to another network of channels under its skin. For this reason, either the moisture from the air or the water collected by contact can reach the edges of the lizard's mouth through these channels. The skin of the thorny devil lizard absorbs water like a sponge. Thanks to this mechanism, the lizard challenges the hot and arid desert environment (Gans et al., 1982).

Although the skin of the thorny devil lizard, consisting of sharp thorns, is enough to scare other living things in the desert environment, it also serves another functions. These protrusions, which cover the entire body of the lizard, resemble the physical structure of mountains, but they create an air current on the surface of the skin of the thorny devil lizard. As stated above, when the lizard catches the moisture in the air, it causes a cooling effect with the air flow formed on the body surface. This prevents the lizard's body temperature from rising excessively in the hot desert environment (Joel et al., 2021). (see Figure 4.20.)

Figure 4.20. Thorny Devil Lizard - *(Moloch horridus)*
Photo by Martin Hingst

By imitating the mechanisms of the thorny skin of the devil lizard, the test box is cooled more effectively. It is predicted that the biomimetic envelope system, inspired by the thorny devil lizard, will improve air, light, water and heat parameters with minimum energy. If the lizard's thorny skin not only protects it from its enemies, but also improves its access to water, cooling, protection from the sun and maintaining body temperature so that it can survive in the desert environment, the envelope system developed for the test box will have the same performance.

4.4.1.4. Abtraction – Biomimetic Envelope Units' Design

The abstraction includes an orientation to the design of the targeted biomimetic envelope system (shading device) by purging all details without disturbing the basic characteristic structure of the mechanisms and features of the thorny devil lizard against the harsh desert environment. With this orientation, a more sustainable and efficient system has been developed by combining biomimicry, an approach that mimics the solutions and strategies of the thorny devil lizard, in order to create an energy efficiency-based biomimetic envelope system.

4.4.1.4.1. Form

Design to Biology Approach / Organism Level

For geometry (form) of the biomimetic envelope units is inspired by the skin of the thorny devil lizard to improve both the energy efficiency and indoor quality of the test box when the units are combined and integrated into the test box facade. The inspiration process is explained step by step below. In addition, Figure 4.21. (Adapted from Comanns et al., 2017) showing the formation process of the biomimetic envelope unit, inspired by the thorny scales of the thorny devil lizard.

- The skin morphology of the thorny devil lizard is well suited for the biomimetic envelope units (shading device units) geometry.
- Thorns consisting of flakes cover the entire body of the lizard.
- These thorns are formed in rows by the combination of large and small hexagons with irregular proportions.
- The hexagonal grid system is essential in nature and highly efficient to fill the targeted area effectively.
- The lizard thorns system can divide the hexagonal shape into 12 equal parts.
- Each of the 12 equal triangles is divided into two, and the triangles adjacent to the side of the hexagonal shape are left fixed.

- The triangles on the inside, not adjacent to the edge of the hexagon shape, have a movable system.
- Similar to the thorn system covering the lizard's body in form, a geometry that can be tapered outward from the building facade has been created.

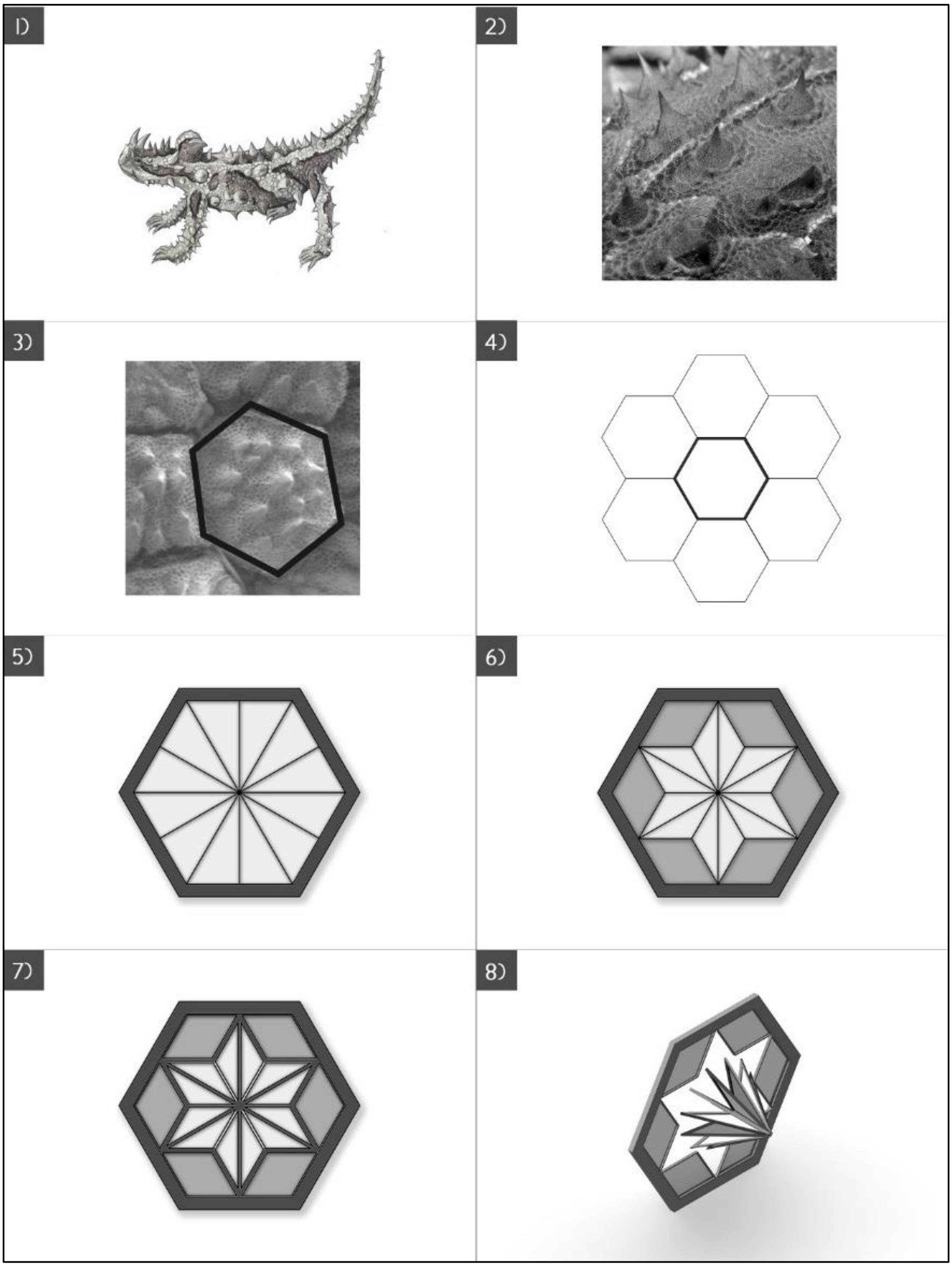


Figure 4.21. Units inspired by the skin morphology of the (*Moloch Horridus*)

1) Thorny devil lizard, **2)** Skin system of the thorny devil lizard, **3)** Irregular hexagonal scales surrounding the thorns, **4,5,6,7.8)** Abstraction process

4.4.1.4.2. Material

The materials that provide the shaping in the design, formation and use process of the biomimetic envelope system are of a quality that will contribute to the performance and energy efficiency of the test box to which it will be applied. The materials determined within the scope of design decisions play an active role in fulfilling its responsibilities despite the harsh conditions of the targeted biomimetic envelope system. Within the scope of the study, material selections were guided by being inspired by the struggle of the thorny devil lizard with harsh desert conditions. In order to obtain the most effective efficiency in the process of adapting the systems and mechanisms developed by the lizard in the desert environment to the design of the biomimetic envelope system (shading device), the materials were determined in accordance with today's technology and trends according to the purpose of use.

❖ **ETFE (Ethylene Tetrafluoroethylene)**

In this design, two different options are proposed for the shading material. These two options are two different variations of the same material. This material is ETFE material, which has been widely used for different purposes recently. Within the scope of the study, single-layer ETFE and double-layer ETFE were preferred as shading materials. An explanatory image for this is given below in Figure 4.22. The general features that play an important role in the preference of ETFE material are as follows:

- Lightweight, durable, flexible, transparent and high tensile strength,
- High visibility, light transmittance, daylight control,
- Self-cleaning,
- Good adaptability, can be processed into almost any shape,
- Low coefficient of friction, strong air (wind) resistance,
- Fire resistant,
- Thermal insulation, structural stability, radiation and chemical resistance,
- Low maintenance costs,
- Easy to recycle, cost-effective to manufacture and transport,
- Low energy consumption in all phases

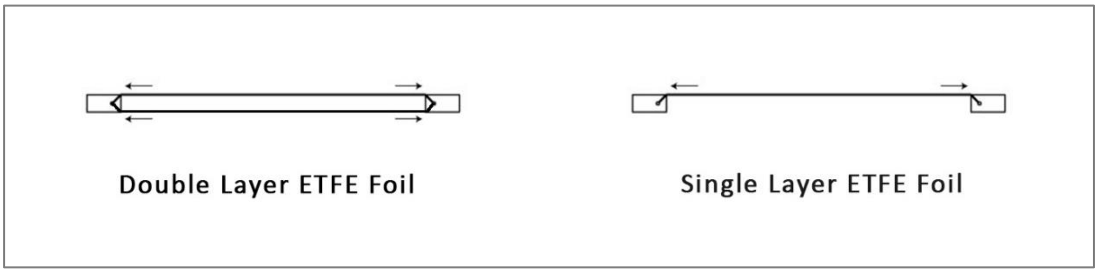


Figure 4.22. Application cases of double-layer and single-layer ETFE

For ETFE material, single-layer applications are created using mechanical stretching, and multi-layer applications are created using pneumatic tensioning. The double-layer variation used in the study is created by filling air into the ETFE foils. For this reason, single and double layer ETFE applications bring some different results. Below is a comparative table for two different variations of the ETFE material preferred for the shading function of the biomimetic envelope system developed within the scope of the study. (see Table 4.3.) The values and properties in this table are the same as the values entered for the simulation outputs.

Table 4.3. ETFE Specifications – Biomimetic Envelope Units' Shading Material

ETFE	Layer	Thickness (µm)	U Value	Solar Transmittance	Solar Reflection	SHGC	Simulation
Option 1	Single	F-200µm	5.6	%93	%6	%93	Energy & Daylight
Option 2	Double	F-200µm F-200µm	2.9	%74	%22	%75	Energy & Daylight

Terminology about the (Table 4.3.) :

- µm Micrometer
- Double Two layer ETFE
- U (W/m2 -K)
- SHGC Solar heat gain coefficient (%)
- % Percentage

❖ Graphene

In this design, inspired by the hexagonal grid system water channels under the scales of the thorny skin system of the devil lizard, a skeletal system was developed that acts as a carrier that can keep the moisture in the air thanks to the pores on it. More detailed information about the design will be given in the following parts of the study. In this part, the graphene material, which will act as the skeleton of the developed biomimetic envelope system, will be emphasized. Graphene has long been the focus of attention of many researchers, but in its normal form it is only one atom thick and can stretch infinitely in two dimensions. A related team from MIT was able to compress small pieces of graphene under heat and pressure to produce an enormous three-dimensional form. With this success, graphene is a candidate to be the best building material used to date (Qin et al., 2017). The visual of the three-dimensional graphene material obtained by the MIT team is given below in Figure 4.23. The general properties of contemporary graphene material are as follows:

- Has a density of 5% of steel,
- 10 times stronger than steel,
- Lightweight, robust and porous structure,
- A self-renewable, recyclable material,
- Easy to manufacture with 3D printing,
- Does not absorb and transmit heat as much as metals

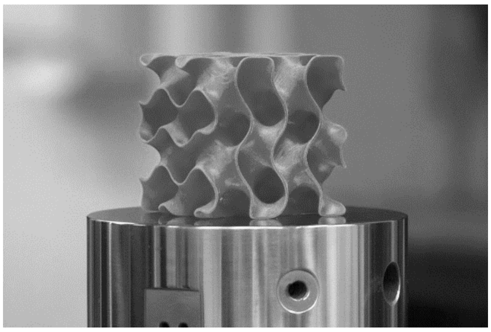


Figure 4.23. 3D graphene produced by the MIT team (Qin et al., 2017)

Graphene material is included in this study because it is an innovative and contemporary material. Thus, it is aimed to contribute to the discovery of other new materials such as graphene and to inspire studies on them. Since it is a new material, it is not detailed in the simulation inputs in this study. It was used only during the design process. The graphene material, which forms the skeletal structure of the biomimetic envelope system developed within the scope of the study, accepted as adiabatic.

❖ **Photovoltaic Panel**

In this design, photovoltaic panel technology is used, which converts the radiation from the sun into usable electrical energy through the panels. Thanks to these panels, the biomimetic envelope system placed on the south façade of Doha, Qatar, which receives intense sunlight, will be able to produce energy directly as well as energy efficiency. (see Figure 4.24.)

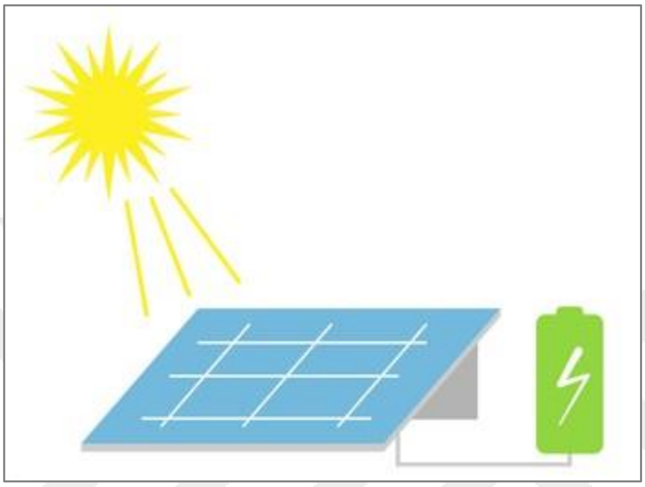


Figure 4.24. Photovoltaic panels and working mechanism

4.4.1.4.3. Construction

The construction process of the biomimetic envelope system (shading device) is detailed in this section. It has been examined in two parts, details and mechanism. In the details part, the dimensions and technical information of the module constituting the biomimetic envelope system are given. In the mechanism part, details about how the modules that make up the biomimetic envelope system are opened and closed at different angles are shared.

❖ **Details**

The modules that make up the biomimetic envelope system (shading device) are derived from the regular hexagonal shape. One side of each module is 200 cm. Porous pipes made of graphene material surround these modules. These pipes will work like water channels that trap moisture in the air, just like the thorny devil lizard. At the same time, it will provide strength to the biomimetic envelope system. Photovoltaic panels will be placed on the parts similar to diamond slices that are left fixed on the modules. These panels will remain motionless on the system. On the inside of the modules, there are ETFE triangles with an umbrella-like movable mechanism. This part can be opened and closed at certain degrees. In the center of each module, there is a stick steel system that controls the opening and closing mechanism and also ensures that the module is attached to the building. In this way, the module works with the building it will be integrated with. The figures containing the general dimensions and technical information of the modules that make up the biomimetic envelope system (shading device) are given below in Figure 4.25. and Figure 4.26.

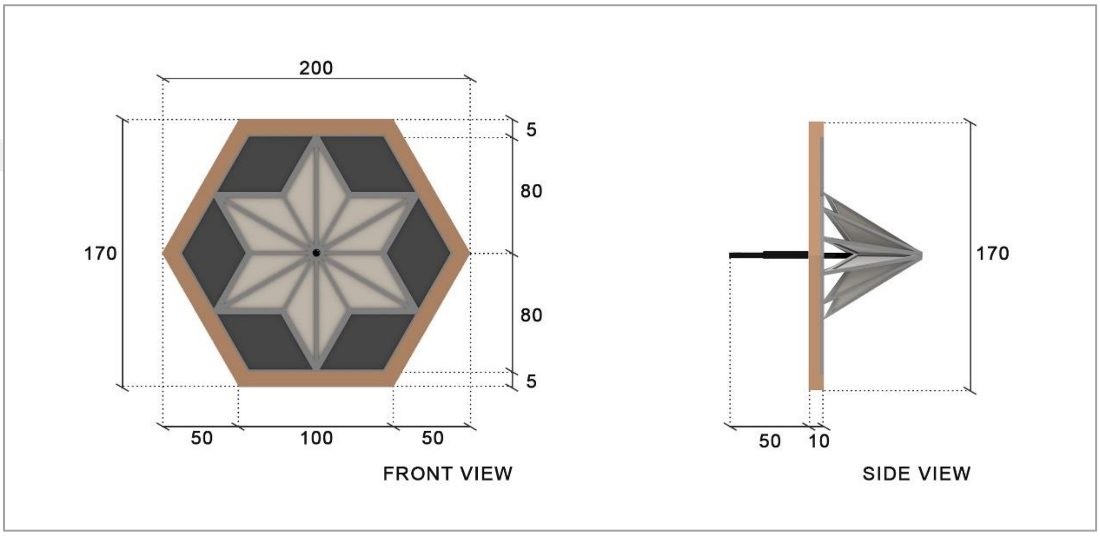


Figure 4.25. General dimensions of the modules

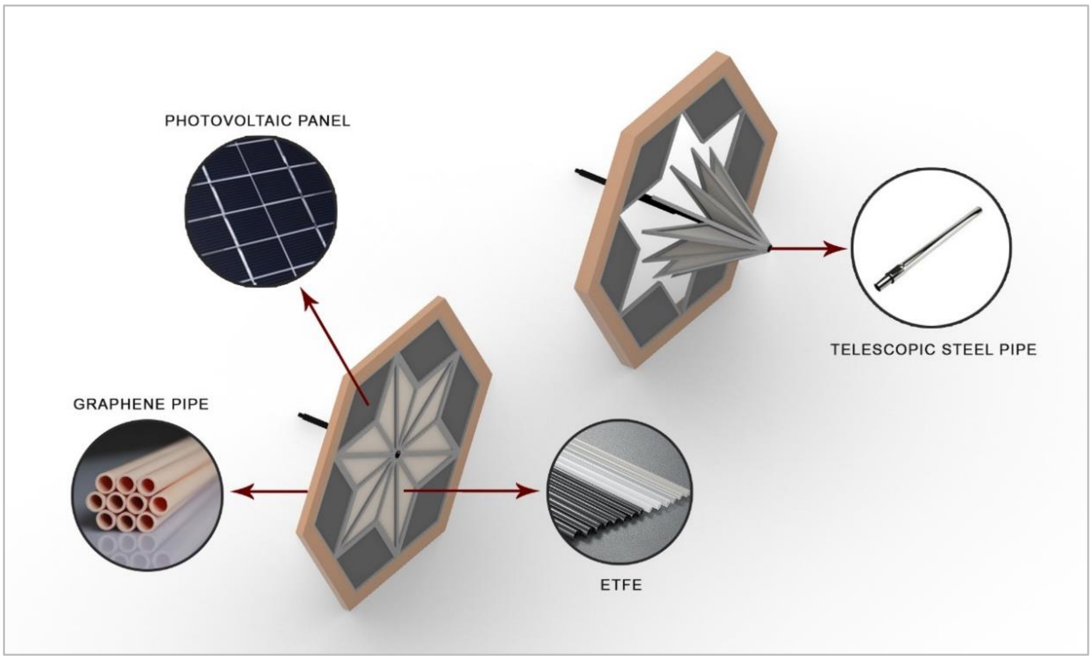


Figure 4.26. Technical information of the modules

- **Mechanism**

In this part, the telescopic steel pipe mechanism in the center of the modules that make up the biomimetic envelope system will be discussed. Thanks to this mechanism, the envelope modules are fixed to the glass facade laths in the test box. In this way, the modules can come together in a balanced way. At the same time, the loads that the modules have to carry are lightened. The simulation images of how the modules are fixed to the test box thanks to this mechanism are shared below in Figure 4.27.

