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Biomimetic approach for energy-efficient building envelope design in Doha

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Abstract

In this study, an approach is proposed for building envelope designs that directly affect the energy consumption of buildings in response to the ever-increasing energy demand of the built environment due to the increasing population around the world. Within the scope of the study, it is aimed to improve the energy efficiency of the building envelope system created with a nature-inspired approach, by considering both the design and simulation processes together. The entire architectural integration process of this envelope system, developed for the office unit located on the south facade of a fictitious office building in Doha, Qatar, with extreme weather conditions, is discussed. The effects of the developed biomimetic envelope design on cooling load and daylight parameters are analyzed along with the simulation outputs generated throughout the study. As a result of the study, it was observed that the building envelope system created with the biomimetic approach improved the building in terms of energy efficiency.

Keywords: *Energy-efficiency, thermal analysis, daylight, biomimetic approach.*

Doha'da enerji verimli bina kabuğu tasarımı için biyomimetik yaklaşım

Öz

Bu çalışmada dünya genelinde artan nüfusa bağlı olarak yapılı çevrenin her geçen gün artan enerji talebine karşılık binaların enerji tüketimini doğrudan etkileyen bina kabuk tasarımları için bir yaklaşım önerilmektedir. Çalışma kapsamında doğadan ilham alan yaklaşımla oluşturulan bina kabuk sisteminin hem tasarım hem de simülasyon süreçleri

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birlikte ele alınarak enerji verimliliği noktasında iyileştirme hedeflenmektedir. Ekstrem hava koşullarına sahip Doha, Katar'da hayali bir ofis binasının güney cephesinde yer alan ofis birimi için geliştirilen bu kabuk sisteminin tüm mimari entegrasyon süreci ele alınmaktadır. Çalışma boyunca oluşturulan simülasyon çıktıları ile birlikte geliştirilen biyomimetik kabuk tasarımının soğutma yükü ve gün ışığı parametreleri üzerine etkileri analiz edilmektedir. Çalışma sonucunda biyomimetik yaklaşımla oluşturulan bina kabuk sisteminin binayı enerji verimliliği açısından iyileştirdiği gözlemlenmiştir.

Anahtar kelimeler: *Enerji verimliliği, termal analiz, gün ışığı, biyomimetik yaklaşım.*

1. Introduction

The increase in the world population every year brings with it concerns about energy demand. Demologists expect world population growth to continue for several decades, let alone stop. Spanish researcher Gilles Pison predicts that the world population may increase by another 2 billion by the end of the 21st century [1]. The energy demand that emerged with the increase in the world population in the last half century is one of the main reasons for the sharp increase in energy consumption [2]. Changes in the basis of energy consumption arise from the need to improve living standards day by day along with technological developments [3]. On the other hand, rapidly increasing energy consumption, difficulty in accessing energy, depletion of natural resources and current global problems (climate change, global warming, carbon emissions, ozone layer depletion, etc.) have kept energy-related issues on the agenda in recent years [4].

Energy is an indispensable factor for all living things, especially humanity, to continue their vital activities. People need energy in most parts of their daily lives. For this reason, it should be considered normal that concerns about meeting the increasing energy demand around the world are increasing day by day. Because with technological developments, all vital functions of humanity are becoming more dependent on energy day by day. Changes in basic needs such as shelter, heating, cooking, production, communication and transportation, which directly affect people's daily lives, increase energy demand [5]. Countries with rich and developed economies have improved daily life by meeting the energy demand of the increasing population with clean and renewable energy sources as much as possible [6]. However, in order to meet the increasing energy demand worldwide, there is a trend towards non-renewable, environmentally harmful energy sources. A large part of the world's energy needs are met from environmentally harmful and non-renewable energy sources such as oil, coal and natural gas. In response to the increasing energy demand worldwide, serious measures need to be taken regarding the use of renewable and clean energy resources [7].

According to the International Energy Agency's 2021 report, existing buildings and building construction sectors have an undeniable impact on total global energy consumption. Increasing energy consumption along with the increasing population around the world directly triggers the increase in carbon emissions. As can be seen, these interrelated situations reveal what an active role the building sector plays in terms of both energy consumption and carbon emissions. Buildings are not sources of energy, but every building has the potential to save energy. Environmentally friendly building designs based on energy efficiency and supporting renewable energy sources play an important role at this point [8]. Thus, savings in final energy consumption of the building sector can firstly reduce the energy demand worldwide and, accordingly, a serious reduction in carbon emissions can be seen in the global context.

Buildings must meet the energy needs of all the systems that make up them in order to fulfill their functions. For this reason, significant amounts of energy savings can be achieved in buildings whose entire systems are designed on the basis of energy efficiency [9]. In particular, facade or envelope systems, which are one of the most important building blocks of a building, directly affect the energy consumption of the building [10]. Just like living organisms, buildings also struggle with changing external environmental conditions through their envelope (facade) systems. Building envelope systems designed on the basis of energy efficiency reduce the energy consumed by the buildings they belong to for their needs such as heating, lighting, cooling and ventilation in order to keep the indoor comfort suitable and stable for the users [11].

Envelope systems, which act as a kind of buffer between the inside and outside of buildings, are decisive in the scope of energy efficient building designs. Building envelope systems, designed with inspiration from the methods and strategies used by living organisms to continue their vital activities with minimum energy consumption despite harsh conditions, play an active role in energy efficiency-based building designs. This is where the discipline of biomimicry comes into play. The discipline of biomimicry, which focuses on nature's most effective and proven solutions in many issues, especially energy efficiency, has become very popular in recent years. Biomimicry in architecture is a design tool that aims to use the superior power of nature with modern systems and methods [12].

Solutions and strategies developed by imitating the systems developed by nature provide inspiration for envelope systems, which are indispensable components of energy-efficient building designs [13-14]. Building envelopes created with biomimetic approaches can be tested in the most effective way, thanks to technological developments and computer-aided programs and software, before architectural integration and application processes [15]. Within the scope of this study, a envelope system was developed with a biomimetic approach. Within the scope of study, the entire architectural integration process of this envelope system, developed for the office unit located on the south facade of a fictitious office building in Doha, Qatar, with extreme weather conditions, is discussed. Unlike other studies, it is aimed to improve the energy efficiency of the building envelope system created with a nature-inspired approach in this study, by considering both the design and simulation processes together. The effects of the developed biomimetic envelope design on cooling load and daylight parameters are analyzed along with the simulation outputs generated throughout the study. The design process and evaluation criteria developed with the biomimetic approach within the scope of the study will inspire energy-efficient building envelope designs.

2. Method

The study begins with a test box generative model simulation. This productive test box model allows the biomimetic envelope system developed within the scope of the study to be tested. The study continues with the design and simulation of the envelope system created with a biomimetic approach inspired by nature. A solution set consisting of different variations of the biomimetic envelope system with predetermined variables was created. Then, all variations forming the solution set were tested separately on the test box. In summary, the flow sequence of the study is shown in detail in Figure 1.

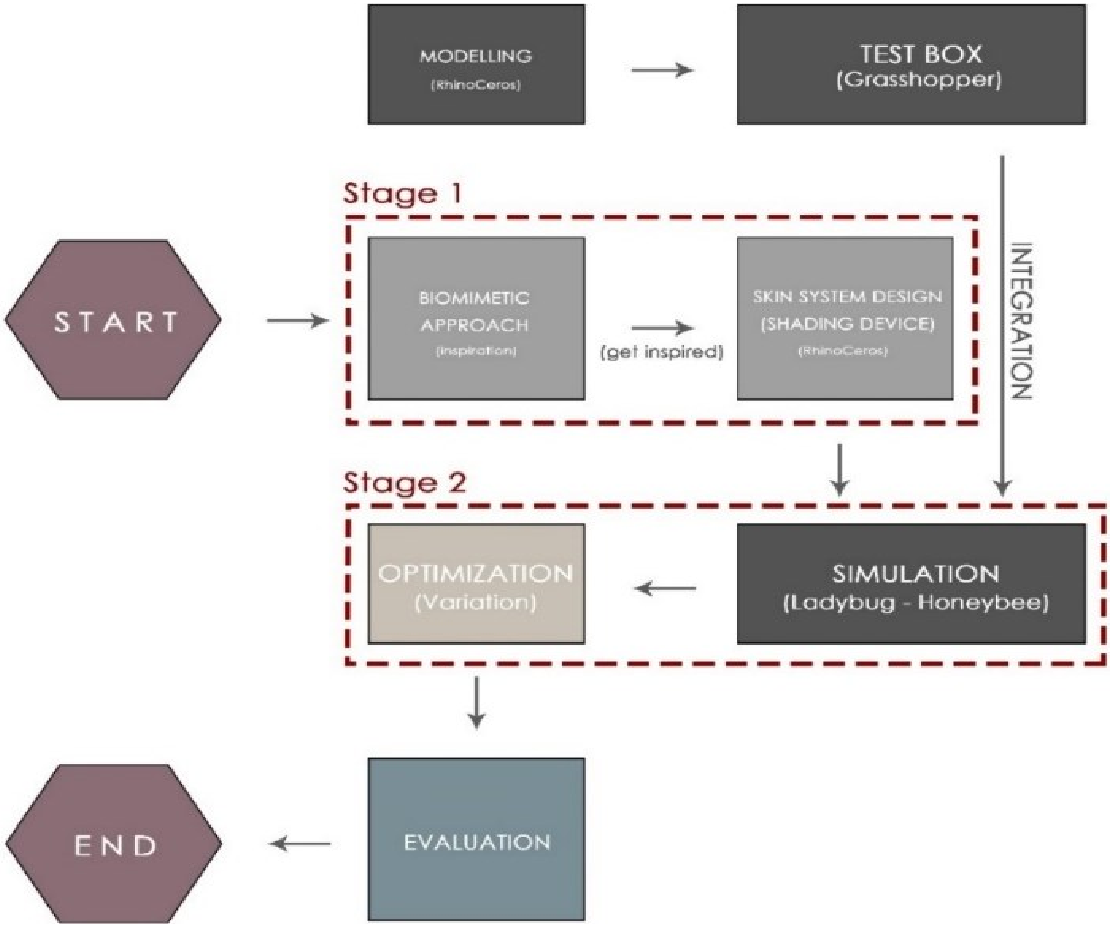

Figure 1. Flow chart about the methodology.

2.1. Tools

A lot of arguments and data are needed for simulation programs to work properly and produce the desired results. However, the more selective one is about the data selected for simulation, the shorter the process and the closer one gets to the targeted simulation [16].

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 its plug-in Grasshopper software. Grasshopper is generally compatible with modeling programs and software in terms of ease of creating various geometries. It is also a useful tool with potential for energy simulation [17].

Secondly, the simulation of the biomimetic envelope system (shading device) integrated on the south side of the test box was also created with the help of the same tools. Additionally, Ladybug-Honeybee tools with Grasshopper plugins were used at this stage. With EPW data transferred to Ladybug-Honeybee vehicles, the test box and its surroundings reflect the regional characteristics of Doha, Qatar. An example visual of the interfaces of RhinoCeros and Grasshopper programs during the development process of this study (simulation model) is given in Figure 2 below.