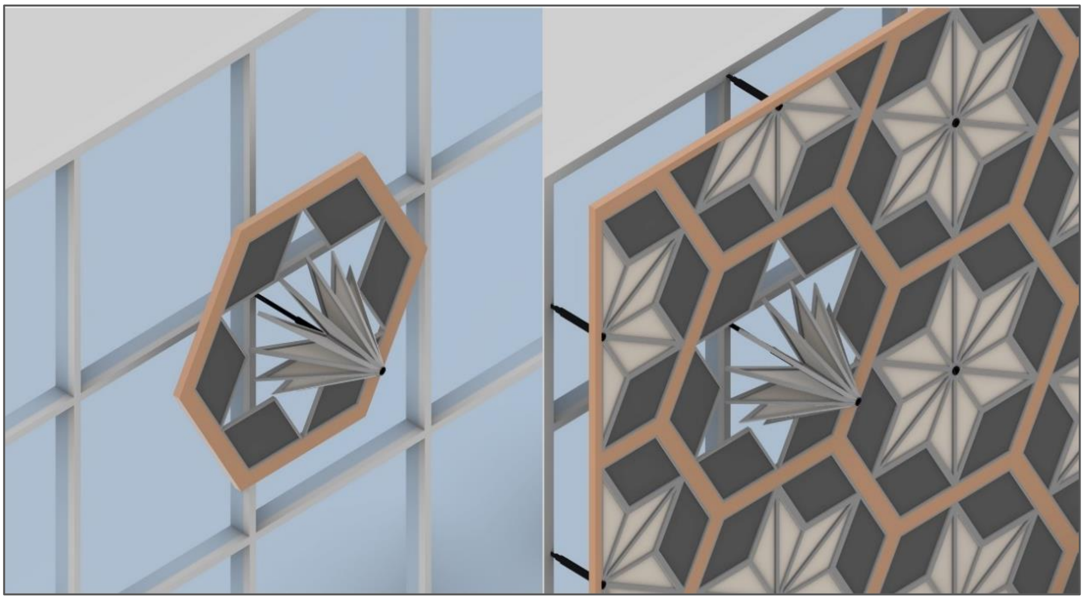


Figure 4.27. Simulation image of how the modules are fixed in the test box

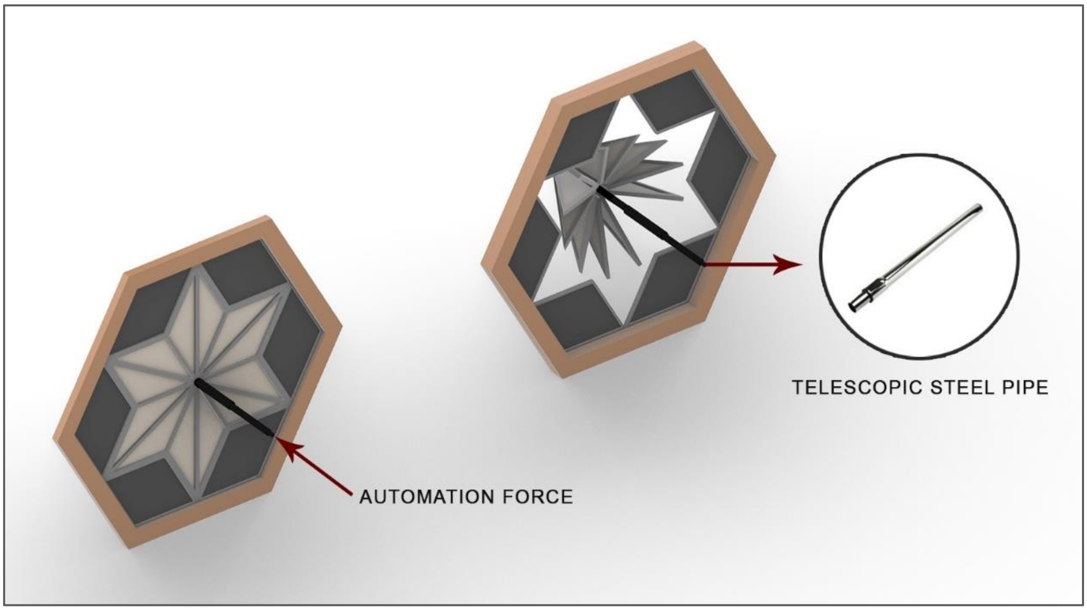


Figure 4.28. Telescopic steel pipe mechanism in the center of the modules

The steel telescopic mechanism in the center of the modules can extend outwards perpendicular to the building facade with the automation of the building managed by the building. (see Figure 4.28.) Meanwhile, the 50 cm part of the mechanism that attaches to the building remains fixed. In this way, each of the modules that make up the biomimetic envelope system (shading device) can taper out of the façade like the spines on the skin of a thorny devil lizard. The closed biomimetic envelope system can be opened thanks to this mechanism. The mechanism that can be opened at 0°, 30°, 45°, 60° and 90° allows the building to benefit from daylight at different rates. In the following parts of the study, simulation outputs related to this diversity will be created. (see Figure 4.29.)

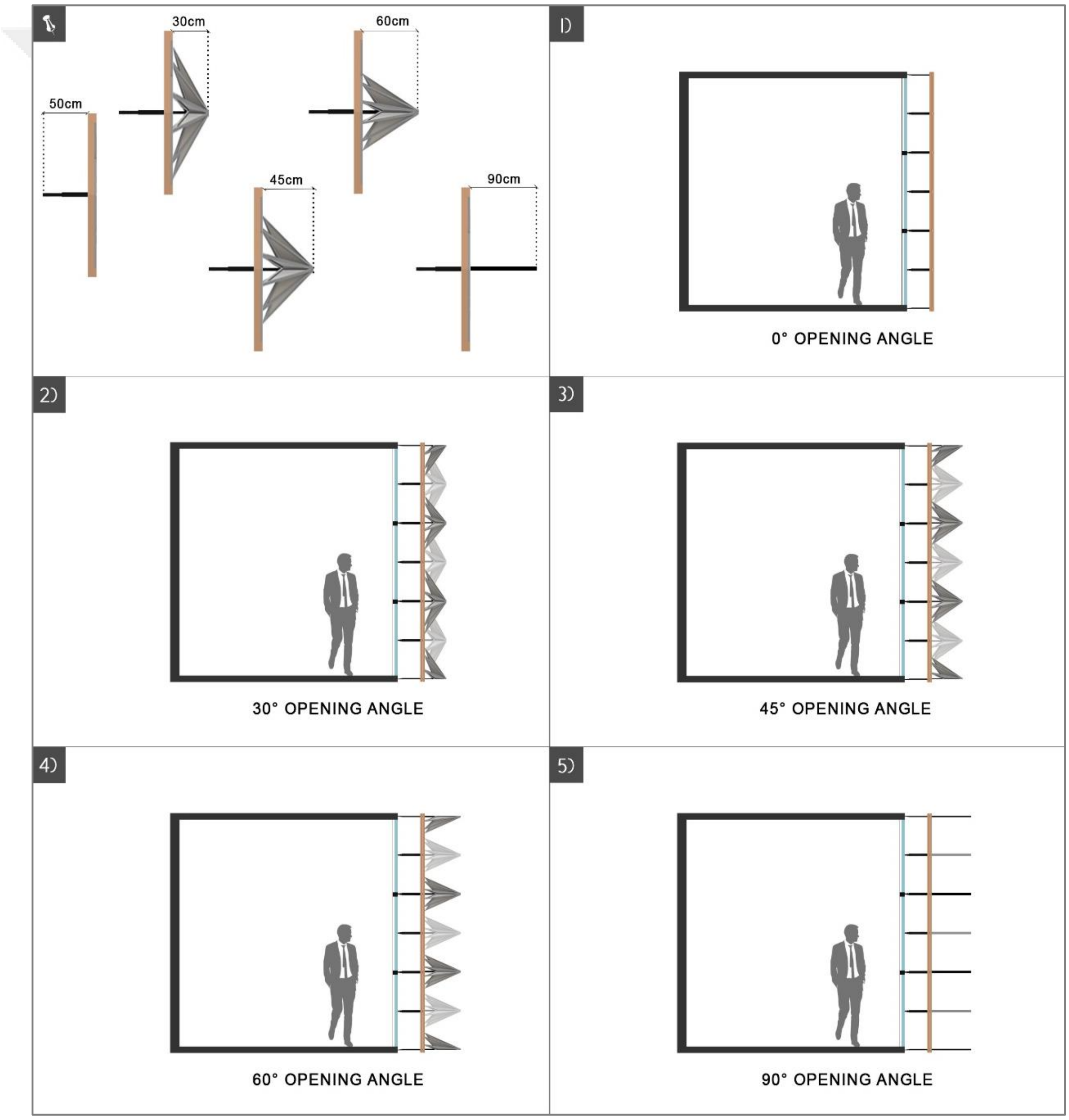


Figure 4.29. Opening angles of modules thanks to the mechanism

4.4.1.4.4. Process

After a selected unit from the imaginary office building in Doha, Qatar was designated as the test box, the biomimetic envelope system inspired by the thorny devil lizard was integrated into the south façade of the designated test box. In this process, cooperation was made with the discipline of biomimicry. The envelope system (shading device), inspired by the thorn skin of the devil lizard, is an example of how nature's solutions are transferred to architecture. Within the proposed design process within the scope of the study, an energy efficiency-based biomimetic envelope system was developed and the architectural integration process was carried out. (see Figure 4.30.)

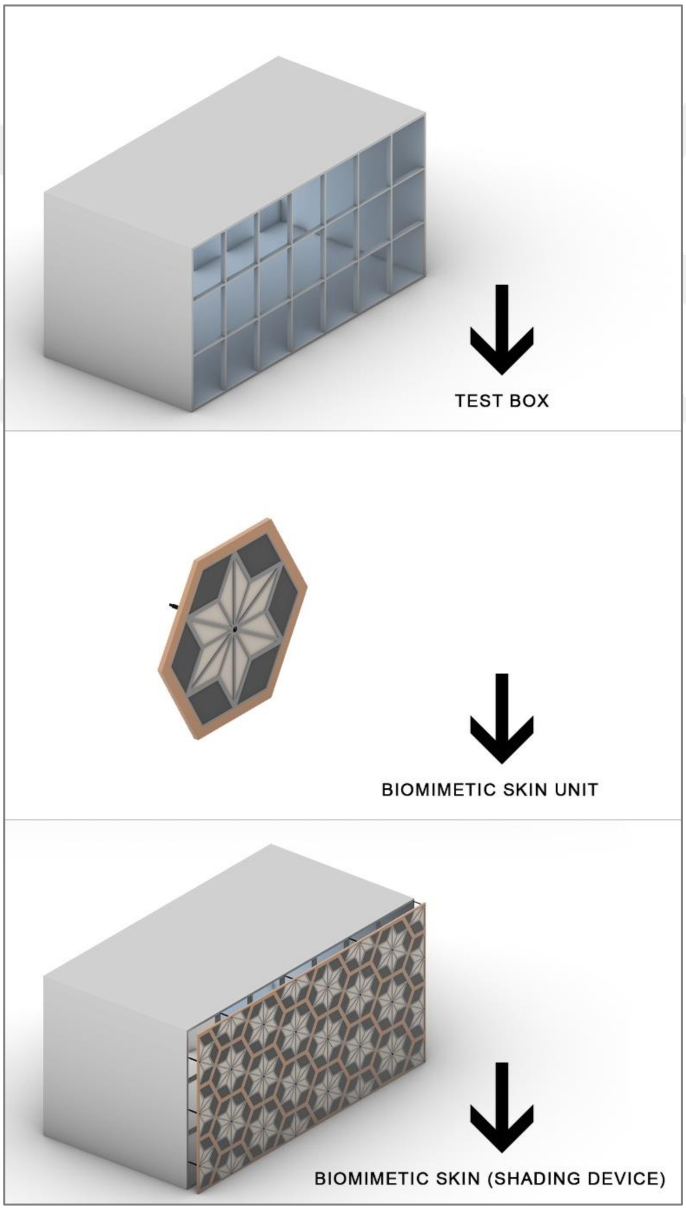


Figure 4.30. Biomimetic envelope design process

4.4.1.4.5. Fuction

As can be seen in the flow chart (see Figure 4.8.), in which the design process developed to create the biomimetic envelope system is explained in detail, nature strategies were used for more innovative and efficient approaches. Design inspirations were drawn from existing technologies and materials available today with the goal of mimicking the behavior and strategies of the thorny devil lizard for more innovative approaches. The biomimetic envelope system serves many different parameters besides shading. In the design process of the biomimetic envelope system, how it was inspired by the strategies and solutions developed by the thorny devil lizard in harsh desert conditions for air, light, water and heat parameters within the scope of energy efficiency was shared below.

- ❖ **Air**

Biology to Design Approach / Organism Level

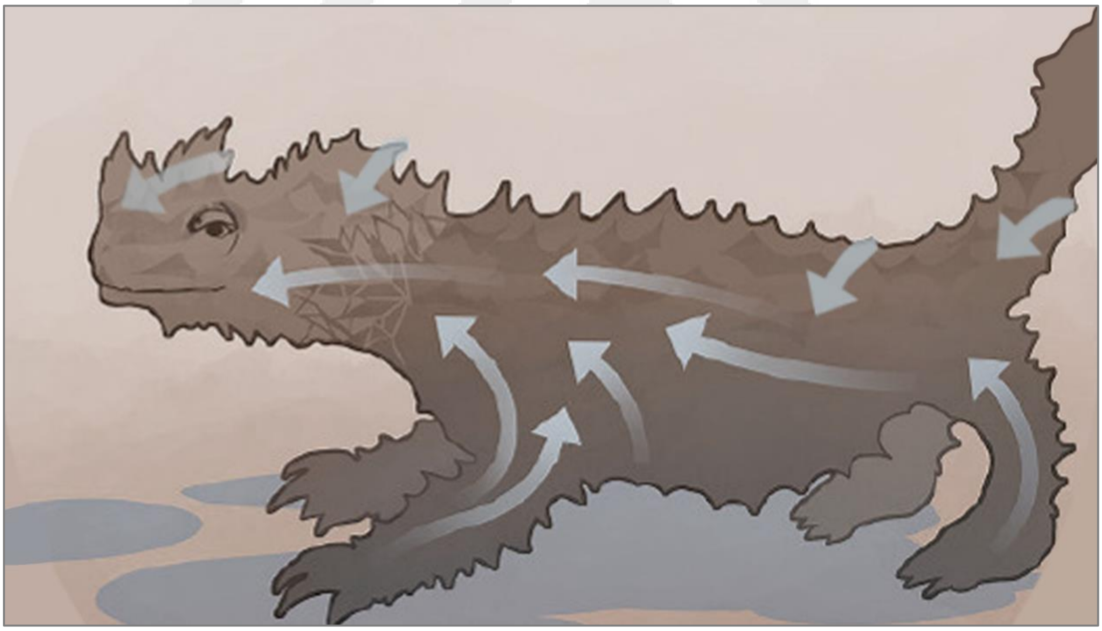


Figure 4.31. The thorny devil lizard's air function

In this step was inspired by the air current formed on the skin of the thorny devil lizard, caused by its thorny structure. In hot desert conditions, the lizard cools a little thanks to the air circulation (see Figure 4.31.) formed between the thorns on its skin. The developed biomimetic envelope system (shading device) also provides cooling of the building by creating an air flow on the surface of the building, just like the lizard's thorny skin surface. At the same time, the biomimetic envelope system, which can be opened at certain angles, allows the building to be ventilated in a controlled manner.

- ❖ **Light**

Design to Biology Approach / Organism Level, Behavior Level

Figure 4.32. The thorny devil lizard's light function

This step was inspired by the natural shading strategy that the thorny structure of the thorny devil lizard creates against the burning and disturbing sun rays in the desert environment. These thorns (see Figure 4.32.) tapering outward from the lizard's body prevent the sun's rays from reaching its body directly. The developed envelope system (shading device) blocks the sun's rays like the prickly skin surface of a lizard, preventing both the heating of the building and allowing controlled daylight to be taken inside. Envelope modules, which can be tapered at different rates, can exhibit the most effective stance for the building, like the lizard's stance according to the sun.

- ❖ **Water**

Biology to Design Approach / Organism Level, Behavior Level

This step is inspired by the water mechanism (see Figure 4.33.), which allows thorny devil lizards to survive in extreme heat. Despite the scorching heat of the sun, lizards can absorb moisture from moist air and sand. The thorns on the surface of its skin are covered with scales. The water sucked through these scales goes up to the lizard's mouth with the help of channels under the skin. The pores in the graphene pipe system, which forms the skeletal structure of the biomimetic envelope system developed from this point of view, allow the building to cool during the day by trapping the moisture in the air despite the heat of Doha, Qatar.

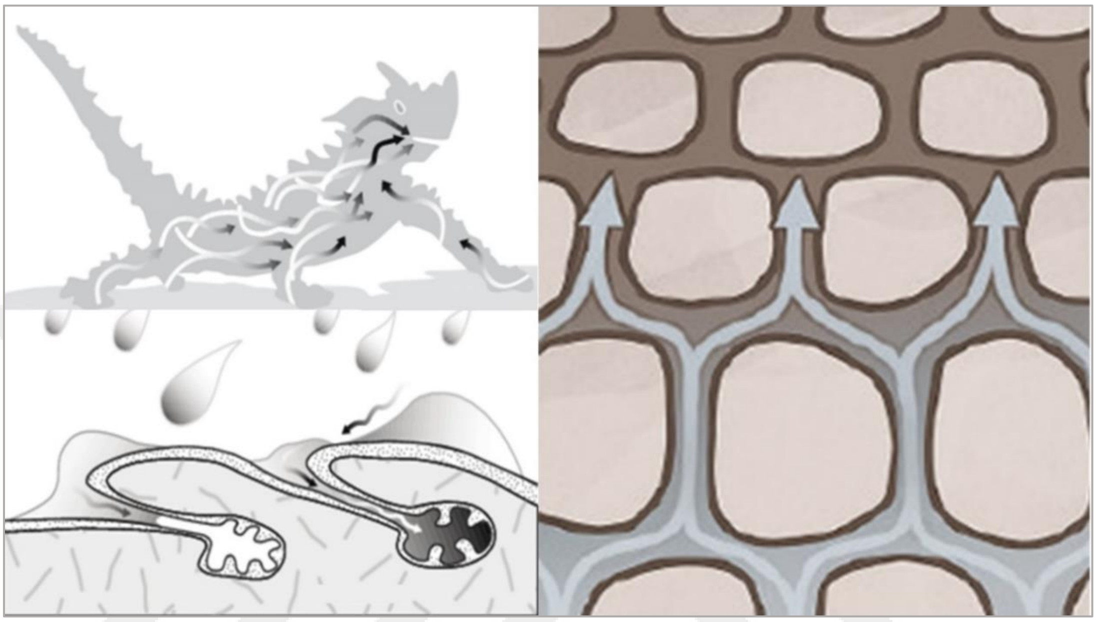


Figure 4.33. The thorny devil lizard's water function

- ❖ **Heat**

Design to Biology Approach / Behavior Level

In this step was inspired by the thorny devil lizard's ability to keep itself cool by keeping moisture in the air on its thorny skin surface in the hot desert climate. The thorny lizard can attract water from both the air and desert sand it comes into contact with. Thus, the body surface remains moist. In this way, it can keep its body temperature in balance in the sweltering desert heat. At the same time, when the sun's rays are very hot, the lizard provides shade by hiding under the sand or under the bushes in the desert ecosystem. (see Figure 4.34.) The biomimetic envelope system developed from this point of view prevents the increase in the temperature of the building by keeping the moisture in the air. At the same time, the biomimetic envelope system modules, which can be opened and closed at certain angles, provide a dark shade to the building when they are fully closed. Thus, it prevents the excessive increase in building temperature in the burning desert heat.

Figure 4.34. The thorny devil lizard's heat function

4.4.2. Second Stage - Simulation Process with Variations

The second stage of the design process was created to measure the design performance potential of the biomimetic envelope system (shading device) developed in the first stage and to evaluate the behavior of the acquired solution set on the test box with variable parameters. Aim to determine the most efficient state of the developed biomimetic envelope system design with information about the final output. Within the scope of the architectural integration process, all variations of the design can be created and tested with modeling and simulation tools, accompanied by variable parameters determined beforehand in the computer environment. In this context, a solution set has been created that arises from the differences in the number of ETFE layer and the opening angles of the modules that provide the shading function of the biomimetic envelope system (shading device) developed as the focus of the study. As a result, at this stage, the simulation outputs of biomimetic envelope system variations integrated into the test box and the features that lead to diversity are discussed separately. In this way, analysis and test outputs can be compared among themselves in the following parts of the study, and the basis for determining the most effective state of the developed biomimetic envelope system on the test box has been prepared. All variations of the biomimetic envelope systems integrated on the T0 - base geometry (test box) created earlier are given below in Figure 4.35. detailed.

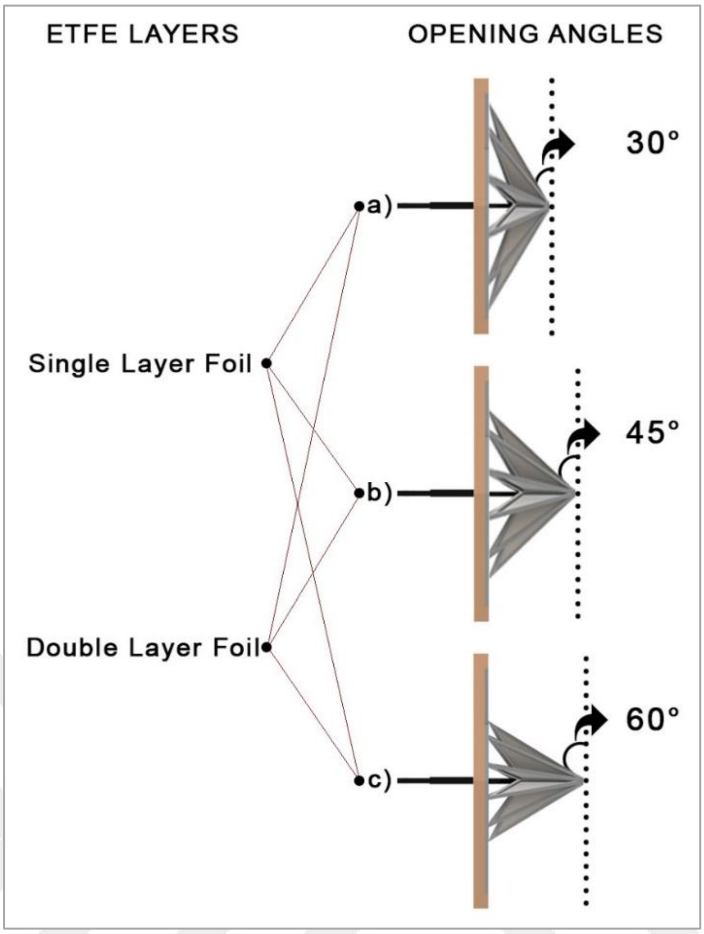


Figure 4.35. Combination of variable parameters
(T1 – T2 – T3 – T4 – T5 – T6)

4.4.2.1. Simulations of T1 and T2

The opening angle was set to 30°. A single ETFE layer was used in the T1 variation. A double ETFE layer was applied in the T2 variation. (see Figure 4.36 and 4.37)

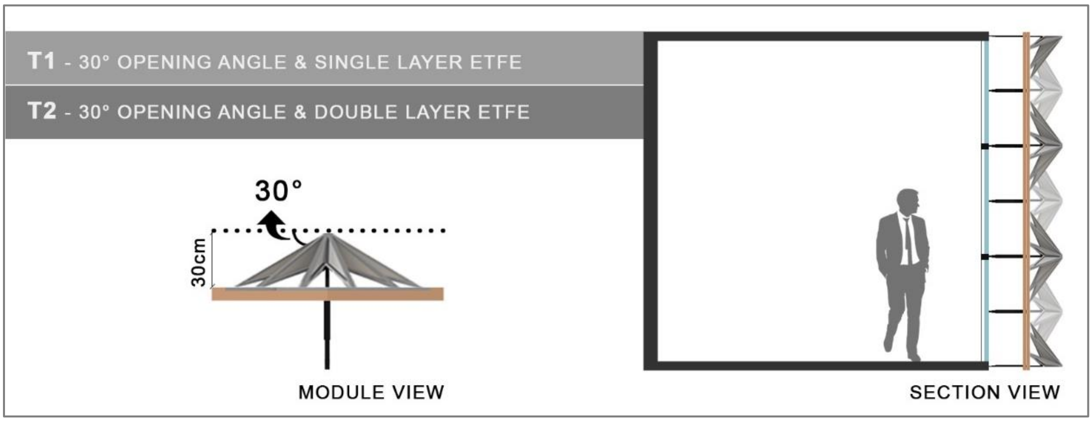


Figure 4.36. T1 and T2 – Variation of Biomimetic Envelope System / Section views

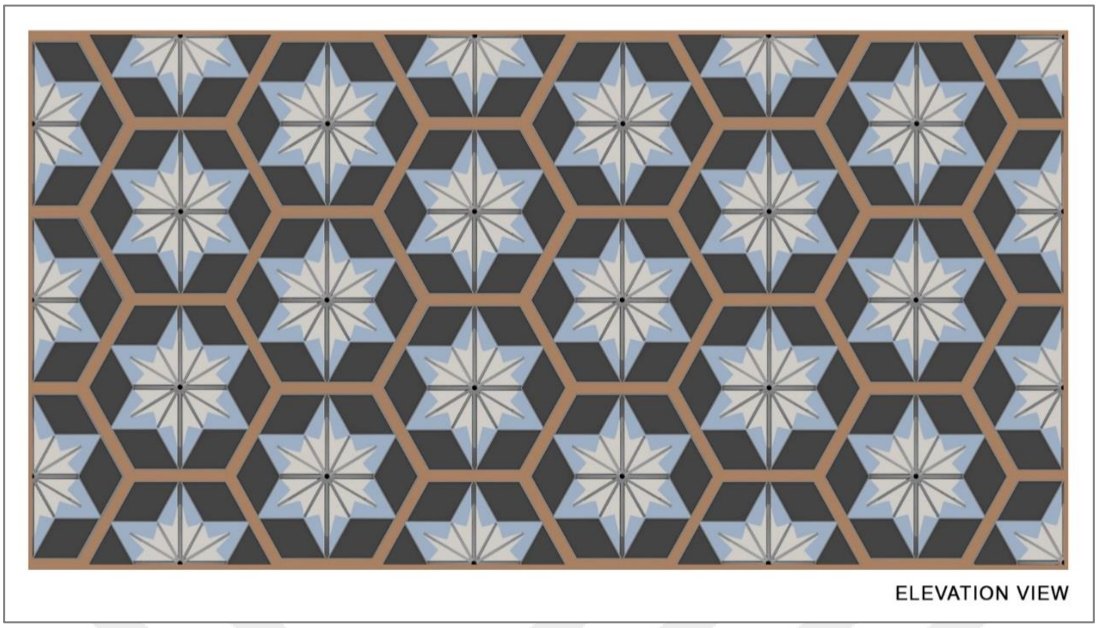


Figure 4.37. T1 and T2 - Variation of Biomimetic Envelope System / Elevation view

As seen above, T1 and T2 variations were taken together. Because the opening angles are the same. The only difference is the number of ETFE layers. Since the number of ETFE layers does not make any difference in the simulation output, it is presented in common figures. These variations are important for the analysis outputs later in the study. In addition, all T1 and T2 biomimetic envelope system variations were integrated into the T0 (see Figure 4.7.) described in the previous sections of the study.

4.4.2.2. Simulations of T3 and T4

The opening angle was set to 45°. A single ETFE layer was used in the T3 variation. A double ETFE layer was applied in the T4 variation. (see Figure 4.38 and 4.39)

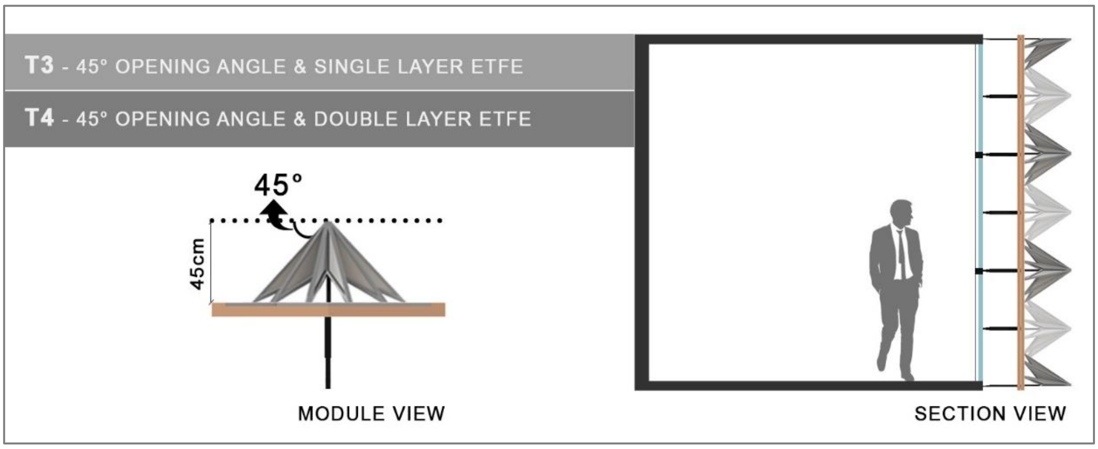


Figure 4.38. T3 and T4 - Variation of Biomimetic Envelope System / Section views

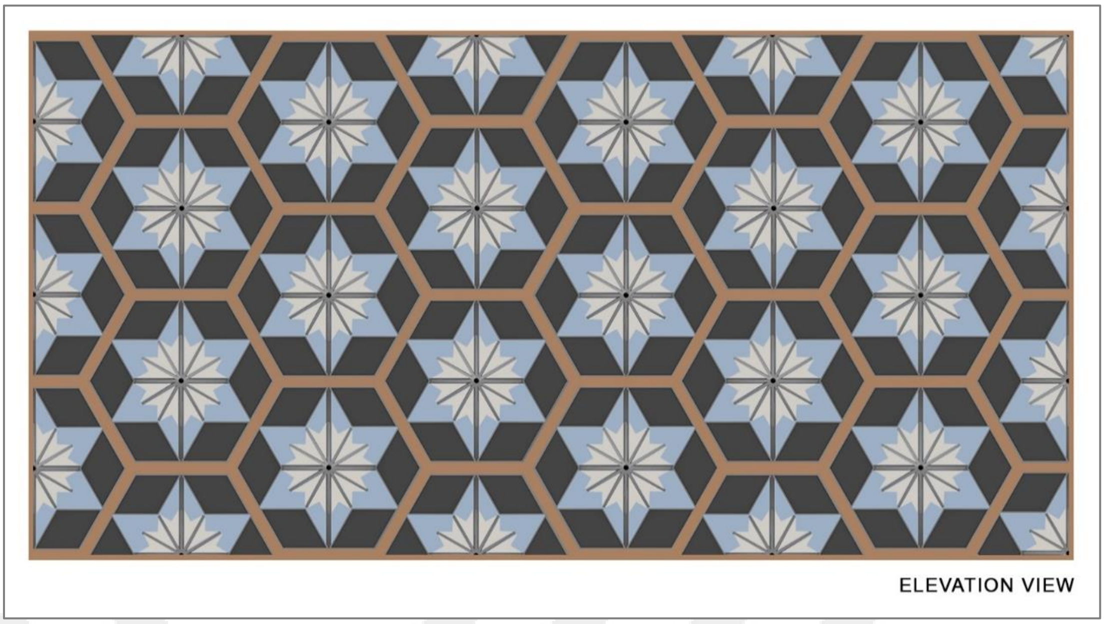


Figure 4.39. T3 and T4 - Variation of Biomimetic Envelope System / Elevation view

As seen above, T3 and T4 variations were taken together. Because the opening angles are the same. The only difference is the number of ETFE layers. Since the number of ETFE layers does not make any difference in the simulation output, it is presented in common figures. These variations are important for the analysis outputs later in the study. In addition, all T3 and T4 biomimetic envelope system variations were integrated into the T0 (see Figure 4.7.) described in the previous sections of the study.

4.4.2.3. Simulations of T5 and T6

The opening angle was set to 60°. A single ETFE layer was used in the T5 variation. A double ETFE layer was applied in the T6 variation. (see Figure 4.40 and 4.41)

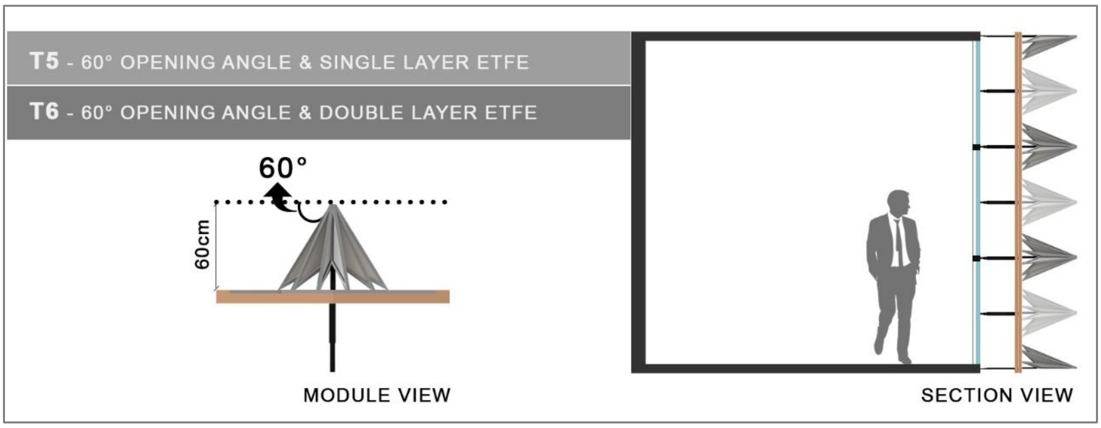


Figure 4.40. T5 and T6 – Variation of Biomimetic Envelope System / Section views

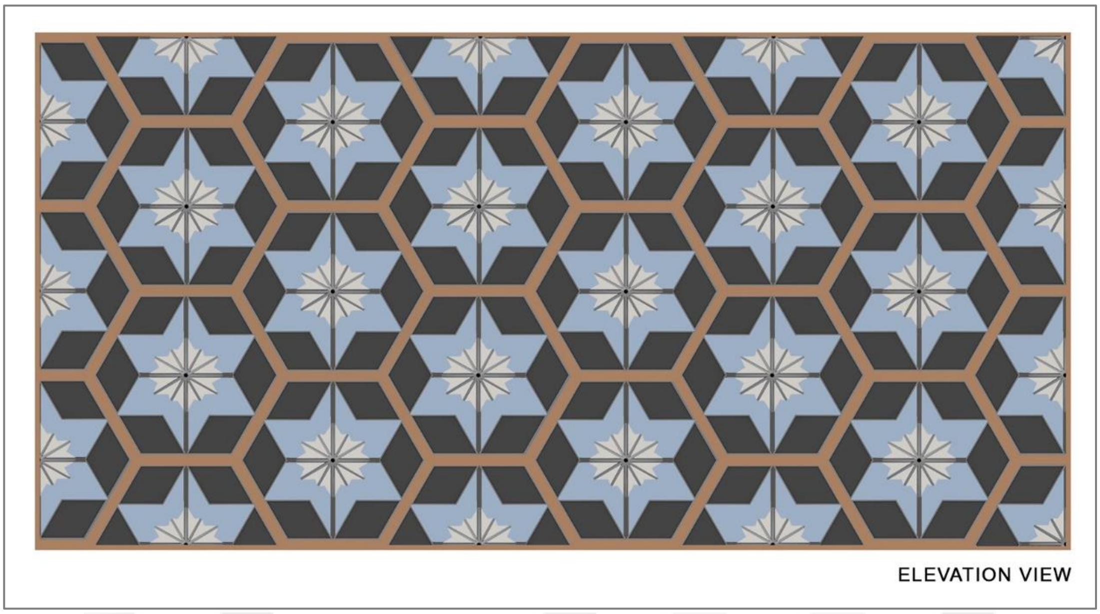


Figure 4.41. T5 and T6 - Variation of Biomimetic Envelope System / Elevation view

As seen above, T5 and T6 variations were taken together. Because the opening angles are the same. The only difference is the number of ETFE layers. Since the number of ETFE layers does not make any difference in the simulation output, it is presented in common figures. These variations are important for the analysis outputs later in the study. In addition, all T5 and T6 biomimetic envelope system variations were integrated into the T0 (see Figure 4.7.) described in the previous sections of the study.