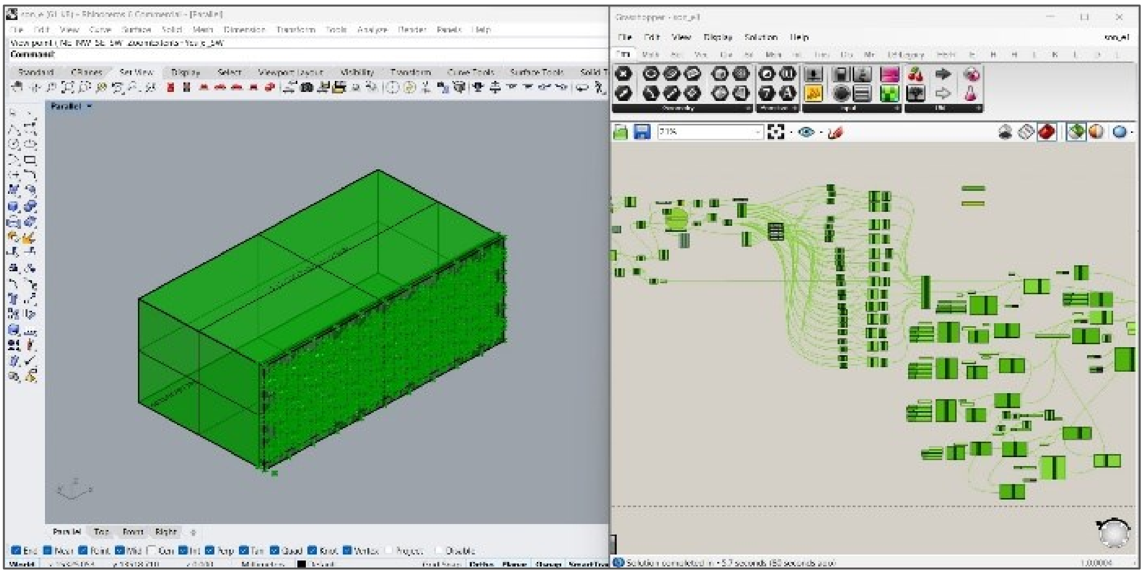

Figure 2. Simulation model creation process.

Finally, the outputs of the simulations were converted into graphics electronically using the Microsoft Excel program. These graphs allow analysis of simulation results. Thus, all tools used within the scope of the study help to analyze and test the targeted design accurately and quickly.

2.2. Climate characteristics

This test box is an office space located in Doha, Qatar, east of the Arabian Peninsula on the Asian continent. Doha, which has extreme weather conditions, was preferred in order to test the biomimetic shading device developed within the scope of the study under the most difficult conditions. According to the Köppen Geiger Climate Classification in Figure 3, Doha's climate type is BWh, which is a hot desert climate. A hot desert climate prevails in Doha, where summers are dry and humid and winters are mild and rainy [18].

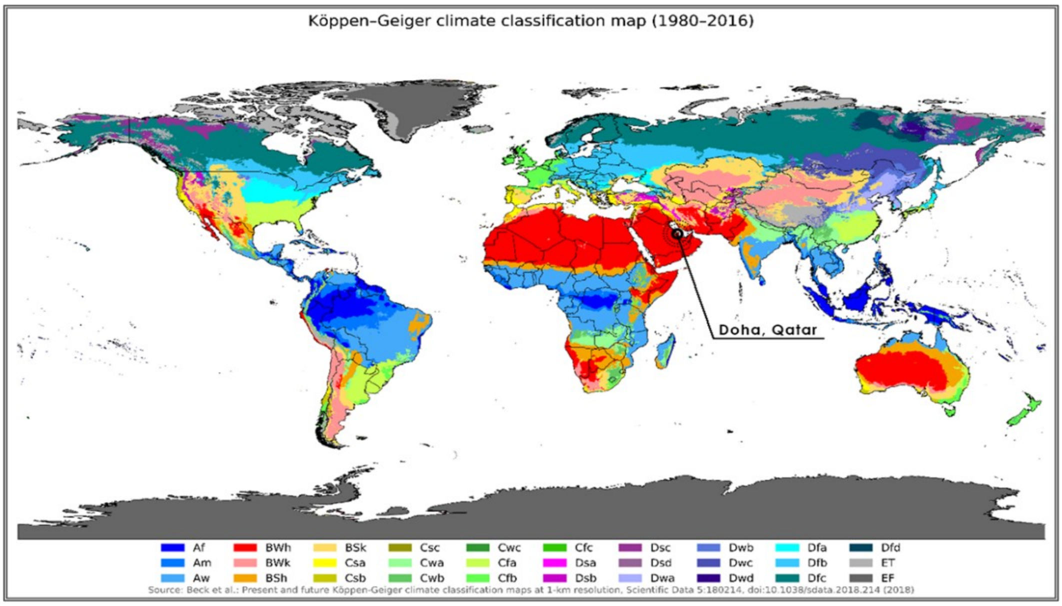

Figure 3. Global Köppen-Geiger Climate Classification Map (1980-2016)

2.3. Test box - base model

The test box-base model created within the scope of the study was designed to receive maximum daylight in terms of room depth and window opening. The test box is rectangular in shape, 10 meters wide, 5 meters deep and 5 meters high. The test box has a window size of 4.7 meters high and 9.6 meters long. In addition, in the simulation, all surfaces forming the test box are defined as structural elements (roof, wall, floor, glass facade) consisting of heat-permeable materials. The south-facing test box has a large window opening for maximum daylight. This allows the performance of the biomimetic envelope system developed for the purpose of the study to be tested under extreme conditions. The test box seen in Figure 4 is named T0. T0 is the non-integrated variation of the developed biomimetic envelope system.

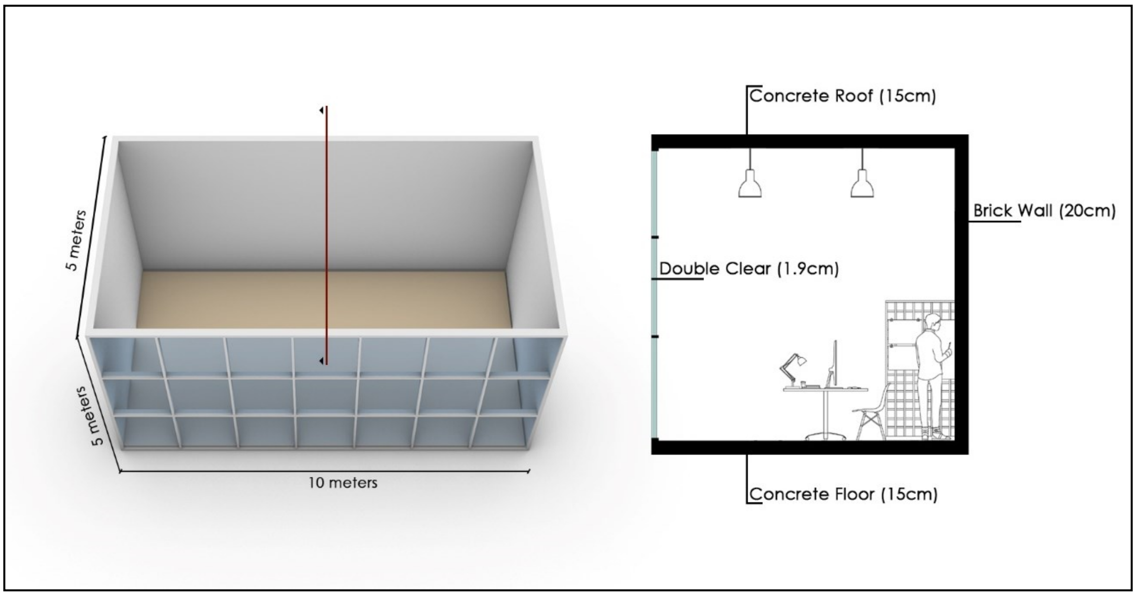

Figure 4. Test box – base model (T0)

2.4. Design process via biomimetic approach

In the design process of the building envelope targeted within the scope of the study, inspiration was taken from nature, which can produce sustainable strategies and solutions under challenging conditions. For this purpose, collaboration was made with the biomimicry discipline during the design process of the study. All living things that survive in nature develop some methods for the difficulties and problems they encounter. Biomimicry is a kind of bridge that makes it easier to transfer these methods to daily life. Based on this, the design of the envelope system developed within the scope of the study was inspired by the solutions and strategies that are effective in helping organisms survive at maximum efficiency with minimum energy consumption under extreme conditions. Production was carried out through a design process that comprehensively addressed the creation of the targeted energy efficiency-based envelope system. In summary, in this study, the envelope system (shading device) was developed within the design process based on the biomimetic approach. This envelope system (shading device) was designed to provide maximum comfort with minimum energy consumption despite the extreme outdoor conditions of Doha, Qatar. Figure 5 shows in detail the steps taken in the design process.

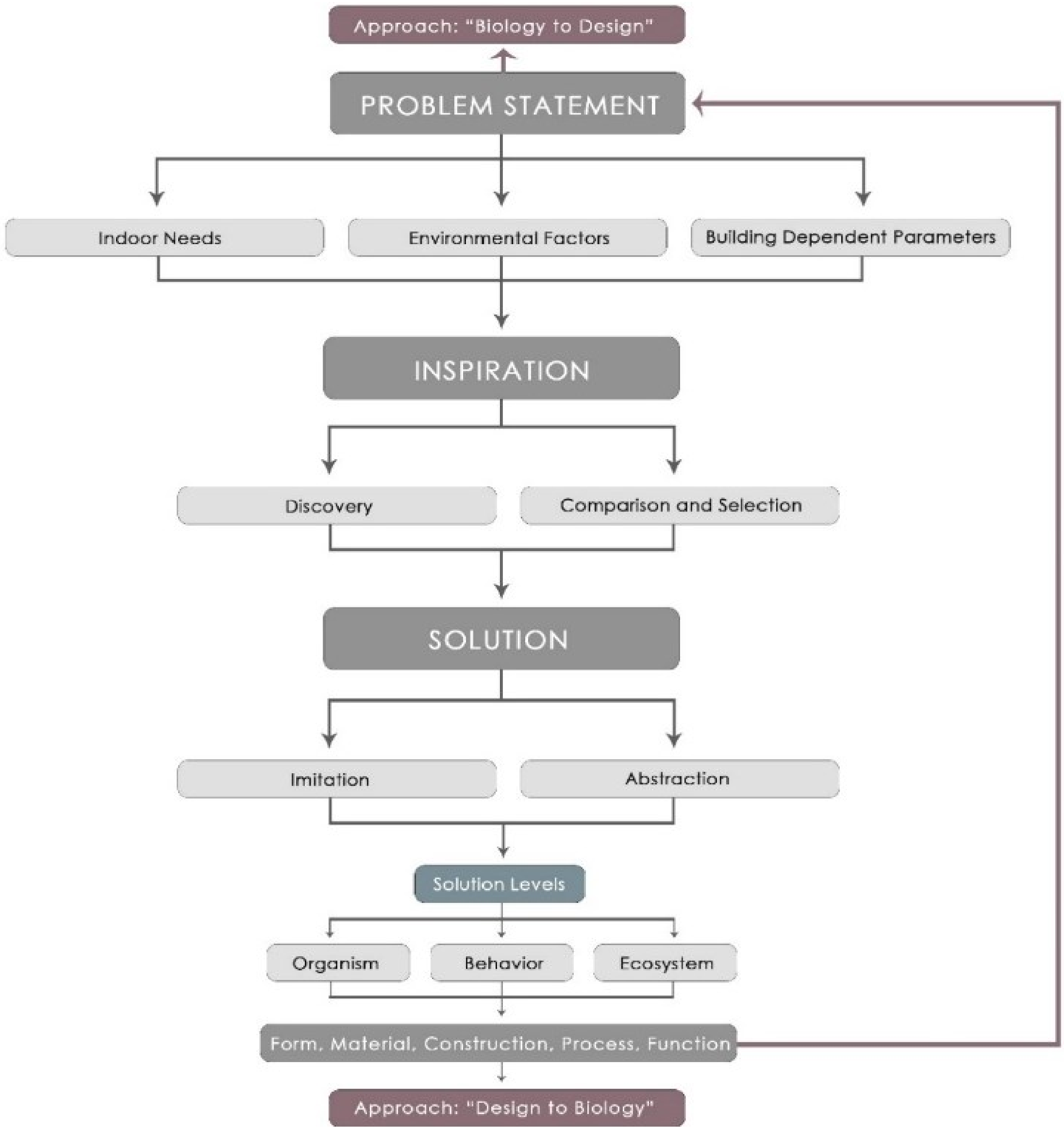

Figure 5. Flow Chart about the design process with biomimicry

In general context, energy efficiency should aim to minimize energy consumption without affecting the comfort level of building users. Because energy efficient buildings save energy without compromising their performance and function [19]. Based on this, it is very important that the office unit (test box) in Doha, Qatar, simulated within the scope of the study, provides maximum comfort for its users despite the hot and disturbing sun rays. One of the most important indoor comfort needs in office spaces is lighting. In addition, in extremely hot climates such as Doha, overheating, which increases the mechanical cooling energy load, should be prevented as much as possible. In summary, with this design process, it is aimed to reduce the energy consumption as well as the indoor comfort level of the simulated office unit (test box) in Doha, Qatar.