4.5. Simulation Settings

Within the scope of the RhinoCeros 3D modeling program related to the test box in which the biomimetic envelope system is integrated, all settings and adjustments are determined before the simulation via the Grasshopper plugin. All settings must be made completely for targeted daylight analysis and cooling energy simulations. There is no adiabatic component among the components used in the test box. On the contrary, all components provide heat conduction. According to the orientation, surfaces such as walls, roofs and floors that make up the test box are defined. The wall material is ASHRAE 189.1-2009 Extwall Climate zone 3. It is 20 cm thick. The walls have Radiance material painted white. The RGB reflectance value is 1 for each color. The floor material is ASHRAE 90.1-2010 Atticfloor Climate zone 3 Semiheated. It is 15 cm thick. The floor has a cream dyed Radiance material. The RGB reflectance value is 0.763. Roof material is ASHRAE 90.1-2007 Extroof Climate zone 3 Semiheated. It is 15 cm thick. The roof has a cream painted Radiance material. The RGB reflectance value is 0.763. Finally, an opening is placed on the south side of the test box. Double clear window consists of 3 mm double clear glass with 13 mm air gap. The U value of the glass façade on the south façade is 2.556 W/m2 -K. After selection and adjustment of test box materials, all surfaces were combined. The climate conditions of Doha, Qatar are taken as the basis for the region. In this context, the EPW file reflecting the annual average climatic conditions of Doha was integrated into the simulation. The indoor conditions of the imaginary office unit, which was determined as the test box for the cooling energy computation, were accepted as 25 degrees dry bulb temperature and 50% relative humidity. The duration for the cooling load computation was determined as one week. July was chosen as the hottest time of the year. Daylight analysis is set to be done between 07:30 and 19:30 (the time period in which people spend the most time in the office in Doha, Qatar) weekly for the month of July. The minimum threshold for daylight performance was defined as 300lux and the maximum threshold as 1500lux. The simulation was set up for 75 cm high table-level daylight outputs. Other important data is related to the developed biomimetic envelope system. The ETFE material, which forms the moving part of the system, consists of two different layer options: single layer and double layer. Single ETFE layer U value is 5.6 W/m2 -K. Double ETFE layer U value is 2.9 W/m2 -K. ETFE layers have a white painted Radiance material. The RGB reflection value is 1. The other two materials constituting the envelope system were adjusted as adiabatic and their colors were determined. The color of the skeleton system made of graphene material is gray, and the color of the fixed photovoltaic panels is black. Detailed information on all components is given in the previous sections. In this section, all the components that make up the simulation are briefly mentioned.

4.6. Simulation Outputs

A set of tools and their outputs that help early decision based on the performance of the developed envelope system (shading device) are used in this study. Various 2D and 3D graphics of the analysis outputs were obtained with Honeybee and Ladybug plugins on the simulations made in collaboration with Rhino-Grasshopper. These plugins work in coordination with the simulation component settings and the weather files (EPW) of the test box location (Doha, Qatar). In this way, the outputs obtained accurately reflect both the simulation components and the environmental conditions.

Climate analyzes were carried out on the current state of the test box (T0) and the integrated variations of the developed biomimetic envelope system (T1, T2, T3, T4, T5, T6), which were detailed in the previous sections of this study. In light of the external temperature, humidity percentage, wind speed data of one-week Qatar Doha in July, which is the hottest month, the data outputs of the simulation variations on surface temperature, interior temperature, cooling load and solar gain have been reached. These data outputs serve as a guide for the comparative analysis of the most effective state of the developed biomimetic envelope system. The developed biomimetic envelope system (shading device) was evaluated on both cooling energy load and daylight simulation outputs. Variable parameters and decisions in the design process of the biomimetic envelope system create different variation outputs. This causes simulations to produce different outputs. Within the scope of this study, the effect of the variations of the biomimetic envelope system developed in the general context on the performance of the determined test box will be examined. On the other hand, it is aimed to determine the variation that offers the most efficient solution to the climate and environmental conditions of Doha, Qatar, thanks to the simulation outputs obtained.

CHAPTER 5
RESULTS AND DISCUSSION

In this section, the results of the developed biomimetic envelope system (shading device) are explained. The results consist of two main parts: the architectural integration process and simulation results of the biomimetic envelope system variations developed for the south facade of the current state of a unit (test box) selected from the imaginary office building in Doha, Qatar. Architectural integration is actually preliminary for simulation results. The simulation results were created in order to improve the office unit (test box) both in terms of energy efficiency and to get maximum efficiency from daylight at the point of illumination.

The simulation results reveal how the developed biomimetic envelope system (shading device) variations improve the test box. Below are the comparisons for the first week of July, the hottest month in Doha, Qatar. The current state of the test box and the values of the biomimetic envelope system (shading device), which has a total of six different types of variations integrated into the south façade, are compared in the charts below. These values are outdoor temperature, surface (glass facade) temperature, indoor temperature and solar gain. Guided by these values, the cooling load values of six different biomimetic envelope variations at the energy efficiency point are compared with the graphics. In addition, daylight analysis outputs were compared with the aim of maximum daylight gain.

All energy (cooling load) and daylight simulations of the biomimetic envelope system (shading device) variations determined in the architectural integration process were made in computer environment. The computer has 16.0GB RAM and 64 bit processor with Intel(R) Core(TM) i7-8750H CPU @ 2.20GHz. The operating system was Windows 11.

5.1. Architectural Integration

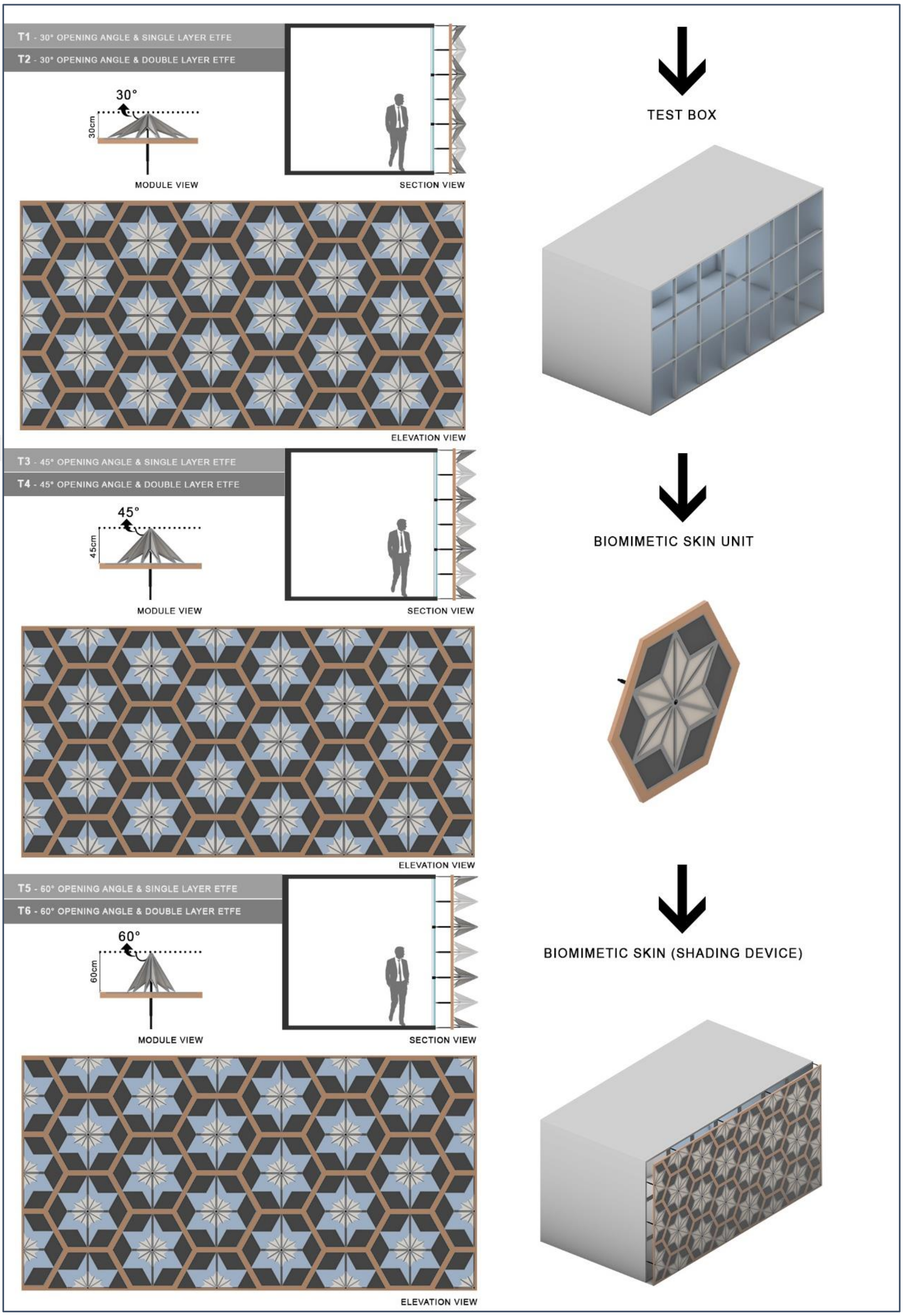


Figure 5.1. (T0) - Test box and (T1 - T2 - T3 - T4 - T5 - T6) - Biomimetic envelope system variations

Within the scope of the architectural integration process, the solution set was determined with the variations (T1 - T2 - T3 - T4 - T5 - T6) created by the differences in the opening angles of the envelope system developed for the south façade of the test box (T0) and the number of ETFE layers. (see Figure 5.1.) With the determined variations, minimum cooling load and maximum daylight gain are aimed. Charts of some of the previously mentioned values are shown for all types of shading devices. The charts show seven days spanning the first week of July, the hottest month in Doha, Qatar. In this direction, before the integration of the envelope system variations developed within the scope of the study, a number of climate analyzes related to the location of the test box (T0) were made. In the light of the **outdoor temperature, humidity percentage, wind speed** data of Doha, Qatar, the surface temperature, interior temperature, cooling load and solar gain data of the test box were obtained. These data will serve as a guide for subsequent analysis outputs. (see Figure 5.2.)

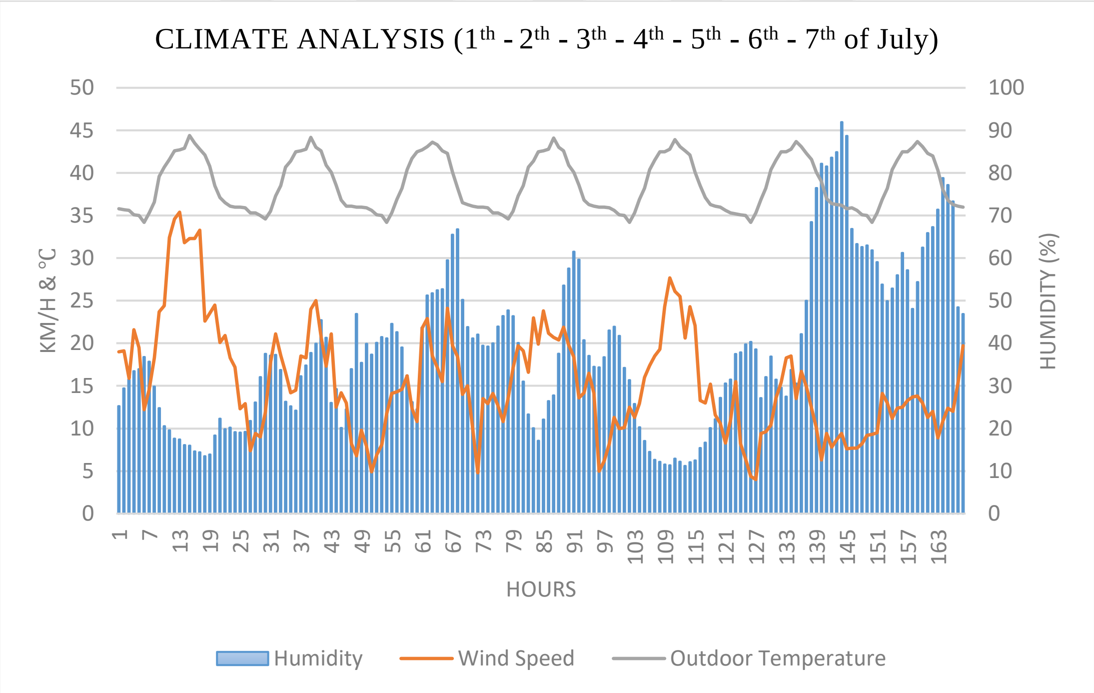


Figure 5.2. Doha, Qatar climate values

5.2. Simulation Results

As discussed in detail in the previous sections of the study in Doha, Qatar, which has a hot and dry climate, a unit of a fictitious office building was chosen as the test box (T0). Six different biomimetic envelope system variations (T1 - T2 - T3 - T4 - T5 - T6) developed for the south façade of this test box were compared both with the current version of the test box and among themselves. In summary, the focus is on two parameters that most affect working performance in office environments. Maximum daylight gain and minimum cooling load are aimed for working comfort. The simulation results created in two steps are shared below.

5.2.1. Cooling Load

Weekly cooling load computation of the current state of the test box **(T0)** was made before any variation of the biomimetic envelope system (shading device) was integrated. July is the hottest month of the year in Doha, Qatar. For this reason, seven days covering the first week of July were taken as a basis throughout the study. For this, firstly, outdoor temperature, surface temperature (glass front temperature), indoor temperature and solar gain data of Doha, Qatar, where the test box is located, were determined. (see Figure 5.3.) As a result of the simulation created in the light of these data, the amount of energy spent for cooling for seven days was reached. (see Figure 5.4.) The **total cooling load** for one week of the current state of the test box (T0) is **398 kWh**.

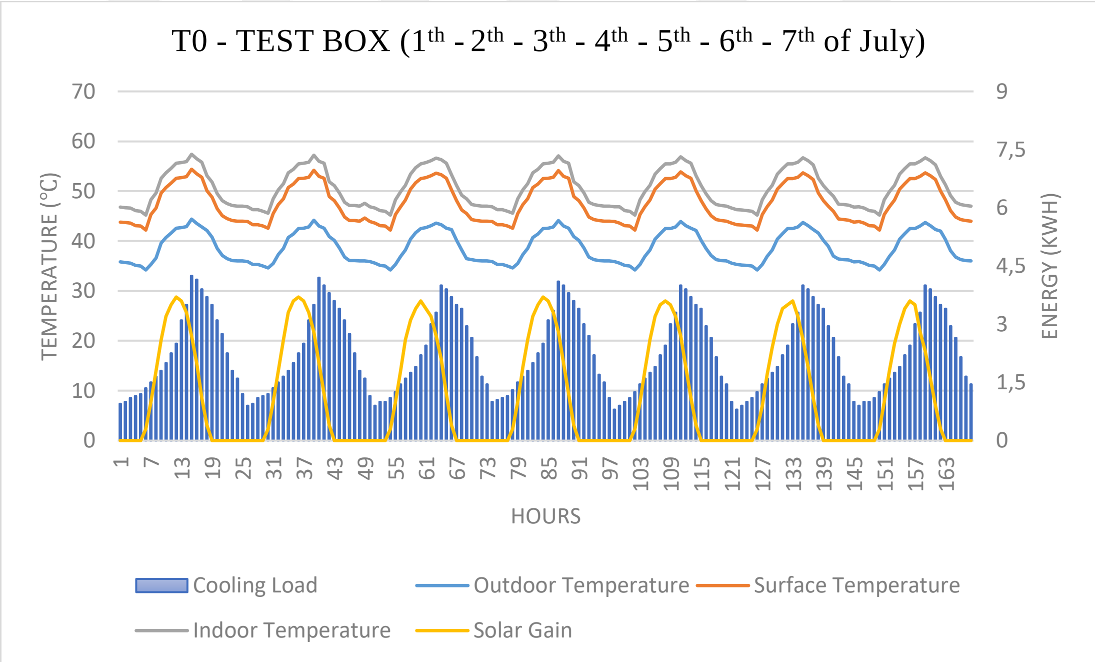


Figure 5.3. Test Box (T0) - Values

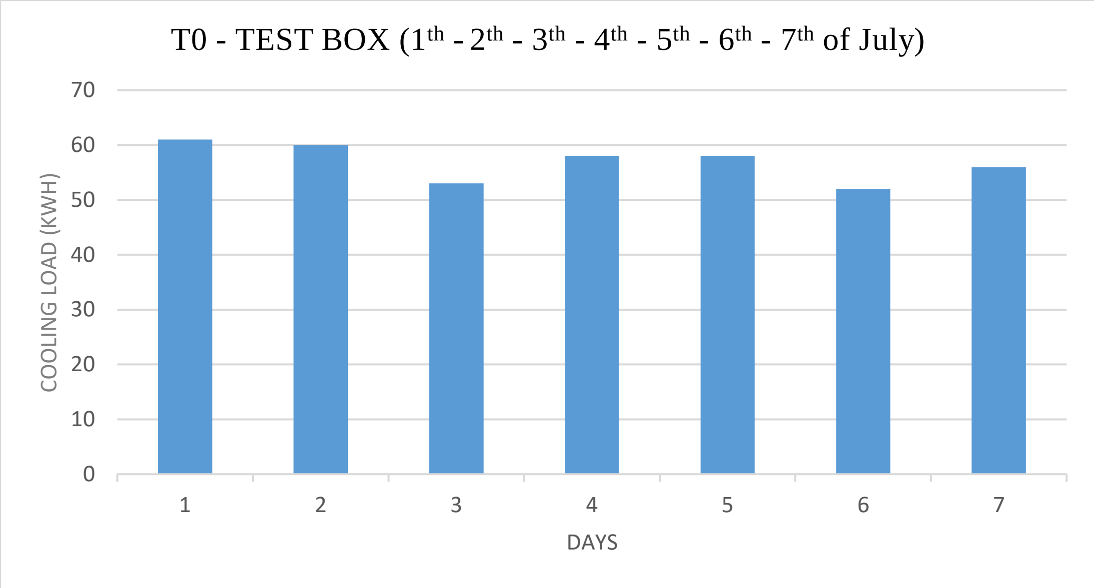


Figure 5.4. Test Box (T0) – Cooling Load Values

In addition, the distribution of cooling loads of the test box (T0) was created. This chart, which shows the distribution of the energy consumed by the test box for cooling against the hot and dry climate of Doha, Qatar, includes parameters such as sun, glazing conduction, wall conduction, infiltration, equipment, lighting and people. As seen in Figure 5.5, most of the cooling load is against the sun. From this point of view, it is seen how much the test box (T0) needs the biomimetic envelope system (shading device) developed within the scope of the study. (see Figure 5.5.)