Nature's experience, which has been going on for millions of years, provides solutions to many problems today. Human beings have always been inspired by other creatures living in nature until today. In recent years, with studies on biomimetic approaches and technological developments, ways of imitating nature have changed and become easier [20]. Within the scope of the study, exploration was carried out in nature for the envelope system design to be developed against the hot and scorching climate of Doha, Qatar. During this discovery, the organism with the most effective solution potential to the problems, function and environmental conditions of the test box was selected.

The potential of organisms proven in nature, living in similar climatic conditions such as Doha, to provide inspiration for producing effective and sustainable solutions was analyzed. The Arabian Desert was observed to directly match the conditions in Doha, Qatar, where the test box is located [21]. Ten different species adapted to living in these conditions were examined. It was analyzed how the strategies and solutions developed by living creatures for the harsh desert conditions contributed to their air, light, water and heat needs. In light of all this, it was determined that the thorny devil lizard was more successful in adapting to the desert than other creatures. It was observed that this lizard developed strategies to cope with parameters such as air, light, water and heat in terms of energy efficiency in the harsh desert environment. For this reason, the biomimetic envelope targeted in the study was developed with inspiration from the lizard.

The thorny devil lizard has developed many strategies to adapt to extremely hot desert conditions. For example, when the temperature of the surface in contact with the lizard increases, it minimizes its contact with the surface. Its sharp, spiky envelope both protects it from other creatures and prevents the burning rays of the sun like a shade device. The lizard can easily collect water droplets from the environment thanks to its thorn-like protruding scales [22]. The protrusions covering its envelope resemble mountains and help create airflow on the body surface [23]. Detailed analysis of the thorny devil lizard, which was inspired by the study, is given in Figure 6.

THORNY DEVIL LIZARD

Reptile - animal

Life Strategy:
- -They regulate body temperature
- -They can camouflage themselves
- -They can absorb moisture from the environment.
- -They cool off by keeping the water on the body surface

Biomimicry Levels	
Organism Level	✓
Behaviour Level	✓
Ecosystem Level	☐

Biomimicry Approach	
Design to Biology	✓
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.	✓

Figure 6. Evaluation of the life strategies of the thorny devil lizard

2.4.1. Form creation

The geometry (form) of the units that make up the biomimetic envelope design is inspired by the skin of the thorny devil lizard. In form, a geometry tapering outwards from the building façade was created, similar to the thornies covering the body of a lizard. In this way, it has become easier to integrate the strategies developed by the lizard to survive against the hot and arid climate with minimum energy consumption into the envelope design. The formation process of biomimetic envelope units inspired by the skin of the thorny devil lizard is shown in Figure 7.

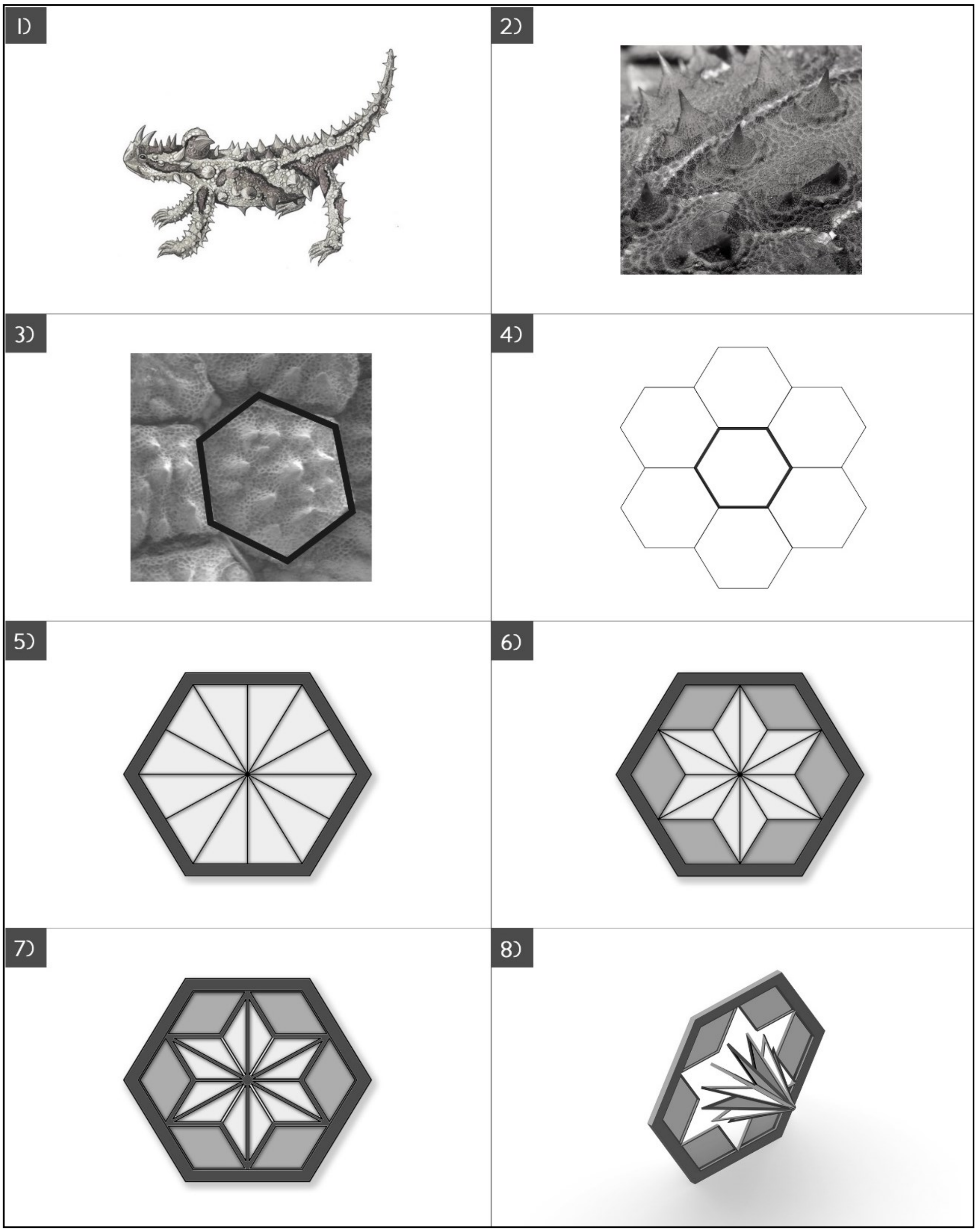

Figure 7. Inspired by the skin of the thorny devil lizard.

2.4.2. Material selection

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, single-layer and double-layer ETFE were preferred as shading materials. In this study, ETFE was preferred because it is light, durable, flexible, transparent, fire resistant, recyclable and cost-effective. A team from MIT managed to create a giant three-dimensional form by compressing small pieces of graphene under heat and pressure. With this success, graphene is a candidate to be the best building material used to date [24]. Graphene has 5% the density of steel and is 10 times stronger. With its porous structure, it is light, durable and recyclable. Material details of the modules that make up the biomimetic envelope are given in Figure 8.

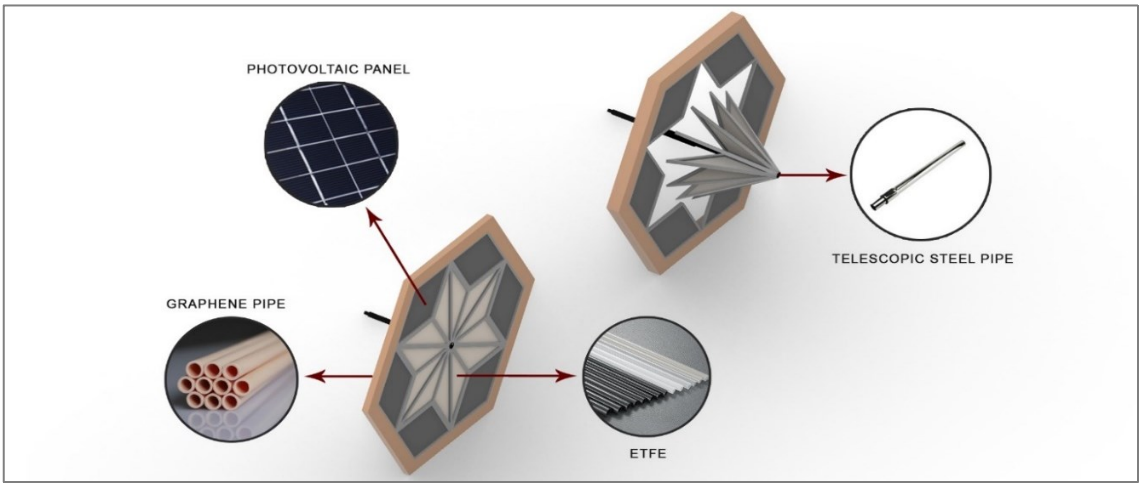

Figure 8. Material details of the biomimetic envelope modules.

2.4.3. Construction

Each module forming the biomimetic envelope system (shading device) has a side of 200 cm. These modules are surrounded by porous pipes made of graphene material. These pipes work like water channels that trap moisture in the air, just like in the spiny devil lizard. ETFE triangles have an umbrella-like moving mechanism that can open and close at certain degrees. As shown in Figure 9, there is a steel rod system at the center of each module that controls the opening and closing mechanism.

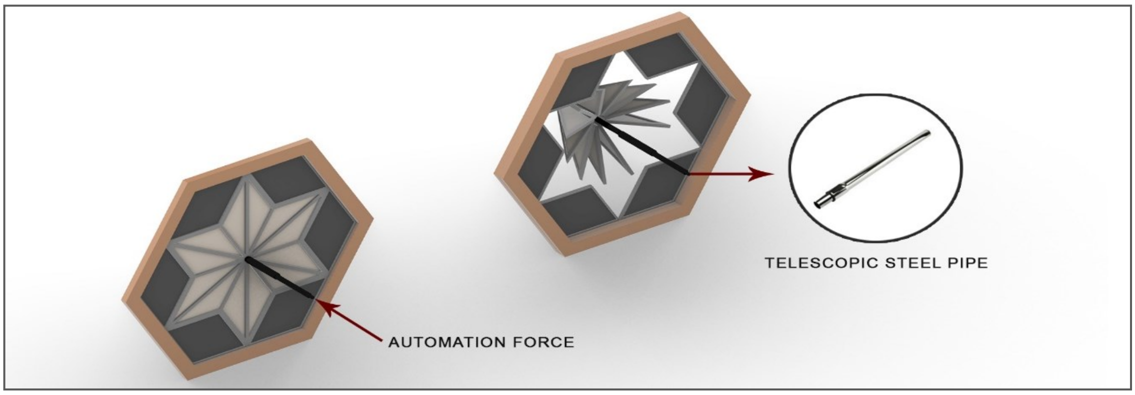

Figure 9. Mechanism of the biomimetic envelope modules.

This system also allows the modules to be mounted on the building. The biomimetic envelope modules are fixed to the glass facade laths in the test box as seen in Figure 10. The steel telescopic mechanism in the center of the modules can extend outwards perpendicular to the building facade with the automation of the building. This situation is similar to the skin form of the spiny devil lizard. The mechanism allows to be opened at 0°, 30°, 45°, 60° and 90° to benefit from daylight at different rates.

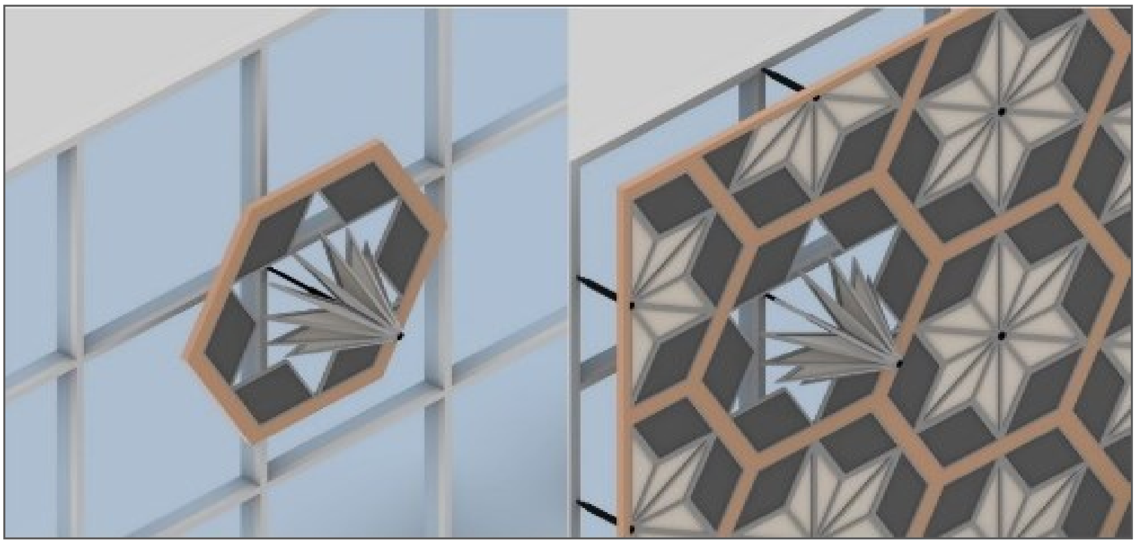

Figure 10. Relationship between biomimetic envelope and test box.

2.4.4. Function

The design process of the biomimetic envelope system was inspired by the strategies and solutions developed by the thorny devil lizard in desert conditions regarding air, light, water and heat parameters, shown in Figure 11, within the scope of energy efficiency.

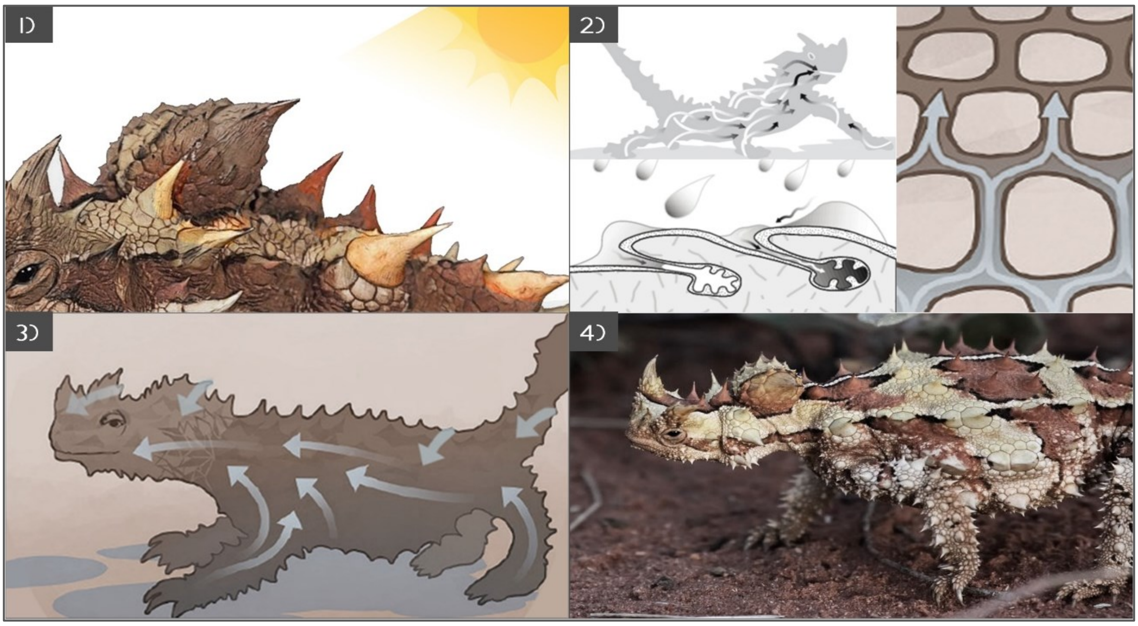

Figure 11. Strategies developed by the thorny devil lizard.
1)Light, 2)Water, 3)Air, 4)Heat

In hot desert conditions, air circulation between the lizard's thornies helps cool its body. The developed biomimetic envelope system mimics the principle in thorny devil lizard to cool the surface of the building in which the system is integrated. The developed biomimetic envelope system blocks the sun's rays like the spiky skin of a lizard, preventing the building from heating up and allowing daylight to be let in in a controlled manner. Just as the thornies on the surface of the devil lizard's skin are covered with scales that absorb water and transfer it to the lizard's mouth through channels under the skin, the pores in the graphene pipe system in the biomimetic envelope system trap moisture in the air, allowing the building to cool down during the day. The devil lizard can extract water from both the air and the desert sand thanks to its thornies. This helps reduce body temperature despite the hot desert conditions. Based on this, biomimetic envelope system modules designed to open and close at certain angles help shade the building and prevent it from overheating.

2.4.5. Envelope design alternatives

At this stage, different design alternatives are being developed for the biomimetic envelope system. In this context, a solution set consisting of differences in the number of ETFE layers and the opening angles of the modules, which provide the shading function of the biomimetic envelope system (shading device), was created. Biomimetic envelope variations integrated on the created test box (T0) are explained below.

As seen in Figure 12, the opening angle has been set to 30° while a single and double ETFE layers have been used for variation T1 and T2 respectively.

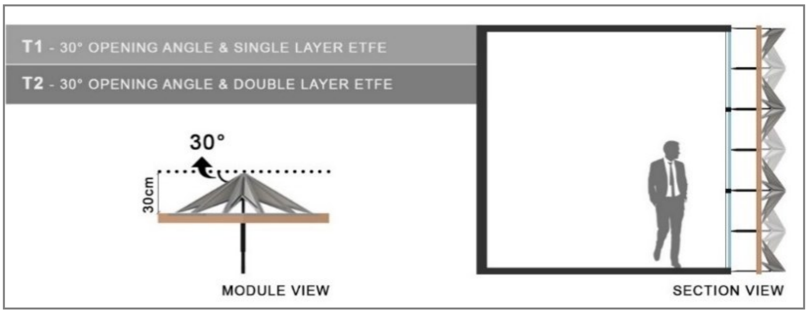

Figure 12. T1 and T2 – variation of biomimetic envelope system.

As seen in Figure 13, the opening angle has been set to 45° while a single and double ETFE layers have been used for variation T3 and T4 respectively.

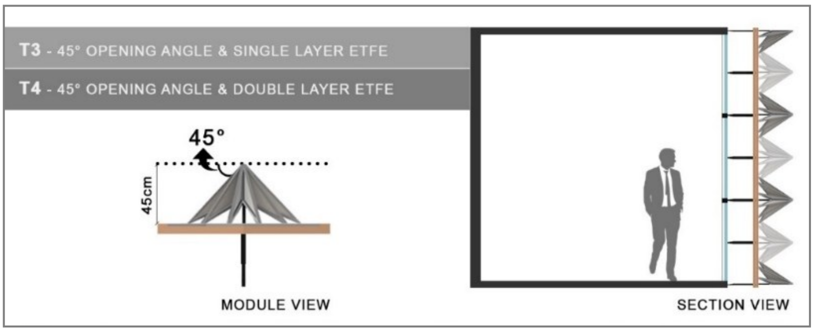

Figure 13. T3 and T4 – variation of biomimetic envelope system.

As seen in Figure 14, the opening angle has been set to 60° while a single and double ETFE layers have been used for variation T5 and T6 respectively.

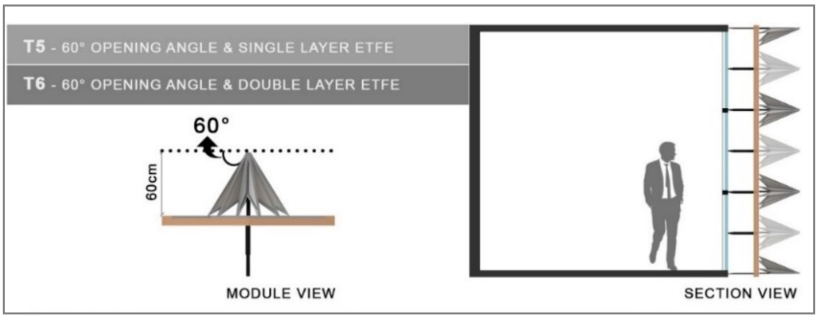

Figure 14. T5 and T6 – variation of biomimetic envelope system.

2.5. Simulation settings

The biomimetic envelope system (shading device) and test box (T0) developed within the scope of the study were modeled in the RhinoCeros 3D modeling program and then simulated by making the necessary adjustments via the Grasshopper plug-in. In addition, Grasshopper extension Ladybug and Honeybee tools were also used for energy and daylight simulation computations.

The glass surface (double clear window) located on the south side of the test box allows the performance of the biomimetic envelope system developed within the scope of the study to be analyzed. The double clear window has a 13 mm air gap and consists of 3 mm double clear glass. The U value of this glass material is 2.556 W/m2 -K. The other facades of the test box consist of wall material. Wall material is ASHRAE 189.1-2009 Extwall Climate Zone 3. The walls are 20 cm thick, white painted Radiance material and have an RGB reflectance value of 1. Floor material is ASHRAE 90.1-2010 Atticfloor Climate Zone 3 Semiheated. The floor is made of 15 cm thick, cream-painted Radiance material and has an RGB reflectance value of 0.763. The roof material is ASHRAE 90.1-2007 Extroof Climate Zone 3 Semiheated. The roof is 15 cm thick, has cream painted Radiance material, and its RGB reflectance value is 0.763. Among the materials used in the biomimetic envelope system, ETFE covers the most area in the system. The U value of a single ETFE layer is 5.6 W/m2 -K. The double ETFE layer U value is 2.9 W/m2 -K. ETFE layers feature Radiance material painted white and have RGB reflectance values of 1. The other two materials (graphene and photovoltaic panels) that make up the biomimetic envelope system were adjusted adiabatically.

The climatic conditions of Doha, Qatar were taken as basis for the simulations. In this context, the EPW file reflecting Doha's annual average climate conditions was used. To compute the energy spent for cooling, the indoor conditions of the test box were accepted as 25 degrees dry bulb temperature and 50% relative humidity. The cooling load computation period was determined as one week (the first week of July). The daylight analysis was planned to be carried out in the first week of July between 07:30 and 19:30 (the time period when people spend the most time in the office in Doha, Qatar). The minimum threshold for daylight performance was defined as 300 lux and the maximum threshold was 1500 lux. The daylight simulation was set at table level with a height of 75 cm.

3. Results and discussion

In this section, simulation results of the current state of the test box (T0) and the integrated states of the biomimetic envelope system (shading device) are analyzed. Biomimetic envelope variations (T1 - T2 - T3 - T4 – T5 - T6) integrated into the office unit located on the south facade of a high-rise office building in Doha, Qatar were compared on cooling load, daylight and indoor temperature parameters. Results are discussed within all variations.

The graphs created within the scope of this study show seven days covering the first week of July (1th - 2th - 3th - 4th - 5th - 6th - 7th of July), the hottest month in Doha, Qatar. In this regard, some climate analyzes in Figure 15 were carried out for the test box (T0) before the simulation outputs of the biomimetic envelope system variations. This climate data allows the biomimetic envelope variations developed within the scope of the study to be tested realistically. In the light of the outdoor temperature, humidity percentage and wind speed data of Doha, Qatar, the location where the test box was simulated, the surface temperature, indoor temperature, cooling load and solar gain data of the test box were obtained. Within the framework of these data, the performance of biomimetic envelope system variations was evaluated with simulastion outputs.

All energy (cooling load) and daylight simulations of the biomimetic envelope system (shading device) variations designed in the scope of the study 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.