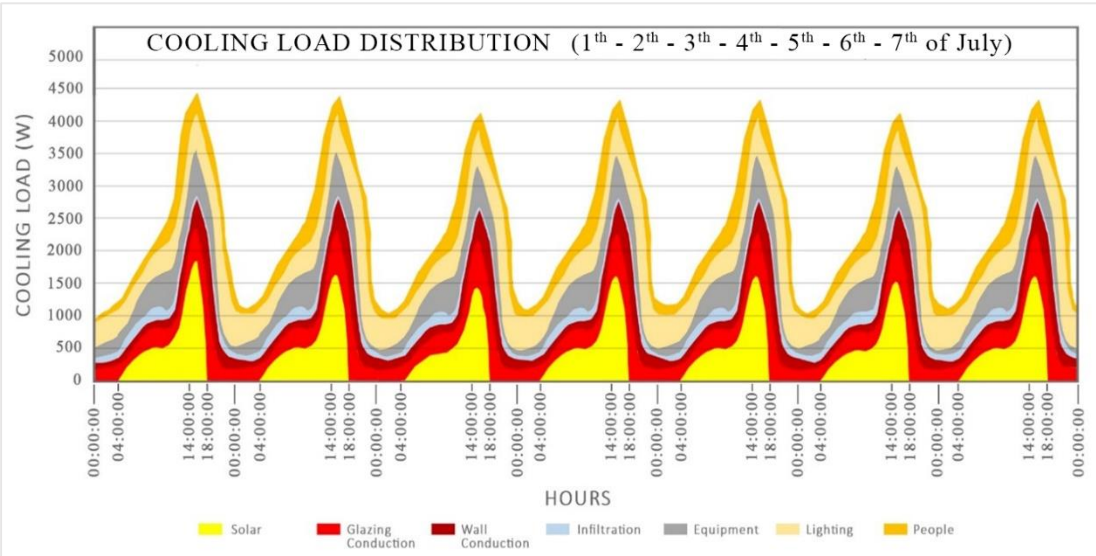


Figure 5.5. Test Box (T0) – Cooling Load Distribution

5.2.1.1. T1 - 30° Opening Angle & Single Layer ETFE

The opening angle was set to 30° in the **T1** variation. A single ETFE layer was used in this variation (T1). The technical information of the modules that make up the T1 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. The **total cooling load** for a week, computated after integrating the T1 biomimetic envelope system variation into the test box, is **297.50 kWh**. (see Figure 5.6.) and (see Figure 5.7.)

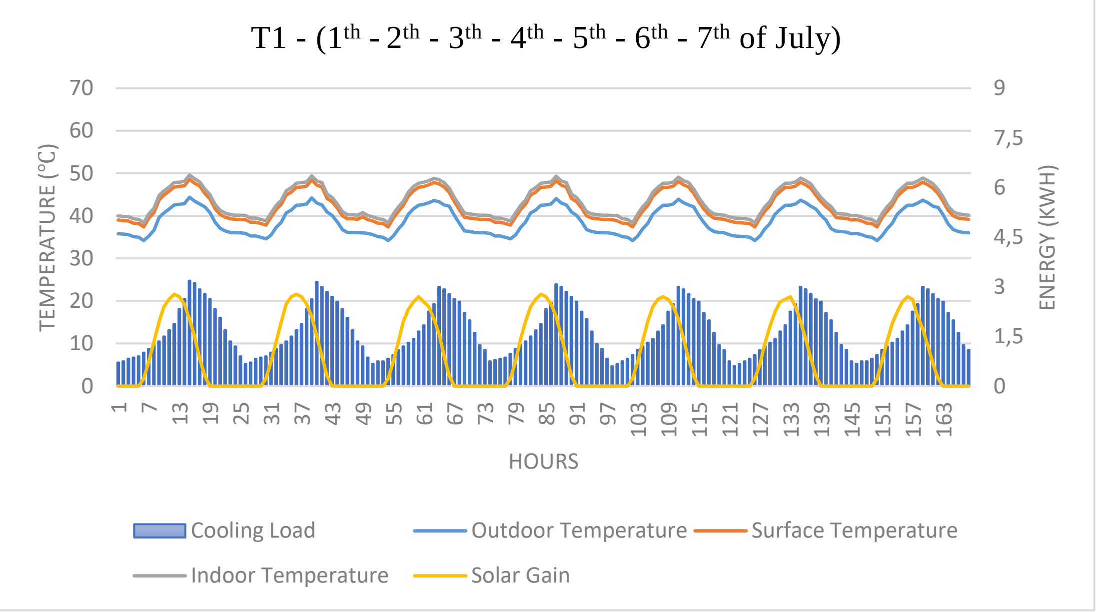


Figure 5.6. T1 – Values

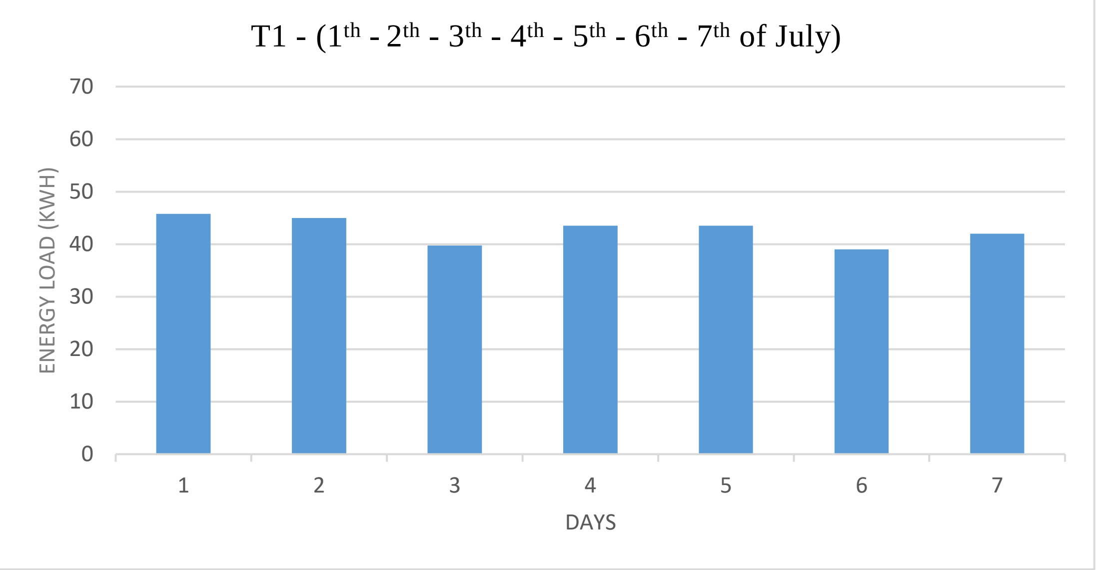


Figure 5.7. T1 – Cooling Load Values

5.2.1.2. T2 - 30° Opening Angle & Double Layer ETFE

The opening angle was set to 30° in the **T2** variation. A double ETFE layer was used in this variation (T2). The technical information of the modules that make up the T2 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. The **total cooling load** for a week, computated after integrating the T2 biomimetic envelope system variation into the test box, is **268,65 kWh**. (see Figure 5.8.) and (see Figure 5.9.)

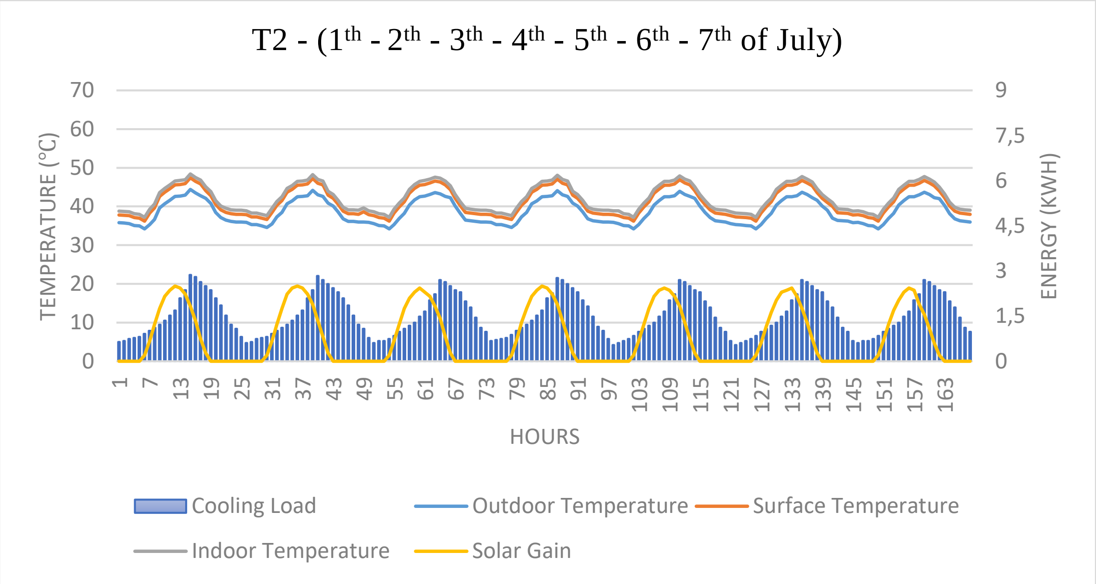


Figure 5.8. T2 – Values

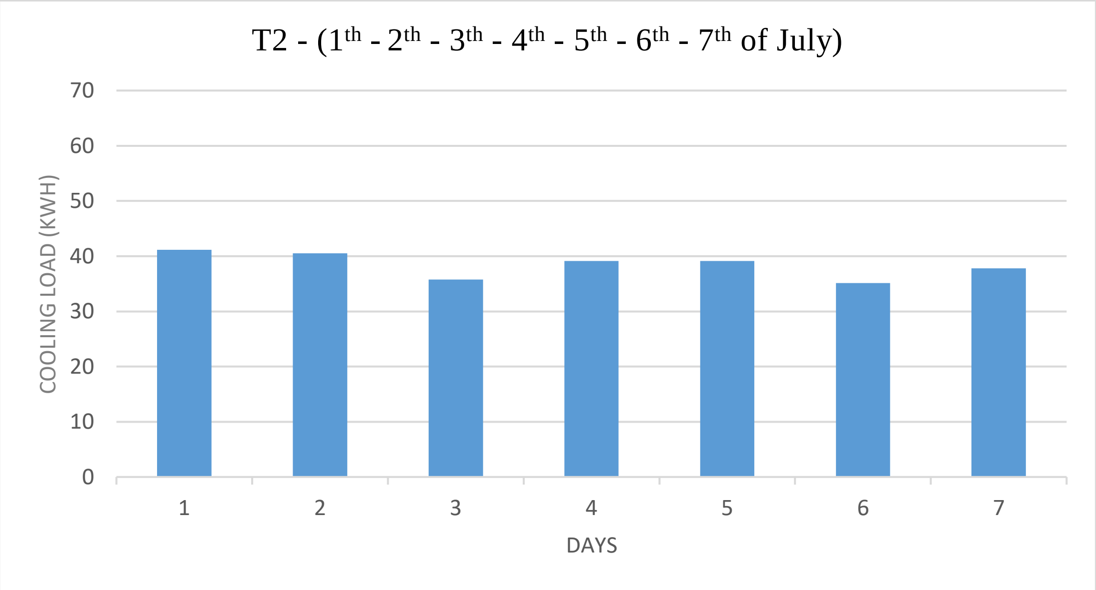


Figure 5.9. T2 – Cooling Load Values

5.2.1.3. T3 - 45° Opening Angle & Single Layer ETFE

The opening angle was set to 45° in the **T3** variation. A single ETFE layer was used in this variation (T3). The technical information of the modules that make up the T3 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. The **total cooling load** for a week, computated after integrating the T3 biomimetic envelope system variation into the test box, is **317,30 kWh**. (see Figure 5.10.) and (see Figure 5.11.)

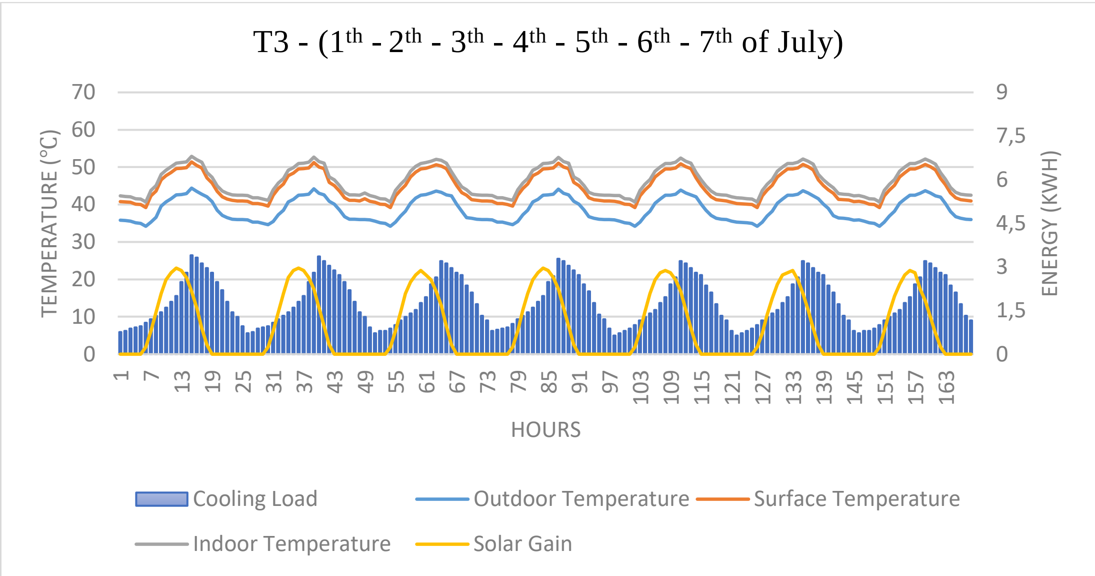


Figure 5.10. T3 – Values

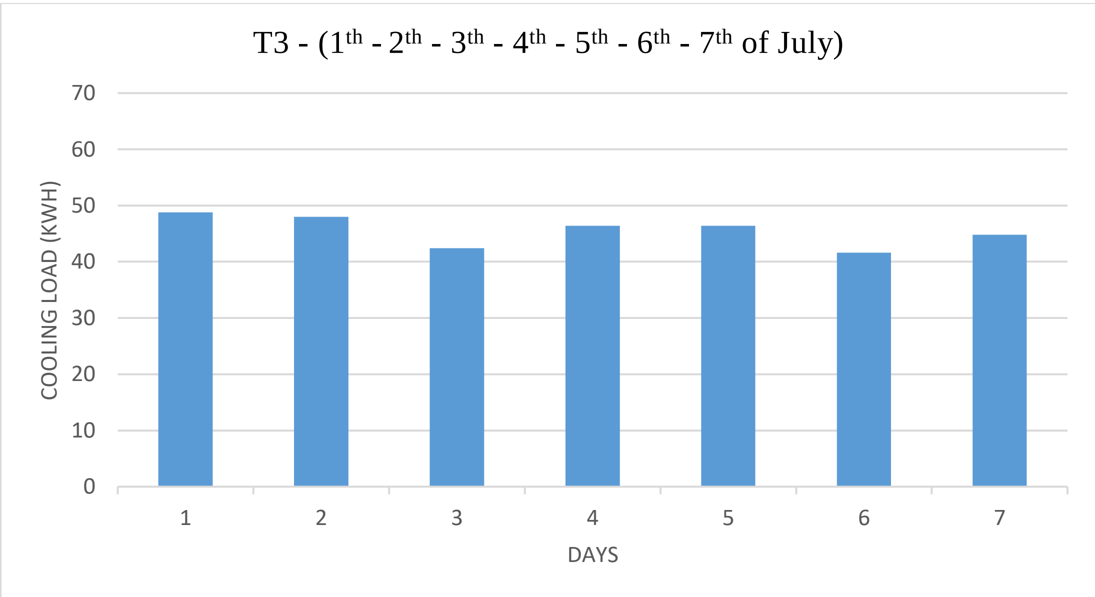


Figure 5.11. T3 – Cooling Load Values

5.2.1.4. T4 - 45° Opening Angle & Double Layer ETFE

The opening angle was set to 45° in the **T4** variation. A double ETFE layer was used in this variation (T4). The technical information of the modules that make up the T4 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. The **total cooling load** for a week, computated after integrating the T4 biomimetic envelope system variation into the test box, is **306,55 kWh**. (see Figure 5.12.) and (see Figure 5.13.)