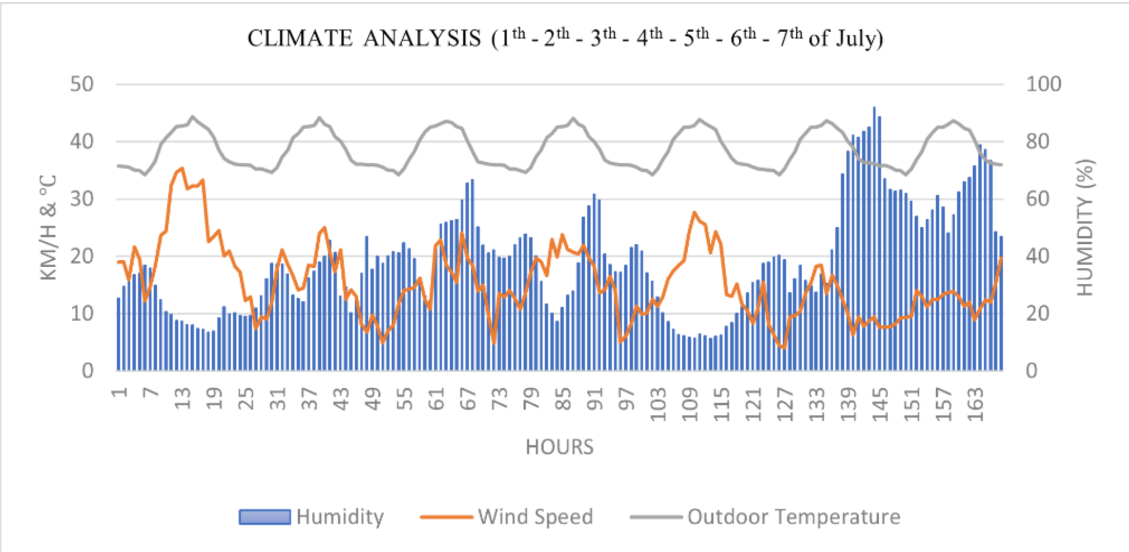

Figure 15. Climate data for Doha, Qatar.

3.1. Cooling load

In this section, computations were made on the amount of energy consumed by the test box (office unit / T0) for cooling to balance the indoor temperature against the hot outdoor temperature. The indoor norms accepted for these computations are specified in the simulation settings section. Computations were made in the first week of July, which is the hottest week in Doha. The weekly cooling load computation for the current state of the test box (T0) was performed before integrating any variation (T1 - T2 - T3 - T4 – T5

- T6) of the biomimetic envelope system (shading device). For this, firstly, the outdoor temperature, surface temperature (glass front temperature), indoor temperature and solar gain data of the test box (T0) were determined. As a result of the simulation outputs created in the light of these data, the amount of energy spent for cooling for seven days (1^{th} - 2^{th} - 3^{th} - 4^{th} - 5^{th} - 6^{th} - 7^{th} of July) was reached in Figure 16. The total energy (cooling load) consumed by the test box (T0) for one week, despite the external environmental conditions, is **398 kWh**.

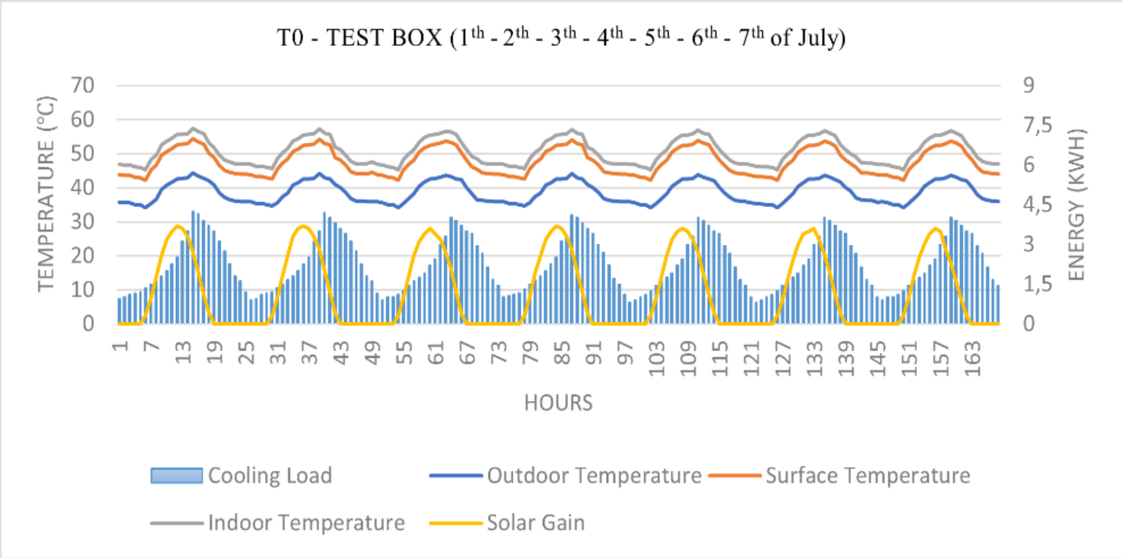

Figure 16. Test box (T0) – values.

3.1.1. T1 - 30° opening angle & single layer ETFE

The **opening angle** was set to **30°** in the **T1** variation and a **single ETFE layer** was used in this variation. Figure 17 shows that the total cooling load for a week, computated after integrating the T1 biomimetic envelope system variation into the test box, is **297.50 kWh**.

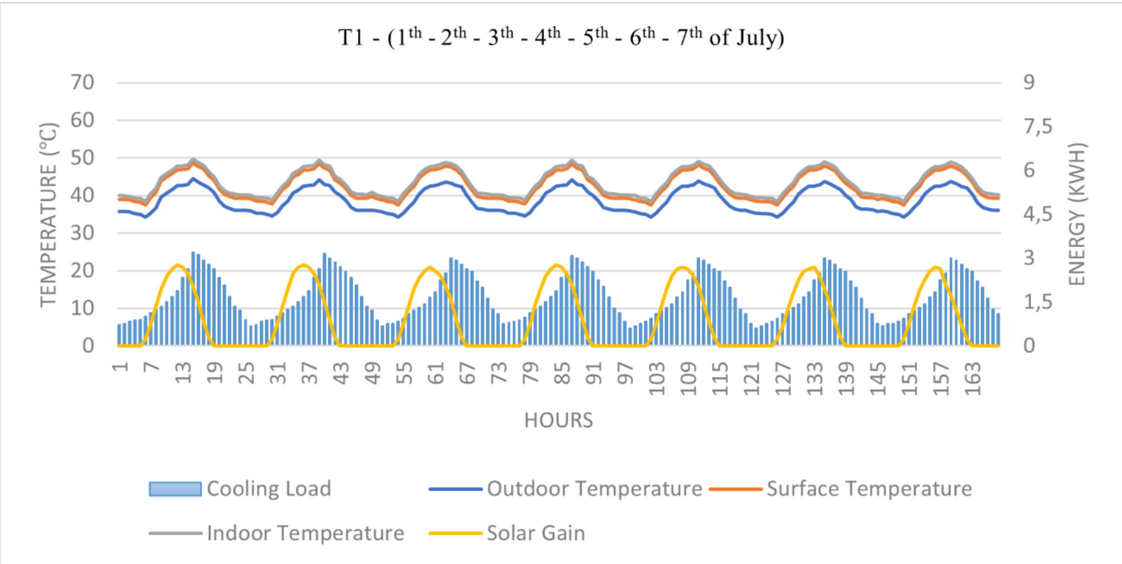

Figure 17. T1 – values.

3.1.2. T2 - 30° opening angle & double layer ETFE

The **opening angle** was set to **30°** in the **T2** variation and a **double ETFE layer** was used in this variation. Figure 18 shows that the total cooling load for a week, computated after integrating the T2 biomimetic envelope system variation into the test box, is **268.65 kWh**.

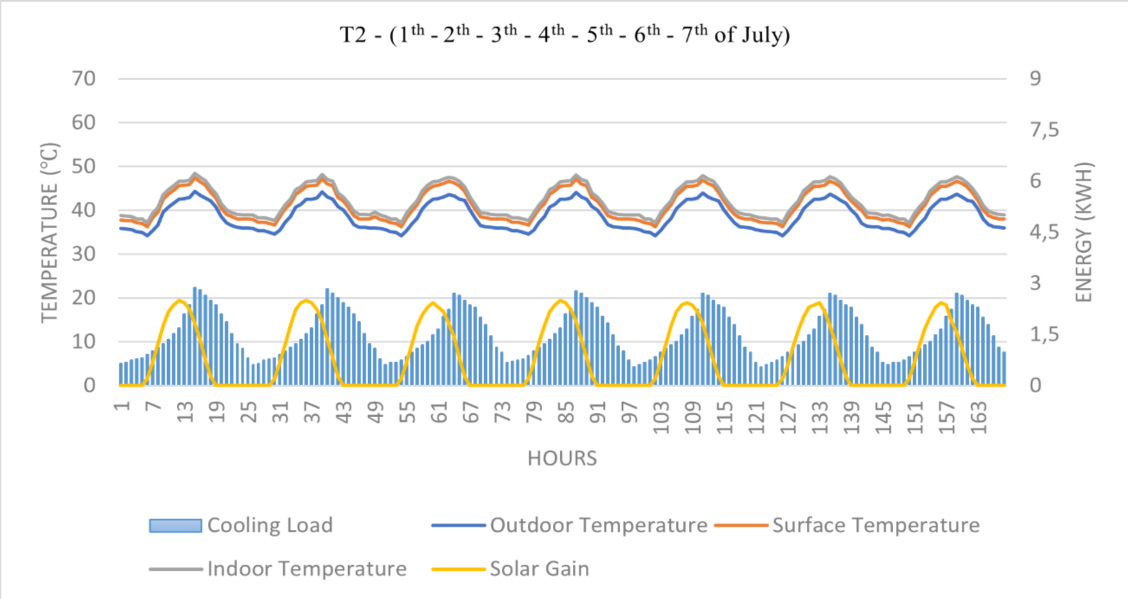

Figure 18. T2 – values.

3.1.3. T3 - 45° opening angle & single layer ETFE

The **opening angle** was set to **45°** in the **T3** variation and a **single ETFE layer** was used in this variation. Figure 19 shows that the total cooling load for a week, computated after integrating the T3 biomimetic envelope system variation into the test box, is **297.50 kWh**.

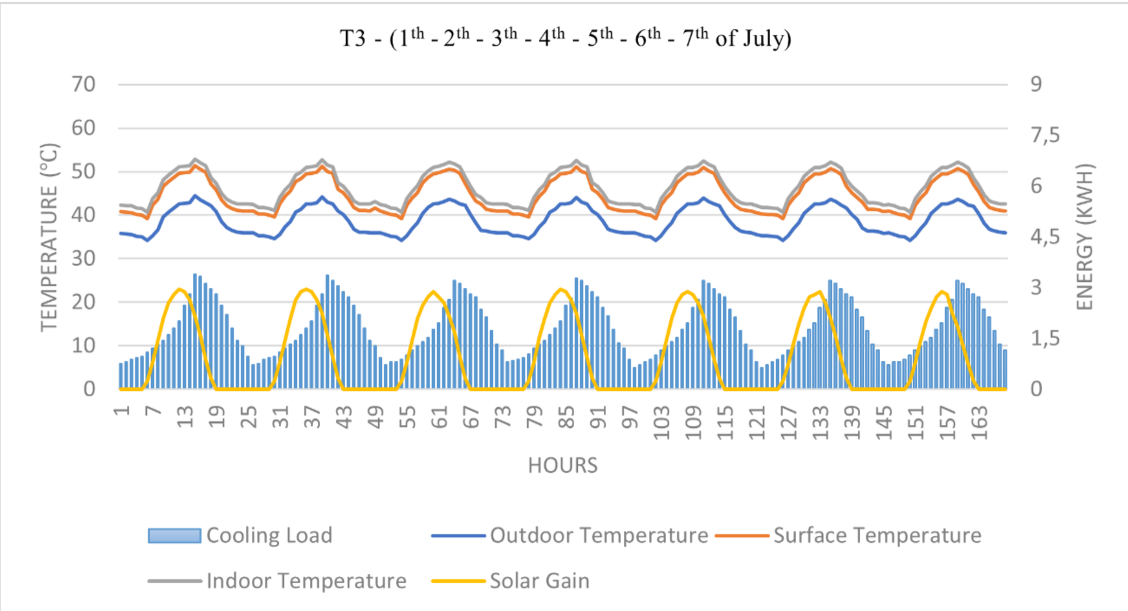

Figure 19. T3 – values.