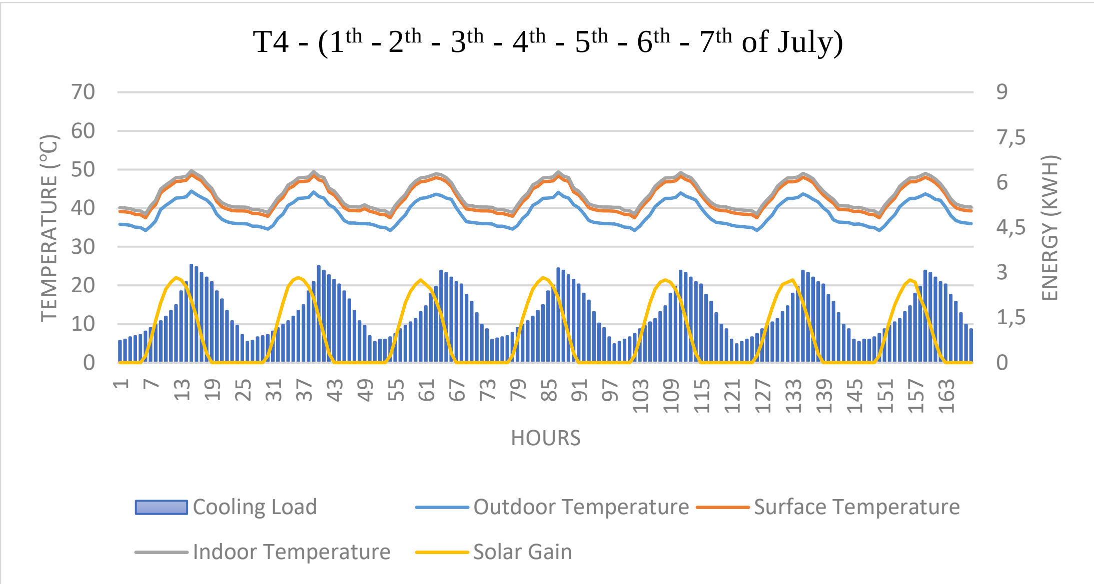


Figure 5.12. T4 – Values

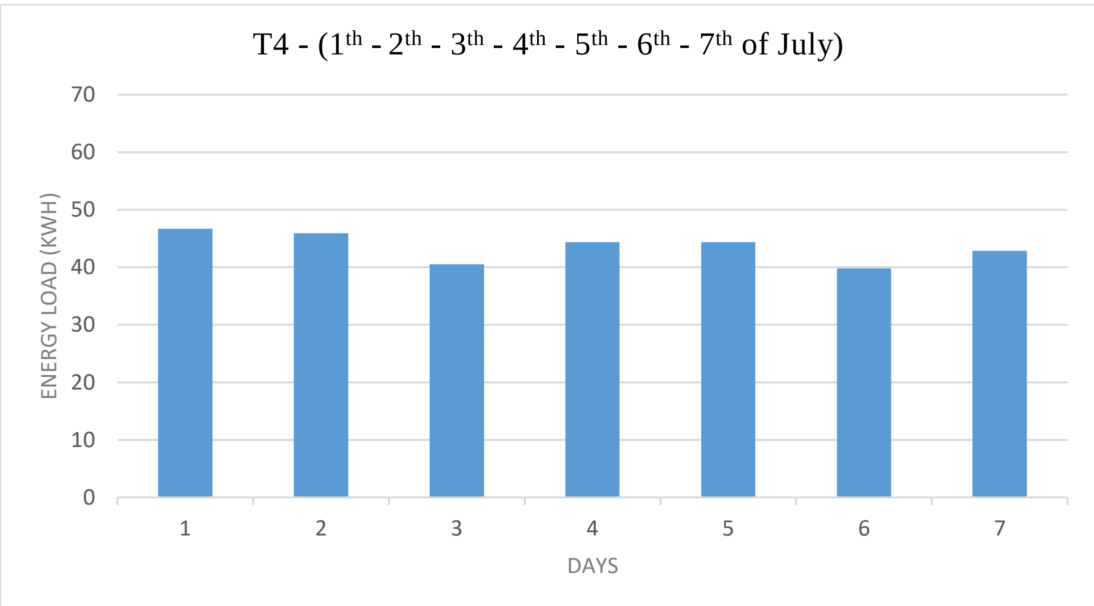


Figure 5.13. T4 – Cooling Load Values

5.2.1.5. T5 - 60° Opening Angle & Single Layer ETFE

The opening angle was set to 60° in the **T5** variation. A single ETFE layer was used in this variation (T5). The technical information of the modules that make up the T5 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. The **total cooling load** for a week, computated after integrating the T5 biomimetic envelope system variation into the test box, is **359,4 kWh**. (see Figure 5.14.) and (see Figure 5.15.)

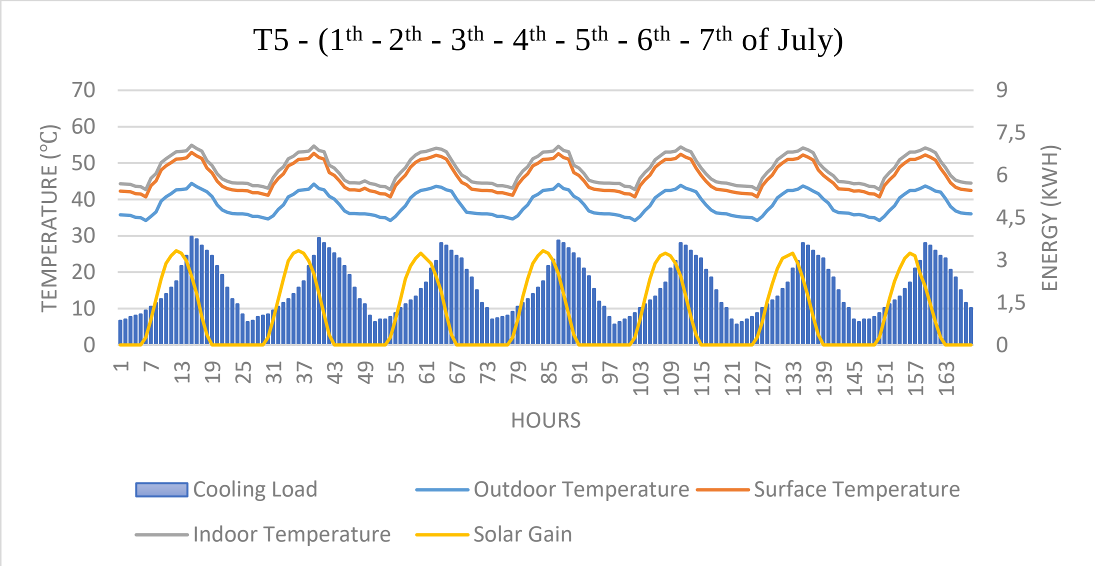


Figure 5.14. T5 – Values

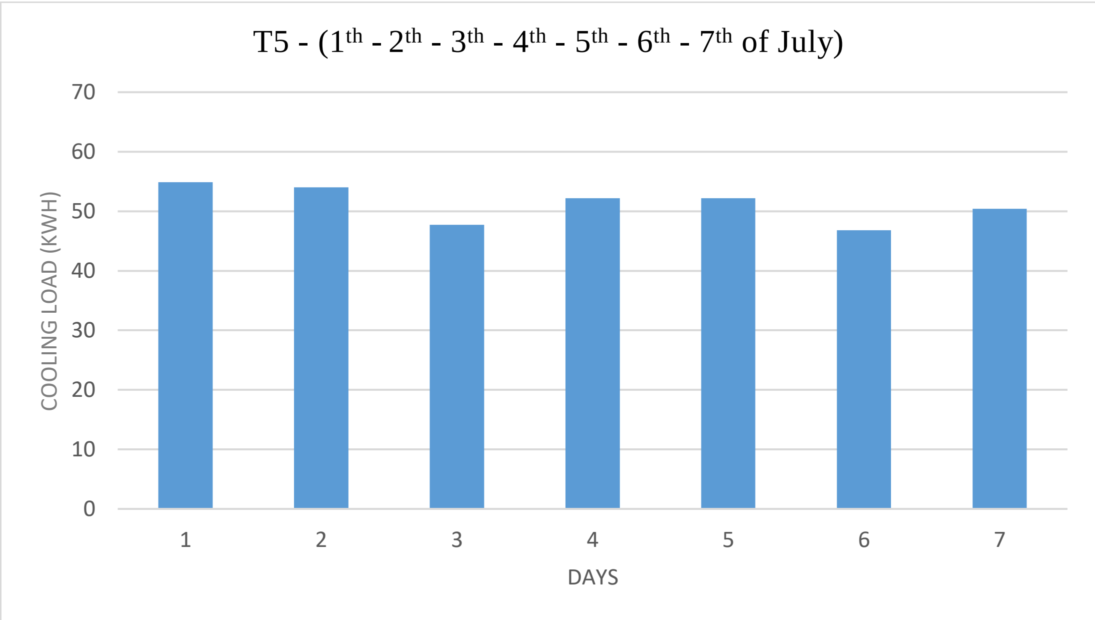


Figure 5.15. T5 – Cooling Load Values

5.2.1.6. T6 - 60° Opening Angle & Double Layer ETFE

The opening angle was set to 60° in the **T6** variation. A double ETFE layer was used in this variation (T6). The technical information of the modules that make up the T6 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. The **total cooling load** for a week, computated after integrating the T6 biomimetic envelope system variation into the test box, is **330,34 kWh.** (see Figure 5.16.) and (see Figure 5.17.)

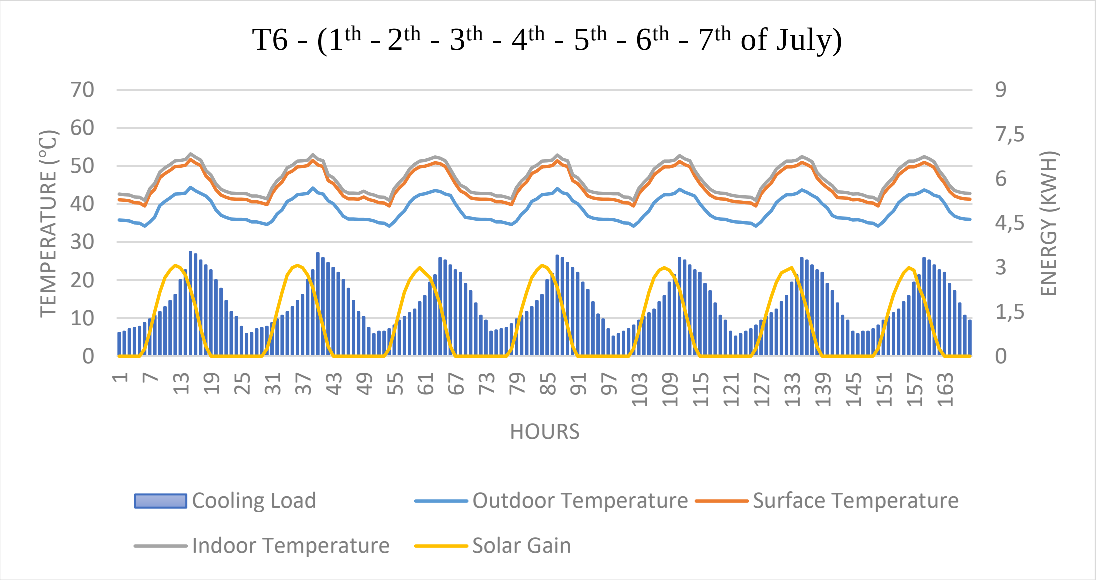


Figure 5.16. T6 – Values

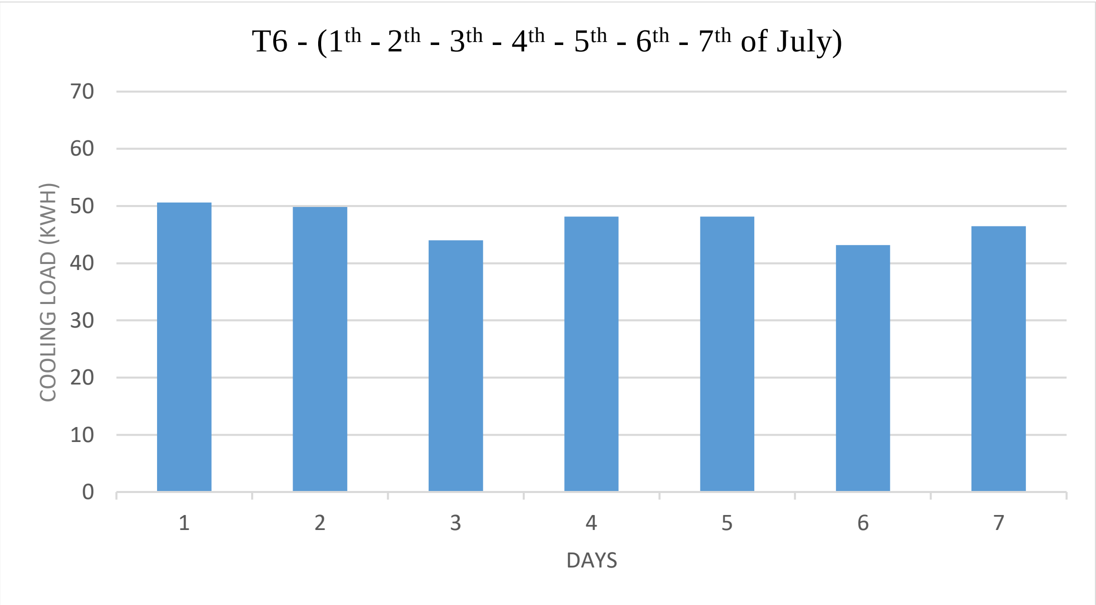


Figure 5.17. T6 – Cooling Load Values

5.2.2. Daylight

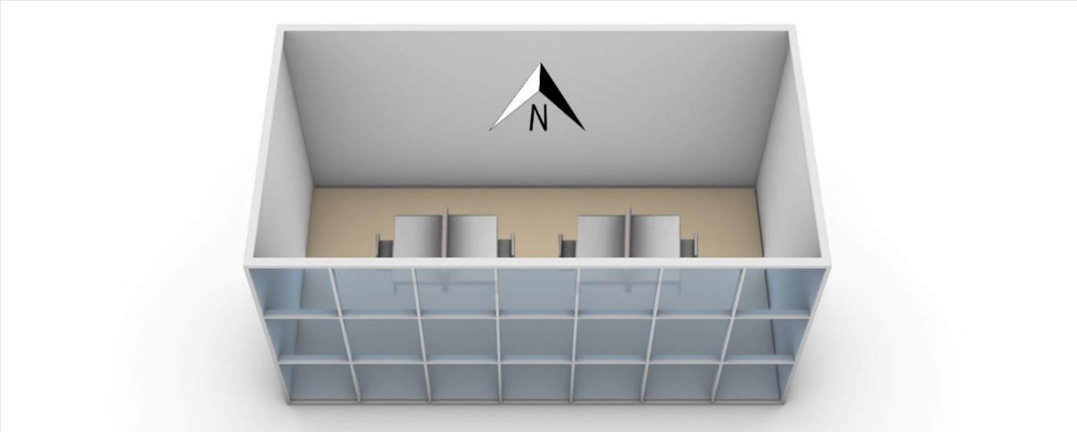


Figure 5.18. Open test box (T0) model for daylight analysis

Figure 5.18. shows that pen test box model developed within the scope of daylight analysis which shows the model for the importance of biomimetic envelope system (shading device). Most of the energy consumed within the scope of cooling load is to prevent solar heating. The office unit (test box), located on the south façade of the imaginary office building in Doha, Qatar, needs both natural lighting for the working comfort of its users and shading to prevent overheating. For this reason, daylight analyzes were developed in order to determine the biomimetic envelope system variations (T1 - T2 - T3 - T4 - T5 - T6), which provide **maximum daylight efficiency** by providing sufficient shade. (see Figure 5.1.)

The time zone in which the users spent the most time in the space was accepted as 07.30-19.30. **1th , 2th , 3th , 4th , 5th , 6th and 7th of July (between 07.30-19.30) daylight analysis** of the current state of the test box was performed before the biomimetic envelope system variations were integrated. For the analysis, the work table height (75cm) in the office unit was taken as a basis.

For daylight performance, the minimum threshold was initially defined as 300lux and the maximum threshold as 1500lux. In the legend representation obtained, the points of the test box that provided and did not provide values between **300-1500lux** during the year were expressed with the help of colors as percentages. According to the results of the analysis, it was determined that the areas close to the glass facade on the south side of the test box were outside the value between 300-1500lux. (see Figure 5.19.) These regions were found to be **uncomfortable**.

Afterwards, the minimum threshold was kept constant and the maximum threshold was set as **5000lux**. Thus, it was understood that the test box in Doha, Qatar, looked uncomfortable in the legend display, as it had a **lux value of much more than 1500 lux**. (see Figure 5.20.) It was determined that the biomimetic envelope variations developed from this point of view would be efficient in natural lighting for the test box. Daylight analyzes of all variations (T1 - T2 - T3 - T4 - T5 - T6) were performed.

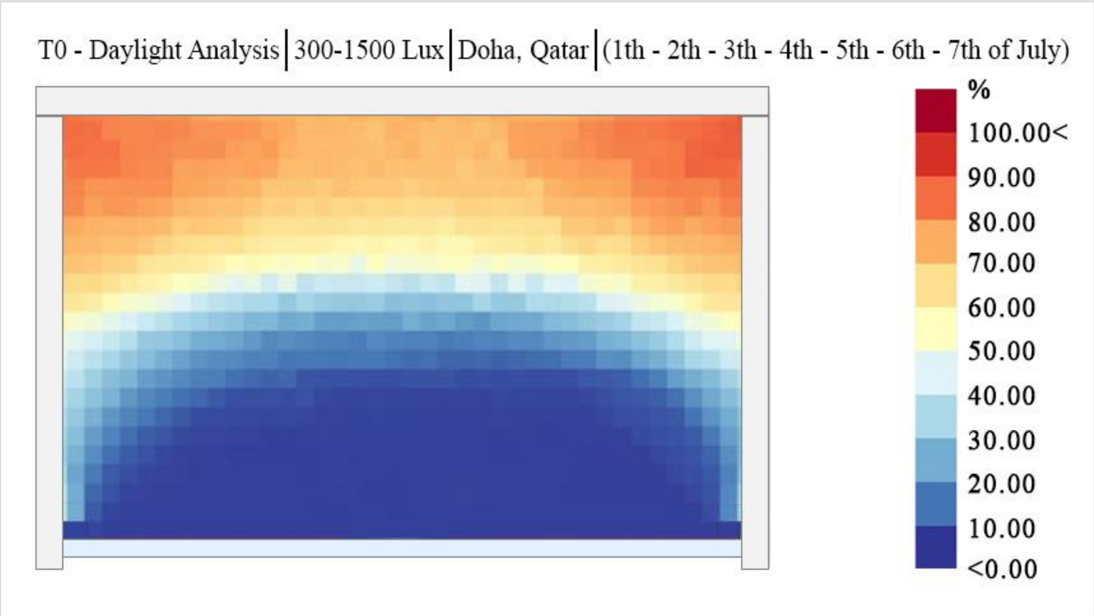


Figure 5.19. Test Box (T0) – Daylight Analysis (300-1500 Lux)

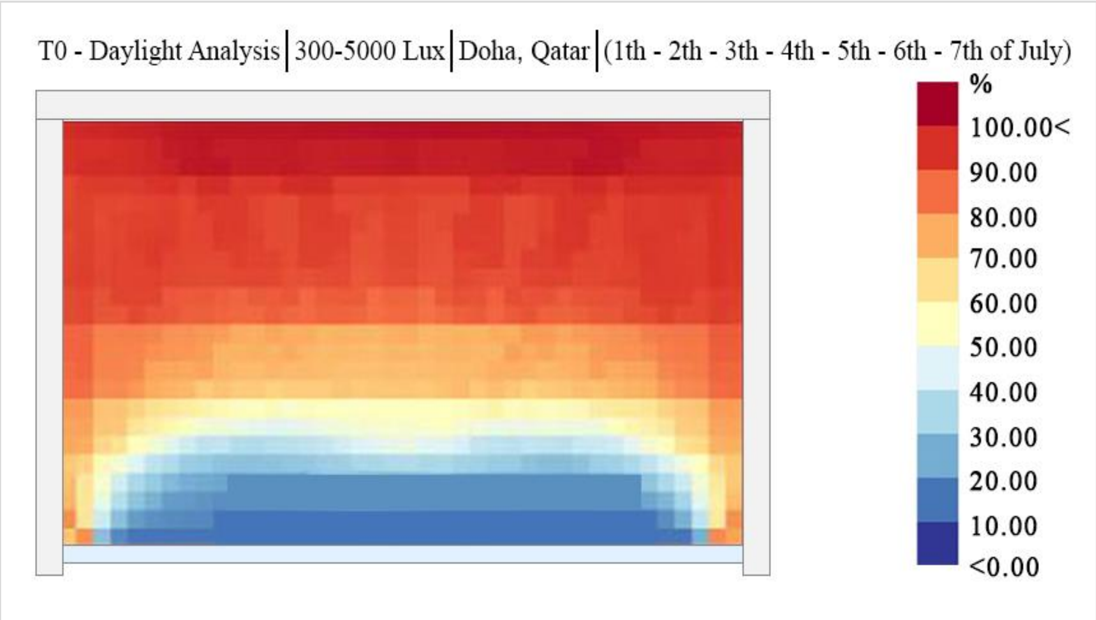


Figure 5.20. Test Box (T0) – Daylight Analysis (300-5000 Lux)

5.2.2.1. T1 - 30° Opening Angle & Single Layer ETFE

The opening angle was set to 30° in the **T1** variation. A single ETFE layer was used in this variation (T1). The technical information of the modules that make up the T1 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. After the T1 biomimetic envelope system variation is integrated into the test box, the one-week **daylight** legend display is as follows. (see Figure 5.21.)

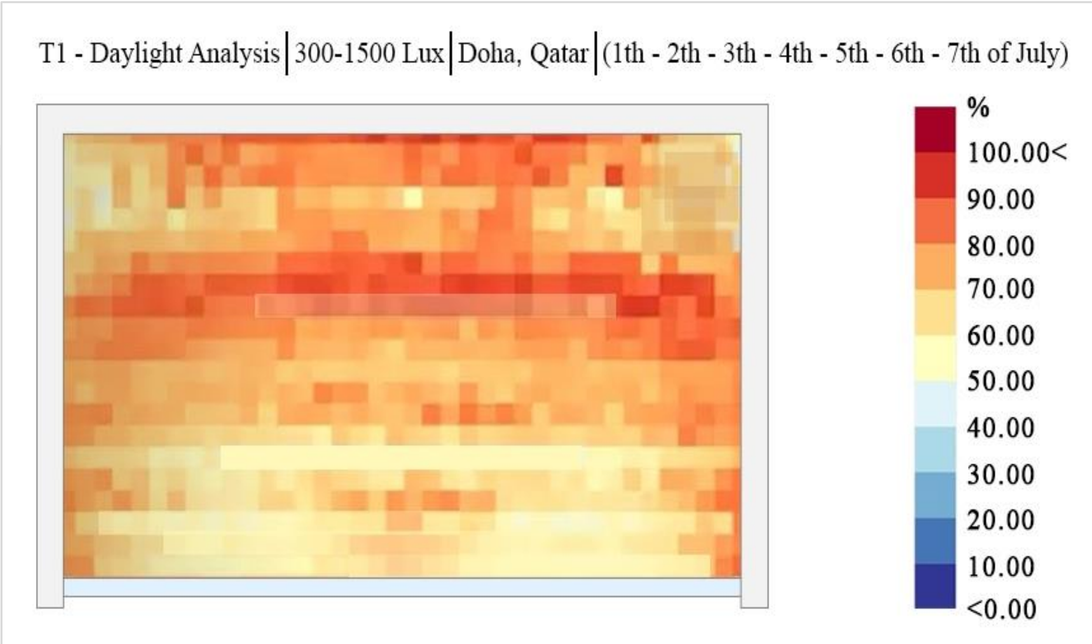


Figure 5.21. T1 – Daylight Analysis (300-1500 Lux)

5.2.2.2. T2 - 30° Opening Angle & Double Layer ETFE

The opening angle was set to 30° in the **T2** variation. A double ETFE layer was used in this variation (T2). The technical information of the modules that make up the T2 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. After the T2 biomimetic envelope system variation is integrated into the test box, the one-week **daylight** legend display is as follows. (see Figure 5.22.)

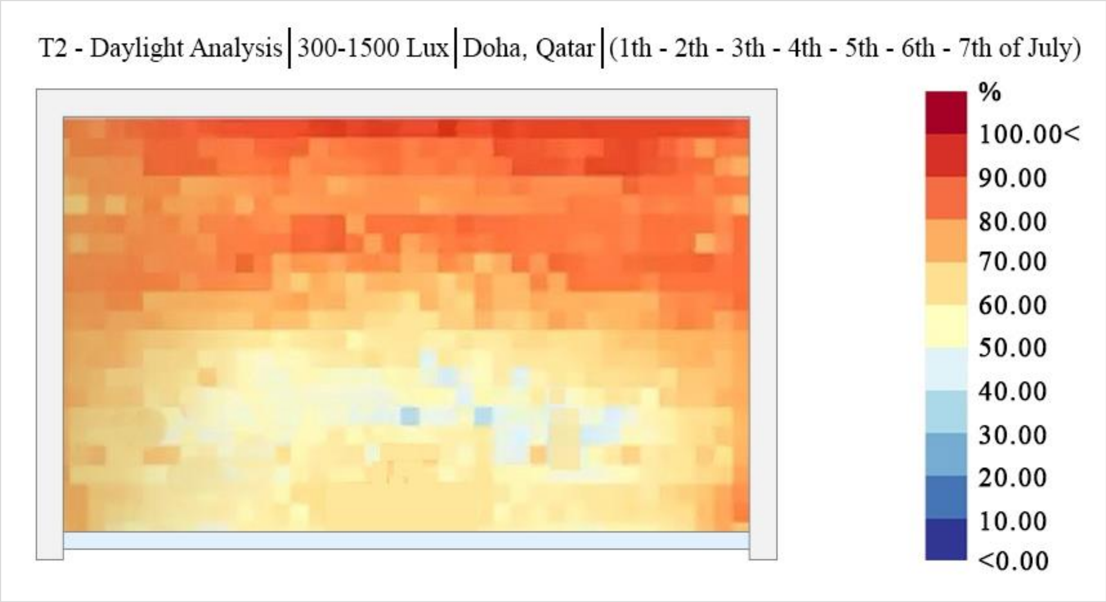


Figure 5.22. T2 – Daylight Analysis (300-1500 Lux)

5.2.2.3. T3 - 45° Opening Angle & Single Layer ETFE

The opening angle was set to 45° in the **T3** variation. A single ETFE layer was used in this variation (T3). The technical information of the modules that make up the T3 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. After the T3 biomimetic envelope system variation is integrated into the test box, the one-week **daylight** legend display is as follows. (see Figure 5.23..)

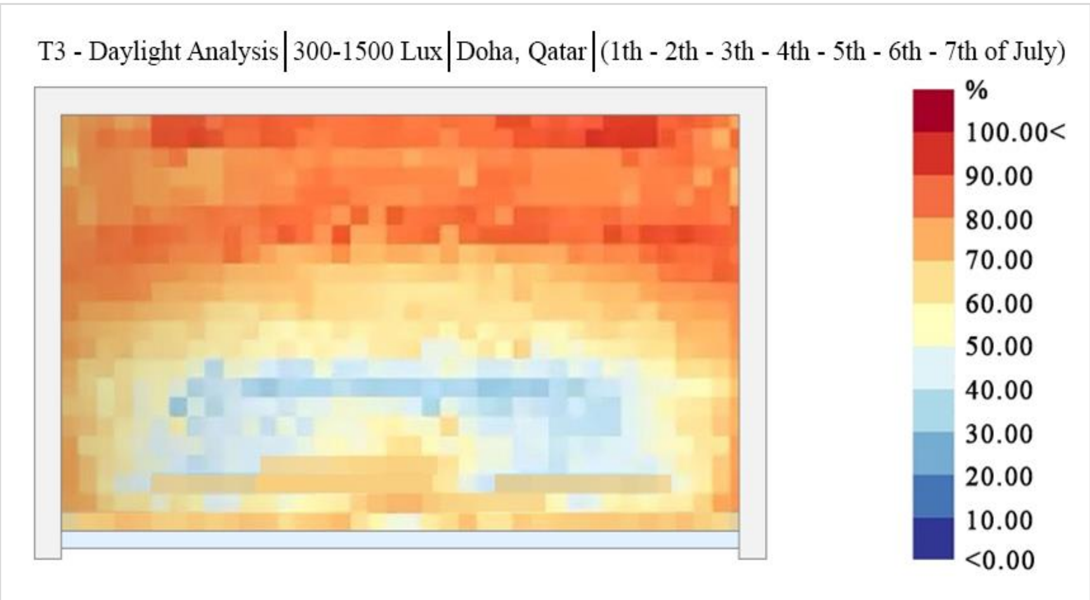


Figure 5.23. T3 – Daylight Analysis (300-1500 Lux)

5.2.2.4. T4 - 45° Opening Angle & Double Layer ETFE

The opening angle was set to 45° in the **T4** variation. A double ETFE layer was used in this variation (T4). The technical information of the modules that make up the T4 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. After the T4 biomimetic envelope system variation is integrated into the test box, the one-week **daylight** legend display is as follows. (see Figure 5.24.)

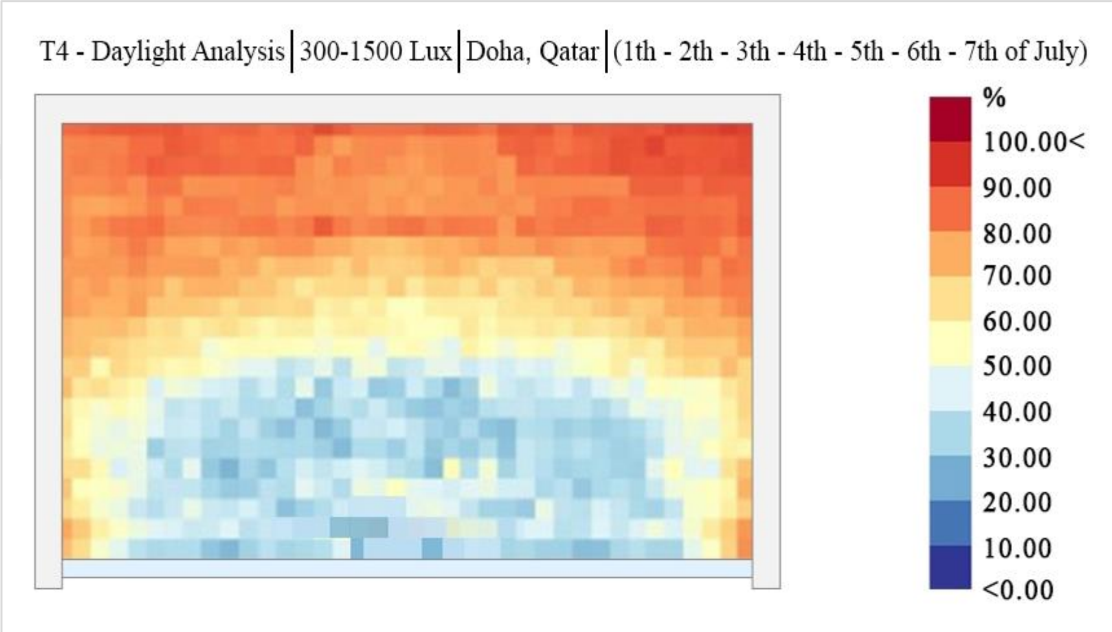


Figure 5.24. T4 – Daylight Analysis (300-1500 Lux)

5.2.2.5. T5 - 60° Opening Angle & Single Layer ETFE

The opening angle was set to 60° in the **T5** variation. A single ETFE layer was used in this variation (T5). The technical information of the modules that make up the T5 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. After the T5 biomimetic envelope system variation is integrated into the test box, the one-week **daylight** legend display is as follows. (see Figure 5.25.)

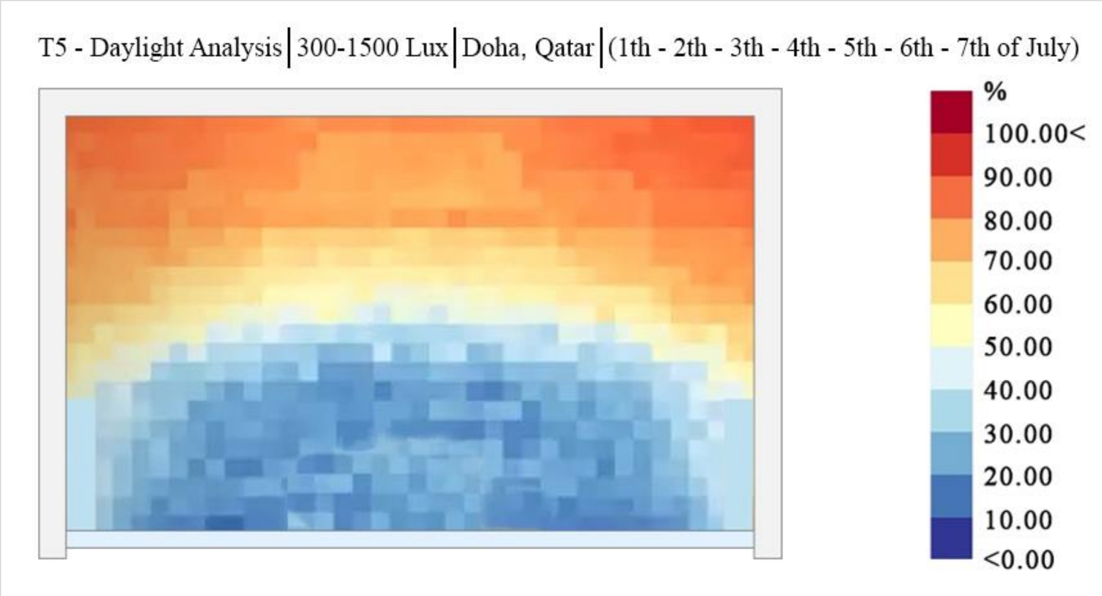


Figure 5.25. T5 – Daylight Analysis (300-1500 Lux)

5.2.2.6. T6 - 60° Opening Angle & Double Layer ETFE

The opening angle was set to 60° in the **T6** variation. A double ETFE layer was used in this variation (T6). The technical information of the modules that make up the T6 and the section and elevation view of this variation integrated into the south façade of the test box (T0) are given in detail in Figure 5.1. above. After the T6 biomimetic envelope system variation is integrated into the test box, the one-week **daylight** legend display is as follows. (see Figure 5.26.)

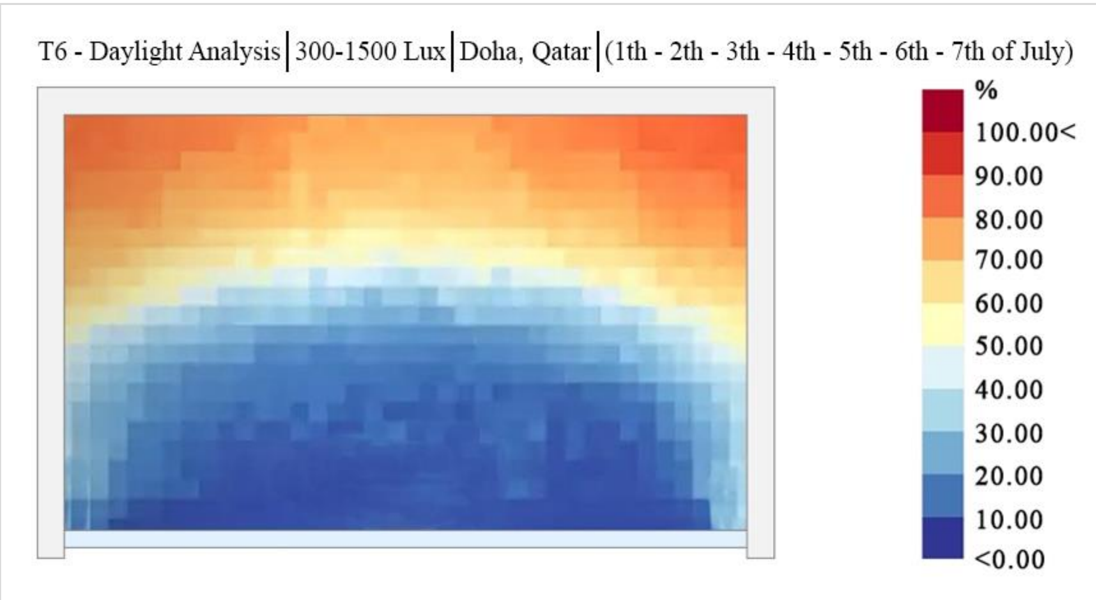


Figure 5.26. T6 – Daylight Analysis (300-1500 Lux)

5.2.3. Comparison of the Simulations

In this section, the variations (T1, T2, T3, T4, T5, T6) are compared with each other in terms of cooling load values, daylight efficiency and indoor temperature by looking at the outputs of their simulations. As seen above, results are for the first week (1th - 2th - 3th - 4th - 5th - 6th - 7th of July) of July for all variations.

5.2.3.1. Cooling Load Values

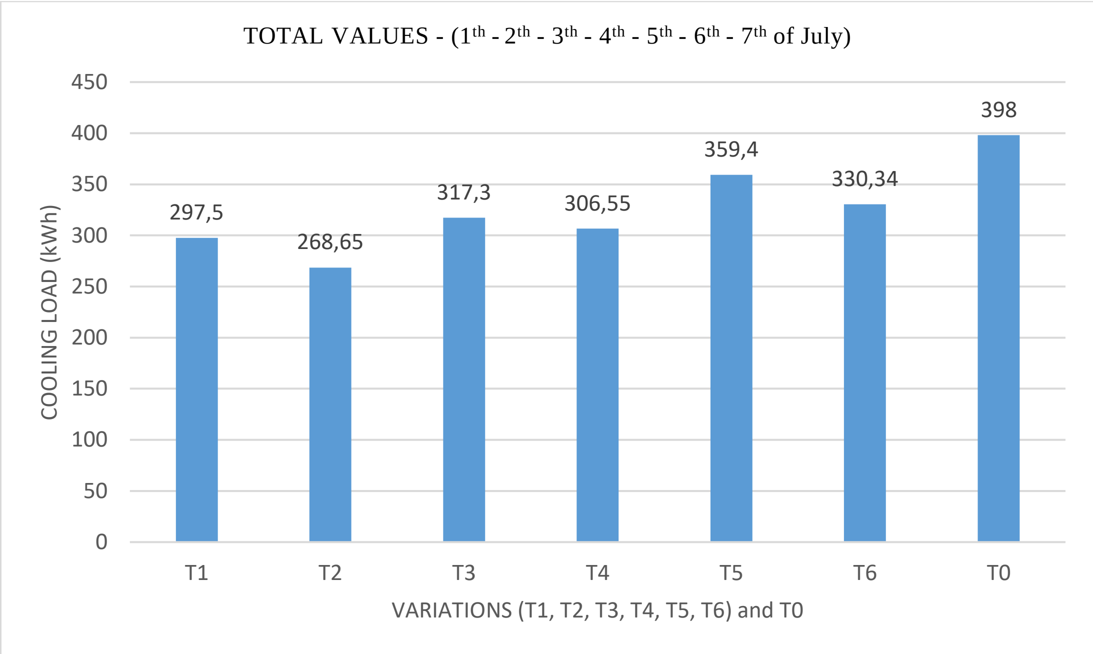


Figure 5.27. Comparison of Cooling Load Values

As seen in Figure 5.27., the total cooling load values of all biomimetic envelope system variations (T1, T2, T3, T4, T5, T6) and the test box (T0) during the week covering the first seven days of July are given. Comparing the existing variation of the test box (T0) with the integrated variations of the developed biomimetic envelope system (shading device) variations, it is observed that Doha, Qatar needs any envelope system variation against the extremely hot climate. (see Figure 5.27.)