3.1.4. T4 - 45° opening angle & double layer ETFE

The **opening angle** was set to **45°** in the **T4** variation and a **double ETFE layer** was used in this variation. Figure 20 shows that the total cooling load for a week, computed after integrating the T4 biomimetic envelope system variation into the test box, is **306.55 kWh.**

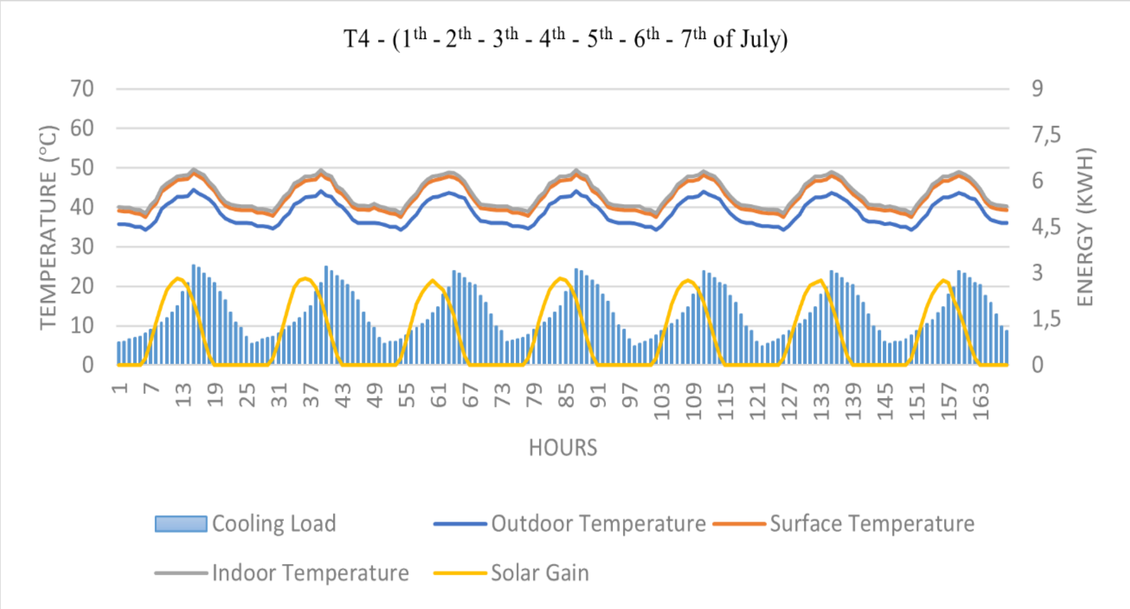

Figure 20. T4 – values.

3.1.5. T5 - 60° opening angle & single layer ETFE

The **opening angle** was set to **60°** in the **T5** variation and a **single ETFE layer** was used in this variation. Figure 21 shows that the total cooling load for a week, computed after integrating the T5 biomimetic envelope system variation into the test box, is **359.40 kWh**.

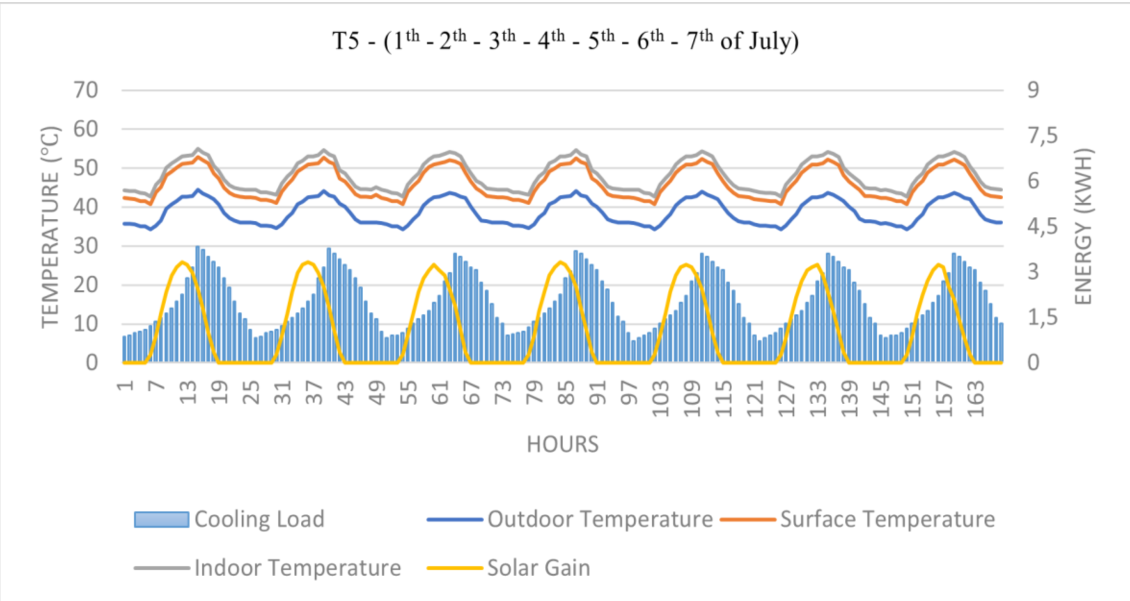

Figure 21. T5 – values.

3.1.6. T6 - 60° opening angle & double layer ETFE

The **opening angle** was set to **60°** in the **T6** variation and a **double ETFE layer** was used in this variation. Figure 22 shows that the total cooling load for a week, computed after integrating the T6 biomimetic envelope system variation into the test box, is **330.34 kWh.**

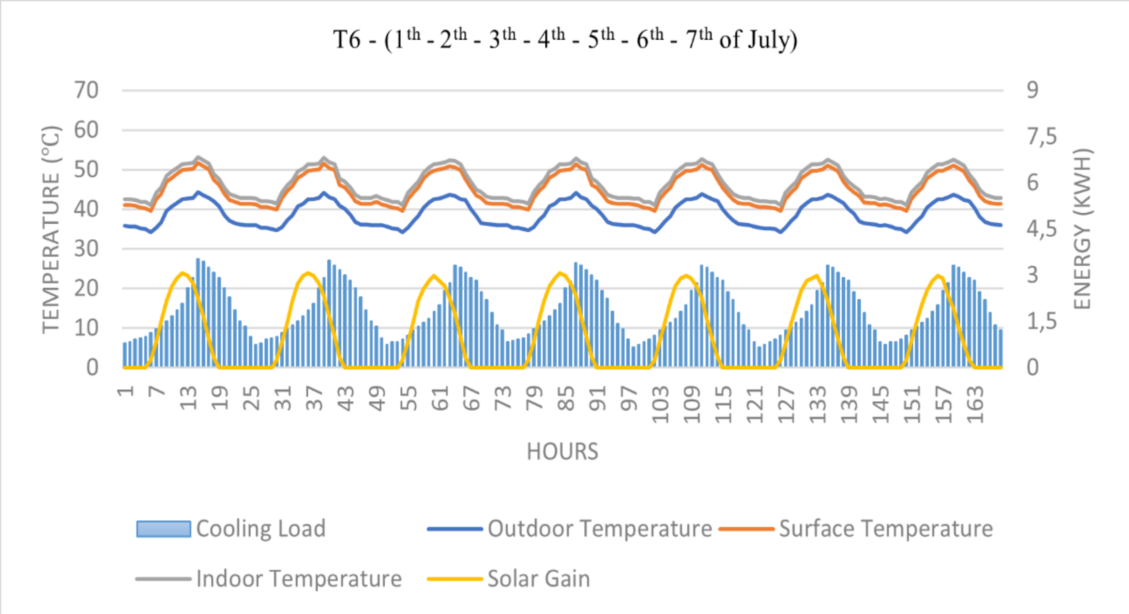

Figure 22. T6 – values.

3.2. Daylight

The test box (office unit / T0), located on the south façade of the high-rise 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 shading.

For the simulation outputs, the time period in which users spent the most time in the office was accepted as 07:30-19:30. Daylight analysis of the current state of the test box (T0) was performed before integrating the biomimetic envelope system variations for the the first week of July July (1th - 2th - 3th - 4th - 5th - 6th - 7th of July).

For the analysis, the work table height (75cm) in the office (T0) 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 (T0) 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 daylight simulation analysis results, it is seen in Figure 23 that the disturbing daylight in Doha, where the test box is located, is much higher than the value of 300-1500 Lux. It is obvious that the test box within the scope of the study, does not offer daylight comfort for users in its current form. For this purpose, a secondary daylight analysis was made by changing the lux range.

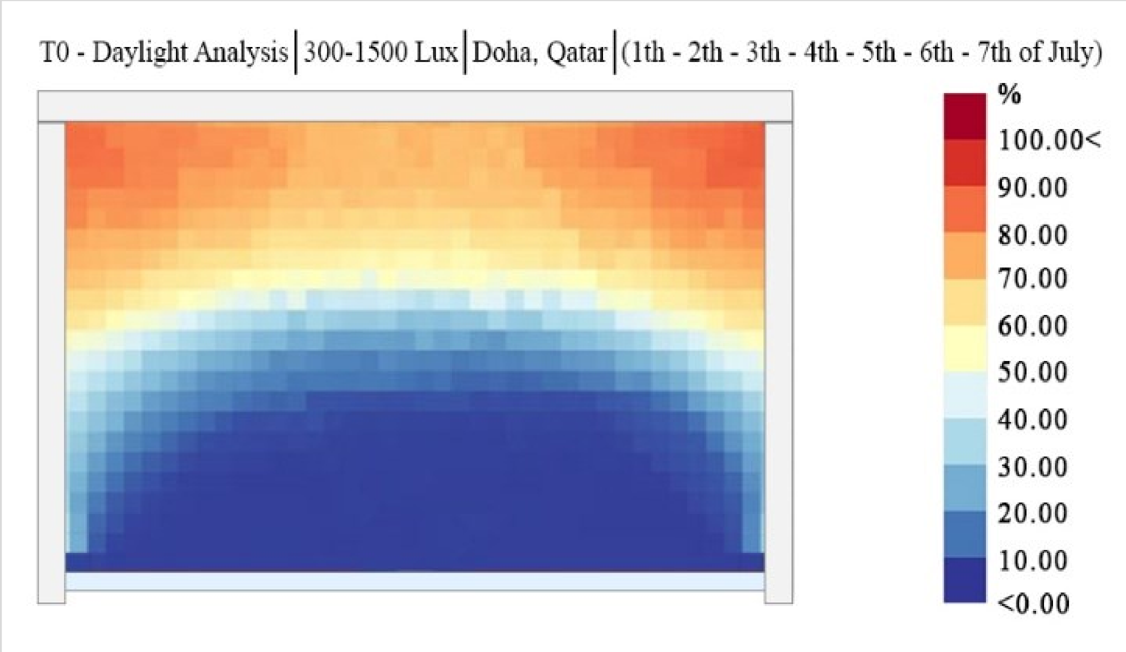

Figure 23. Test box (T0) – daylight analysis (300-1500 Lux).

Then, the range of 300-1500 lux determined in the first daylight simulation was changed and the range of 300-5000 lux was adjusted. In summary, the minimum lux value is kept constant at 300 lux. The maximum lux value has been increased to 5000 lux. Thus, it can be seen in Figure 24 that the daylight values for the south side of the test box (T0) are over 1500 lux. The south side of the simulated test box (office unit) in Doha, Qatar is exposed to disturbing sunlight. Against the this unfavorable situation for the working comfort of office users, it was analyzed how much daylight the test box benefited from in a controlled manner, thanks to the biomimetic envelope variations (T1 - T2 - T3 - T4 - T5 - T6) developed.

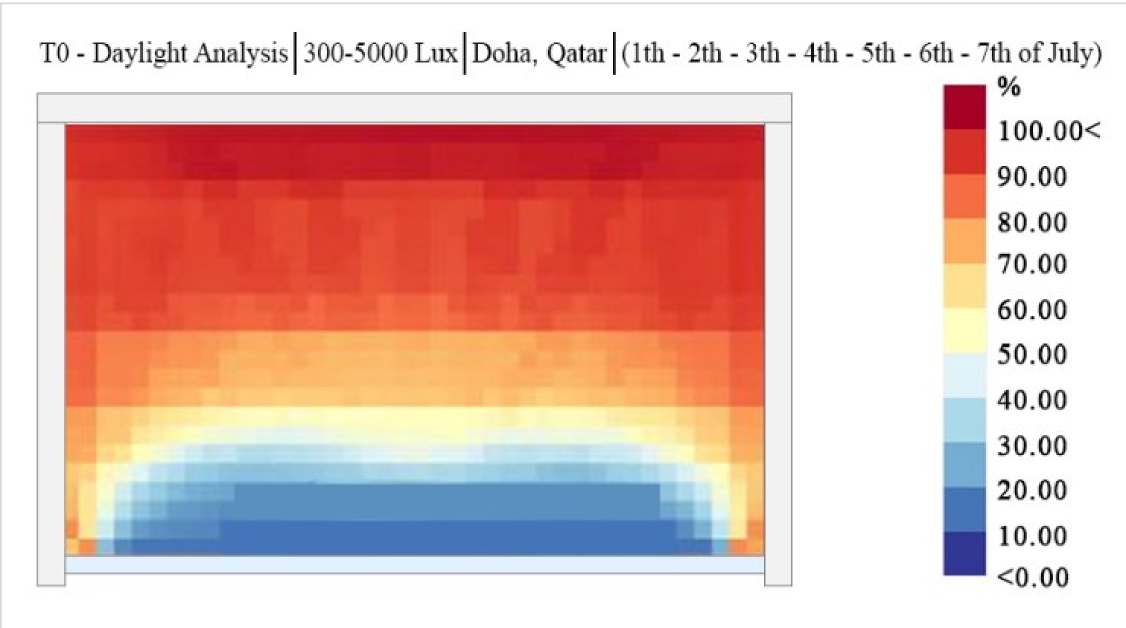

Figure 24. Test box (T0) – daylight analysis (300-5000 Lux).

3.2.1. T1 - 30° opening angle & single layer ETFE

The **opening angle** was set to **30°** in the **T1** variation and a **single ETFE layer** was used in this variation (T1). Figure 25 displays the one-week daylight simulation output after the T1 biomimetic envelope system variation is integrated onto the test box.

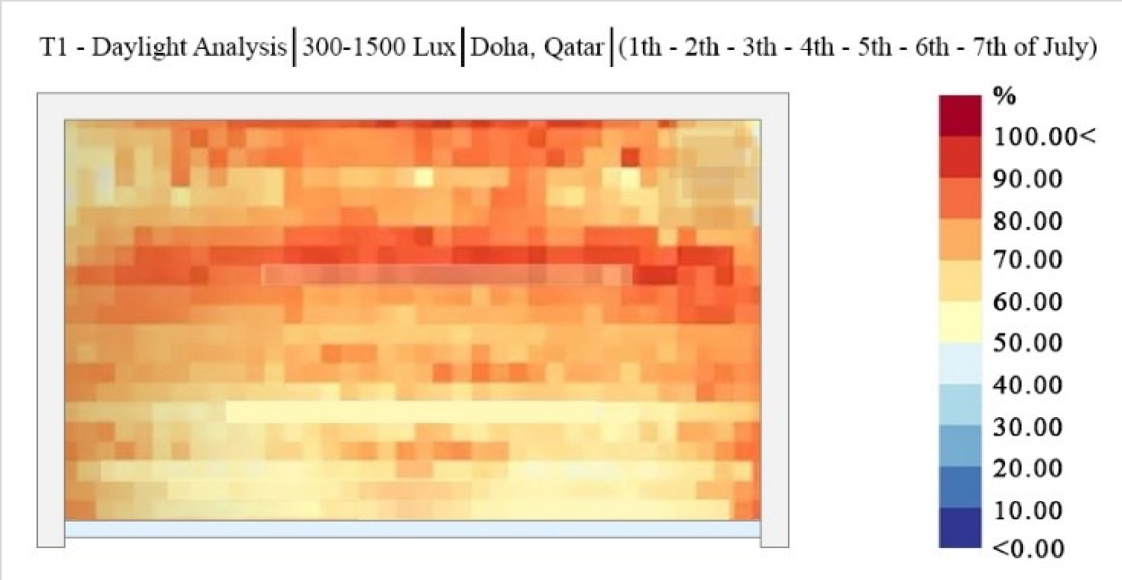

Figure 25. T1 – daylight analysis (300-1500 Lux).

3.2.2. T2 - 30° opening angle & double layer ETFE

The **opening angle** was set to **30°** in the **T2** variation and a **double ETFE layer** was used in this variation (T2). Figure 26 displays the one-week daylight simulation output after the T2 biomimetic envelope system variation is integrated onto the test box.

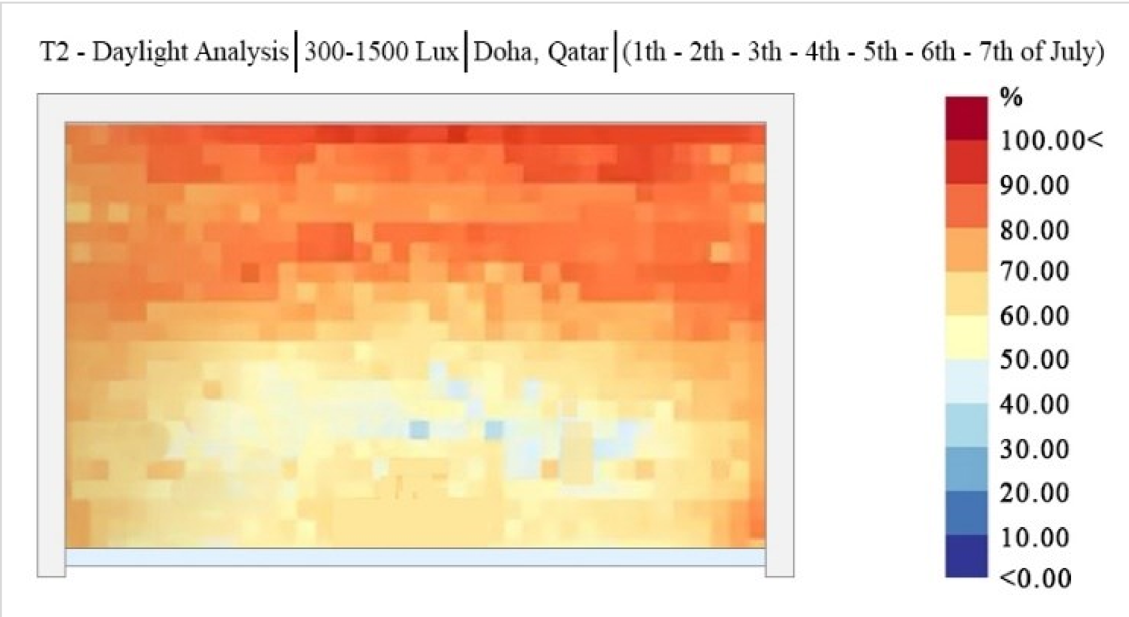

Figure 26. T2 – daylight analysis (300-1500 Lux).

3.2.3. T3 - 45° opening angle & single layer ETFE

The **opening angle** was set to **45°** in the **T3** variation and a **single ETFE layer** was used in this variation (T3). Figure 27 displays the one-week daylight simulation output after the T3 biomimetic envelope system variation is integrated onto the test box.

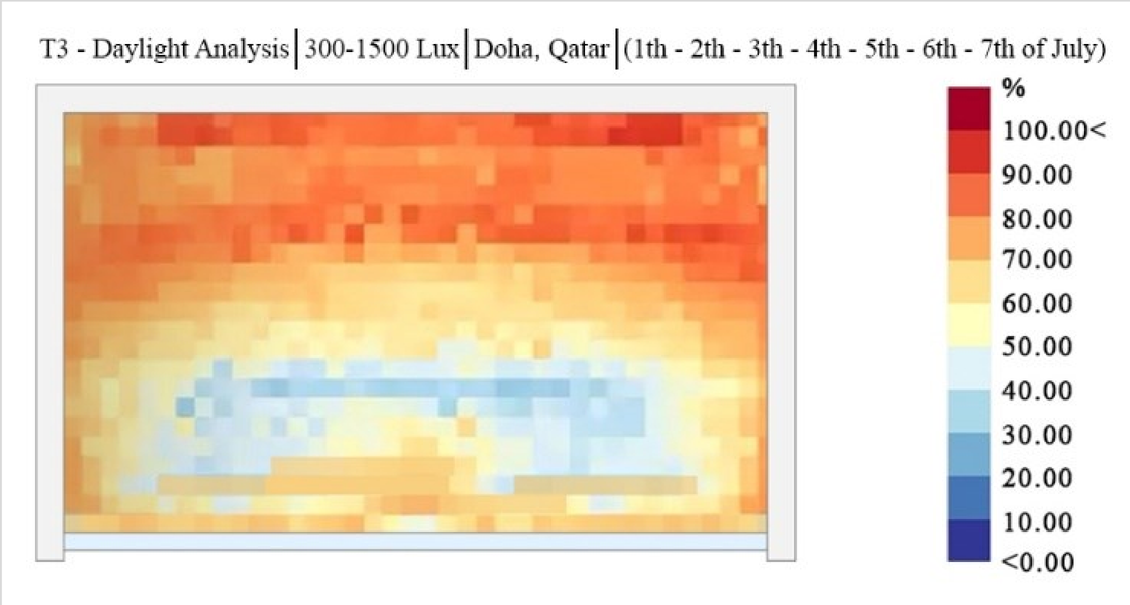

Figure 27. T3 – daylight analysis (300-1500 Lux).

3.2.4. T4 - 45° opening angle & double layer ETFE

The **opening angle** was set to **45°** in the **T4** variation and a **double ETFE layer** was used in this variation (T4). Figure 28 displays the one-week daylight simulation output after the T4 biomimetic envelope system variation is integrated onto the test box.

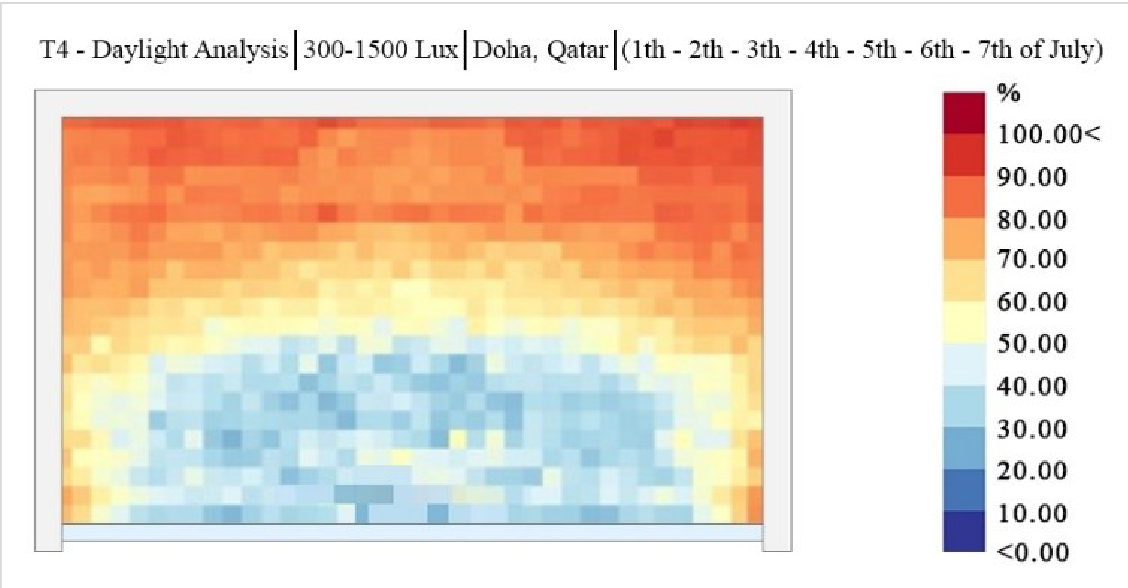

Figure 28. T4 – daylight analysis (300-1500 Lux).