When the cooling load values of the developed variations were compared among themselves, the following conclusions were reached. The differences in the opening angles (30°, 45°, 60°) of the modules that make up the biomimetic envelope system variations and the number of ETFE layers (single & double) change the amount of sun exposure of the test box (T0) during the day. As the opening angles of the modules increase, the south side of the test box is exposed to more direct sunlight. This causes the test box to overheat. Thus, the test box consumes more energy for cooling in order to balance the indoor comfort. As the number of ETFE layers, which is another variable parameter of the modules, increases, the opacity of the modules increases, thus blocking the sun rays more. In this case, the test box heats up more in the variations with modules with single layer ETFE, since they absorb less sunlight compared to the variations with double layer ETFE. Thus, the test box consumes more energy for cooling.

As a result, when the total cooling load values during the week (1th - 2th - 3th - 4th - 5th - 6th - 7th of July) computated separately for all biomimetic envelope system variations (T1, T2, T3, T4, T5, T6) were compared, it was determined that the **T2** (30° Opening Angle & Double Layer ETFE) variation was the **most efficient** in terms of energy spent for cooling. 30 degree opening angle and double layer ETFE are used in the modules that make up the T2 variation. The most **inefficient variation** was also found to be **T5** (60° Opening Angle & Single Layer ETFE). 60 degree opening angle and single layer ETFE are used in the modules that make up the T5 variation. More detailed information about the variations and test box can be found in Figure 5.1.

5.2.3.2. Daylight Efficiency

As seen in Figure 5.28., the daylight analysis results of all biomimetic envelope system variations (T1, T2, T3, T4, T5, T6) and the test box during the week covering the first seven days of July are expressed in colors with the legend of percent. Comparing the existing variation of the test box (T0) with the integrated variations of the developed biomimetic envelope system (shading device) variations, it is observed that Doha, Qatar needs any envelope system variation against the extremely hot climate and extremely sun rays. (see Figure 5.28.)

When the daylight analysis results of the developed variations were compared among themselves, the following conclusions were reached. The differences in the opening angles (30°, 45°, 60°) of the modules forming the biomimetic envelope system variations and the number of ETFE layers affect the daylight efficiency of the test box (T0) during the day. As the opening angles of the modules increase, the bottom parts of the test box away from the facade are directly exposed to more and uncomfortable sun rays, while the parts close to the glass facade receive less daylight due to the extension and steepening of the modules. This shows that the interior is uncomfortable and uncontrolled at the lighting point. As the number of ETFE layers, which is another variable parameter of the modules, decreases, the transparency (light transmittance) of the modules increases, so it absorbs less sunlight. In this case, the test box receives more uncontrolled and uncomfortable daylight in the variations with the modules with single layer ETFE, since they absorb less sunlight compared to the variations with double layer ETFE. (see Figure 5.28.)

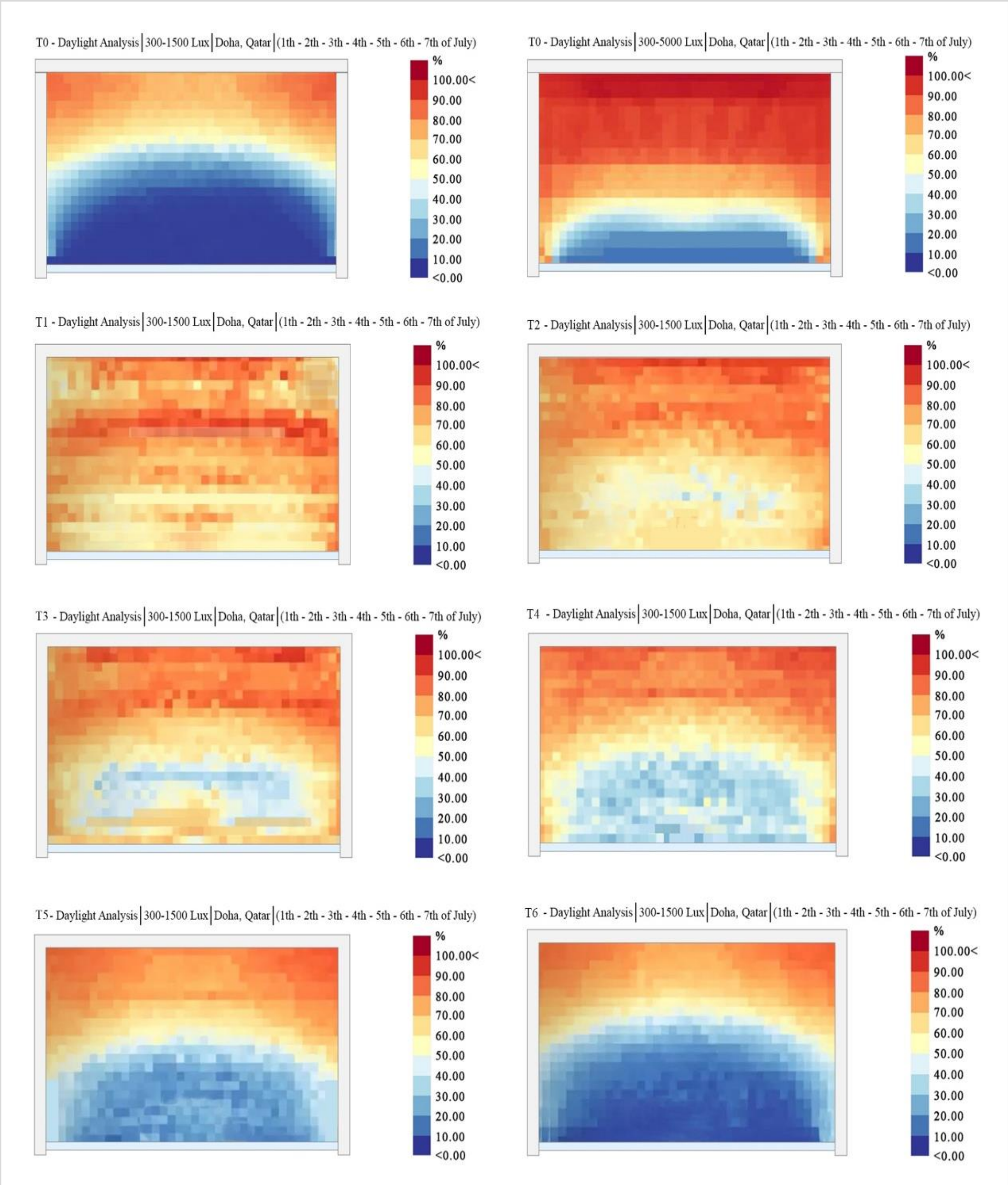


Figure 5.28. Comparison of Daylight Efficiency

In light of the knowledge that the test box serves as an office unit, it should provide comfortable lighting for its users for working during the day. Therefore, the test box has to balance indoor lighting comfort. It is necessary to avoid the test box being dark between working hours. Because the need for artificial lighting sources will increase and there will be more energy consumption. On the other hand, when the test box is exposed to excessive sunlight, an uncomfortable office space will be created for the employees and additional shading device solutions will be required. In summary, it is very important to determine the variation that can bring the most comfortable daylight into the interior from the solution set.

As a result, according to the analysis results obtained separately for all biomimetic envelope system variations (T1, T2, T3, T4, T5, T6), the efficiencies obtained from daylight during the week (1th - 2th - 3th - 4th - 5th - 6th - 7th of July) were compared. Considering the knowledge that an **ideal office lighting** should be between **300/550 lux** lighting levels, it has been determined that **T1 and T2** (30° Opening Angle & Single or Double Layer ETFE) variations are the most efficient in terms of natural daylight gain without much need for artificial lighting sources. 30 degree opening angle and single or double layer ETFE are used in the modules that make up the T1 and T2 variations. The most **inefficient** variations was found to be **T5 and T6** (60° Opening Angle & Single or Double Layer ETFE). 60 degree opening angle and single or double layer ETFE are used in the modules forming the T5 and T6 variations. More detailed information about the variations can be found in Figure 5.1.

5.2.3.3. Indoor Temperature

As seen in Figure 5.29, all biomimetic envelope system variations (T1, T2, T3, T4, T5, T6) and indoor temperatures of the test box are given during the week covering the first seven days of July. Comparing the existing variation of the test box (T0) with the integrated variations of the developed biomimetic envelope system variations, it is observed that Doha, Qatar needs any envelope system (shading device) variation to provide indoor comfort against the extremely hot climate. (see Figure 5.29.)

When the indoor temperature values of the developed variations were compared among themselves, the following conclusions were reached. The differences in the opening angles (30°, 45°, 60°) of the modules that make up the biomimetic envelope system variations and the number of ETFE layers change the indoor temperature of the test box during the day. As the opening angles of the modules increase, the south side of the test box is exposed to more direct sunlight. This increases the indoor temperature of the test box. Thus, the test box consumes more energy for cooling in order to balance the indoor comfort. As the number of ETFE layers, which is another variable parameter of the modules, increases, the opacity of the modules increases, thus blocking the sun rays more. In this case, the indoor temperature of the test box increases even more in the variations with modules with single layer ETFE, since they absorb less sunlight compared to the variations with double layer ETFE.

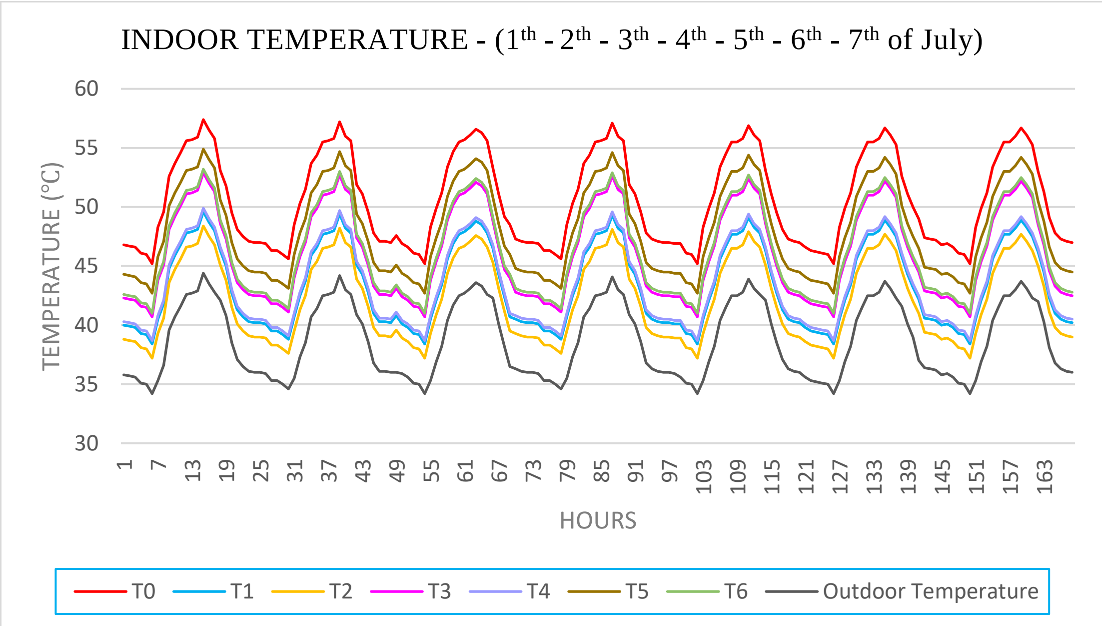


Figure 5.29. Comparison of Indoor Temperatures with Outdoor Temperature

The average **outdoor temperature** during the hottest week (1th - 2th - 3th - 4th - 5th - 6th - 7th of July) in Doha, Qatar, where the test box is located, is **38.60** degrees Celsius. The current state of the test box **(T0)** without any shading device is the average **indoor temperature** of **50.5** degrees Celsius, analyzed according to the climate data of Doha, Qatar. The reason for this is that the selected test box faces south and has a glass facade. As a result, when weekly indoor temperatures were compared for all biomimetic envelope system variations (T1, T2, T3, T4, T5, T6) and test box (T0), it was observed that all biomimetic envelope system variations decreased indoor temperature. T2 (30° Opening Angle & Double Layer ETFE) variation was the type that could reduce the indoor temperature the most compared to other variations. During the aforementioned week (1th - 2th - 3th - 4th - 5th - 6th - 7th of July), the average

indoor temperature when the **T2** variation was integrated into the test box was **42.1** degrees Celsius. 30 degree opening angle and double layer ETFE are used in the modules forming the T2 variation. T5 (60° Opening Angle & Single Layer ETFE) variation has been the type that can reduce the indoor temperature the least compared to other variations. The average **indoor temperature** during the aforementioned week when the **T5** variation was integrated into the test box was **48** degrees Celsius. A 60 degree opening angle and a single layer of ETFE are used in the modules that make up the T5 variation. More detailed information about the variations and test box can be found in Figure 5.1.

CHAPTER 6
CONCLUSION

This thesis research both details the design process and evaluates the performance of the energy efficiency-based biomimetic envelope system, which was developed with a nature-inspired approach for the south façade of an office unit (T0) located in a fictional high-rise office building in Doha, Qatar. Evaluation of the biomimetic envelope system within the scope of both the design and architectural integration process is done by comparing the solution sets consisting of the biomimetic envelope system variations (T1, T2, T3, T4, T5, T6) created with the test box (T0) among themselves. The proposed biomimetic envelope system (shading device) design has detailed structural features and high potential in terms of function. The main purpose of the final design decision of the developed biomimetic envelope system is to improve the target building in terms of air, heat, light and water parameters. Shading units (biomimetic units) developed in the light of these four potential parameters come together to form a system that can be integrated into the façade later. Based on limitations, the research process focuses solely on the biomimetic envelope system. On the other hand, the structural elements of the test box (T0) are not included in the improvement and development process. For this reason, the solution set created with the developed biomimetic envelope system simulation variations was carried out based on the simulation results of the proposed variations, which allowed rational decisions to be made to address the design process of this research at an early stage. The potential function of the research process is to provide a comfortable office for users in Doha, which has a hot and dry climate, by providing maximum shading and achieving minimum cooling load and maximum daylight targets. In addition, the developed shading units produce energy from the sun thanks to the panels. The prospective potential vision of the study is to meet the partial water needs of the building and cool it thanks to the structural capillary pipe system that can hold traces of moisture in the air.

In general, the architectural integration process methodology includes case studies consisting of 6 different variations obtained by differentiating only two elements of the biomimetic envelope system developed for the south façade of a unit of an imaginary office building in Doha, Qatar. This process consists of a series of analysis steps to obtain many outputs and to make the design decision more accurate.

- Temperature analysis (outdoor temperature, indoor temperature, surface temperature)
- Wind analysis
- Moisture analysis
- Solar gain analysis
- Cooling load distribution
- Cooling load values (comparison)
- Daylight efficiency (comparison)
- Indoor temperature analysis (comparison)

Following the analysis steps outlined above, the 3 main factors responsible for the final selection decision of the most efficient of the biomimetic envelope system variations are:

- Cooling load values: minimizing energy consumption for cooling by providing efficient shading
- Daylight efficiency: minimizing the use of artificial lighting sources by obtaining maximum efficiency from daylight
- Indoor temperature: ensuring indoor comfort for users

6.1. Results Comparison and Selection

As a summary of the results of the research;

- The cooling load value of the T0 is at least 40 kWh more than the existing version of the T0, where the biomimetic envelope system variations are integrated. This shows that the developed biomimetic envelope system variations significantly reduce the amount of energy spent for cooling and improve energy efficiency.

- The test box (T0) has much lower daylight efficiency than when biomimetic envelope system variations are integrated. This shows that with the developed biomimetic envelope system variations, daylight gain is achieved and energy efficiency is achieved by reducing the use of artificial lighting sources.
- The indoor temperature is a maximum of 8°C higher than the T0, where the biomimetic envelope system variations are integrated. This shows that the developed biomimetic envelope system variations significantly reduce the indoor temperature and improve indoor comfort.
- The T2 variation is the type with the least cooling load value compared to all other variations. The T2 variation consumes 130 kWh less energy for cooling than theT0 with no variations integrated.
- T1 and T2 variations are the best types that allow controlled and efficient use of daylight compared to all other variations. T1 and T2 best meet the range of 300-550 Lux at the lighting point in office spaces. If T1 and T2 are compared among themselves, T1 variation is the most efficient in daylight.
- The T2 variation lowers the indoor temperature more than all other variations. The T2 variation keeps the interior 8°C cooler than the T0 with no variation integrated.

After summarizing the results, **T2** variation is the most efficient among the envelope system variations created with the energy efficiency-based biomimetic approach within the scope of the thesis.

6.2. Future Studies

The research focused on the energy efficiency of the envelope system design, which was developed with a biomimetic approach, at the point of cooling and lighting. The developed design is completely based on four main parameters. These parameters are air, heat, light and water. However, the research was limited due to the inadequacy of the computational tools. Of all the potential functions targeted, some are constrained during the design process as they cannot be analyzed.

If there is an innovation in the computation tools with the developing technology in the future, all the functions of the proposed design can be evaluated together with the analysis results. To give an example, in the design process, thanks to the porous capillary pipes that provide the structural strength of the modules that make up the biomimetic envelope system, by capturing the humidity in the air, both the partial water requirement of the building and the cooling rate of the building can be computated thanks to the water drops caught from the air. This developed concept can be explored in more detail with the analysis and simulation process. In addition, technologies such as potential energy-generating solar panels used in this study can be included in energy computations, thereby encouraging the use of renewable energy.

The differences in the opening angles of the modules and the number of ETFE layers, which enable the creation of a solution set consisting of biomimetic envelope system variations, can be obtained by using solar path tracking sensors. In this way, the opening angle and transparency level of the modules on the façade can change according to the movements of the sun. Without the need for all the variations created, a single variation can fulfill all its functions with automation according to the solar movements.

In general, this research encourages architects to use biomimetic approaches and to bring more sustainable and permanent solutions to their designs with these approaches.

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