3.2.5. T5 - 60° opening angle & single layer ETFE

The **opening angle** was set to **60°** in the **T5** variation and a **single ETFE layer** was used in this variation (T5). Figure 29 displays the one-week daylight simulation output after the T5 biomimetic envelope system variation is integrated onto the test box.

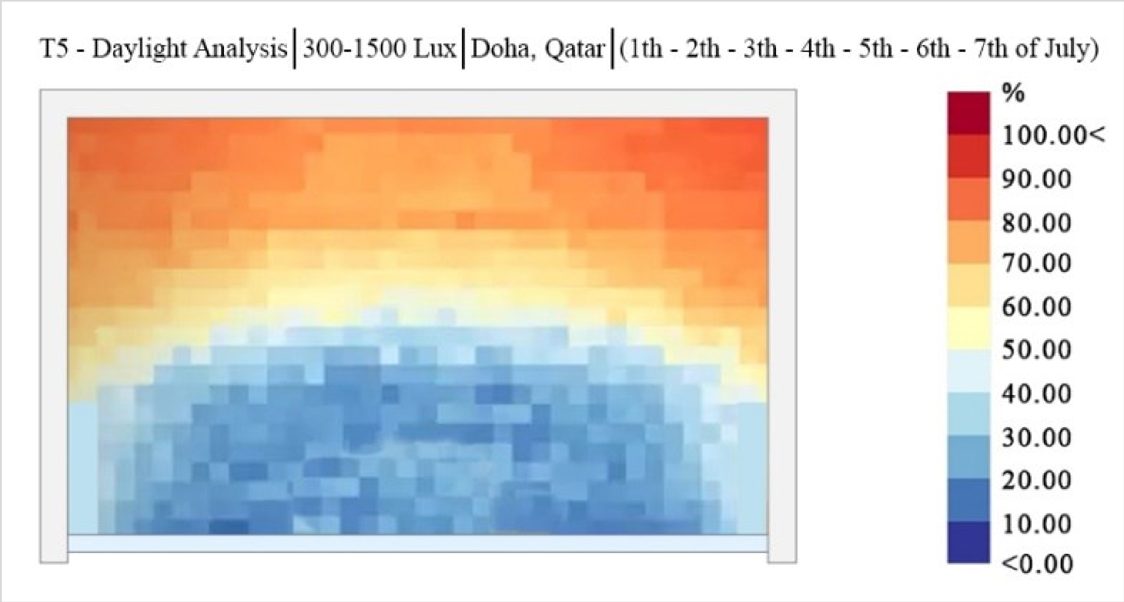

Figure 29. T5 – daylight analysis (300-1500 Lux).

3.2.6. T6 - 60° opening angle & double layer ETFE

The **opening angle** was set to **60°** in the **T6** variation and a **double ETFE layer** was used in this variation (T6). Figure 30 displays the one-week daylight simulation output after the T6 biomimetic envelope system variation is integrated onto the test box.

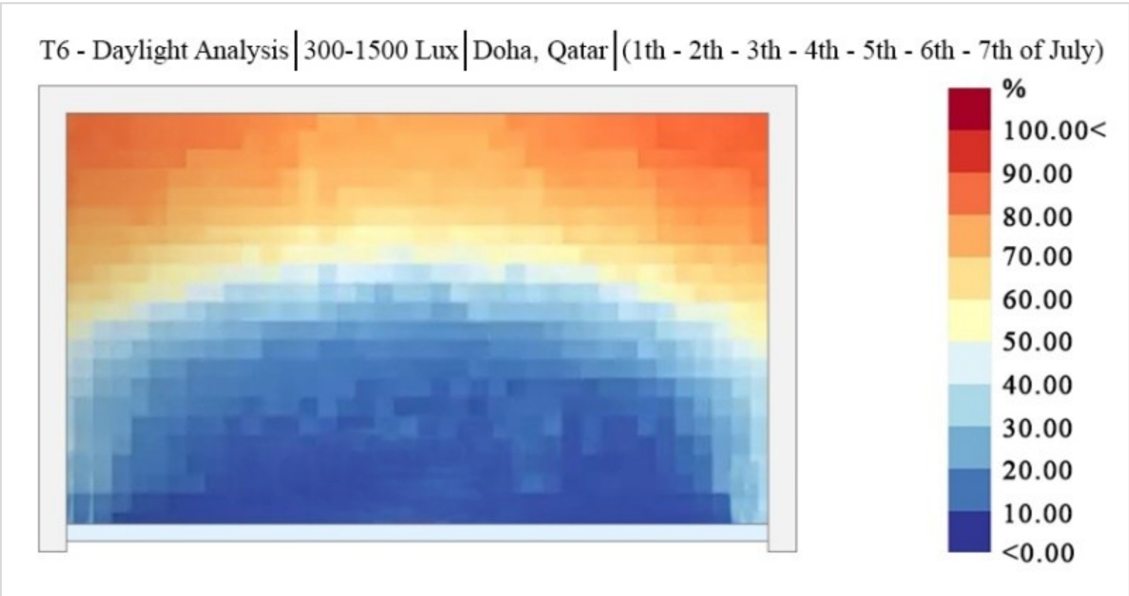

Figure 30. T6 – daylight analysis (300-1500 Lux).

3.3. Comparison of the simulations

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. The results are for the first week (1^{th} - 2^{th} - 3^{th} - 4^{th} - 5^{th} - 6^{th} - 7^{th} of July) of July for all variations.

3.3.1. Cooling load values

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 temperature. 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.

Figure 31 shows that the comparison of the existing variation of the test box (T0) with the integrated variations of the developed biomimetic envelope system (shading device) variations. These data show the total cooling load values for a week for the existing test box and the versions with biomimetic envelope variations (T1 - T2 - T3 - T4 - T5 - T6) integrated into the test box.

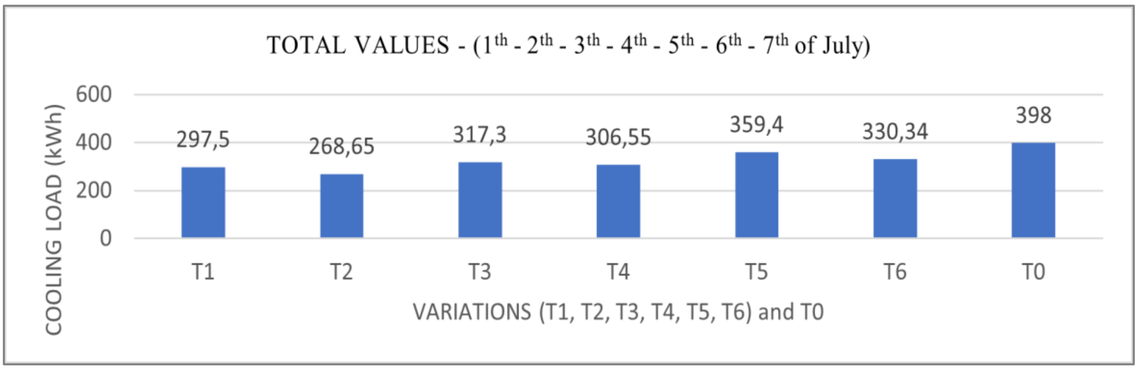

Figure 31. Comparison of cooling load values

As a result, when the total cooling load values during the week (1^{th} - 2^{th} - 3^{th} - 4^{th} - 5^{th} - 6^{th} - 7^{th} of July) were compared separately for all biomimetic envelope system variations, T2 variation was determined to be the most efficient. The modules that make up the T2 variation use a 30 degree opening angle and double layer ETFE. The most inefficient variation was found to be T5. The modules that make up the T5 variation use a 60 degree opening angle and single layer ETFE.

Thus, as the opening angle of the modules forming the biomimetic envelope system increases and the number of ETFE layers decreases, the amount of energy consumed by the test box for cooling also increases. On the other hand, as the opening angle of the modules forming the biomimetic envelope system decreases and the number of ETFE layers increases, the amount of energy consumed by the test box for cooling also decreases.

3.3.2. Daylight efficiency

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.

As a result, when daylight efficiencies during the first week of July (1^{th} - 2^{th} - 3^{th} - 4^{th} - 5^{th} - 6^{th} - 7^{th} of July) were compared separately for all biomimetic envelope system variations, it was determined that T1 and T2 variations were the most efficient. 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 controlled daylight gain without much need for artificial lighting sources. According to daylight performance, the most inefficient variations were T5 and T6 (60° Opening Angle and Single or Double Layer ETFE). When using these variations, indoor comfort decreases when the test box is exposed to uncontrolled daylight.

Thus, as the opening angle of the modules forming the biomimetic envelope system decreases, the daylight gain increases. On the other hand, as the opening angle of the modules forming the biomimetic envelope system increases, the daylight gain decreases.

3.3.3. Indoor temperature

As seen in Figure 32, the outdoor temperature of the test box and the indoor temperature values after all biomimetic envelope system variations (T1 - T2 - T3 - T4 - T5 - T6) are integrated into the test box are given during the week covering the first seven days of July.

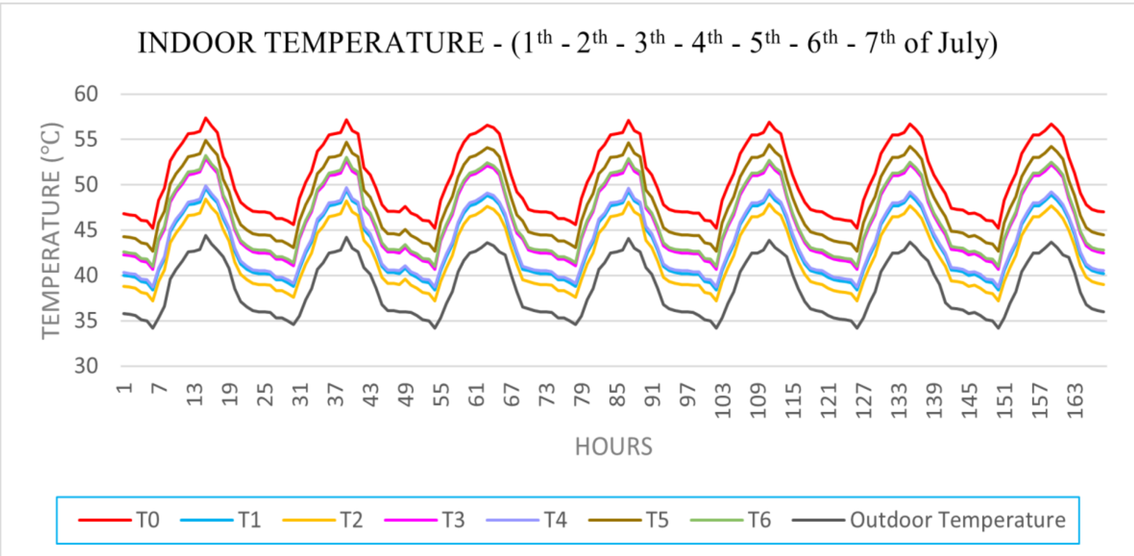

Figure 32. Comparison of indoor temperatures with outdoor temperature

The average outdoor temperature in the hottest week (1^{th} - 2^{th} - 3^{th} - 4^{th} - 5^{th} - 6^{th} - 7^{th} of July) in Doha, Qatar, where an office unit (T0) is located on the south side of a high-rise office building within the scope of the project, was computated as 38.60 degrees Celsius. The average indoor temperature of the test box (T0) without any shading device integrated was 50.5 degrees Celsius. The reason for the difference between the outdoor temperature and the indoor temperature is that the test box is positioned towards the south and has a glass front. In short, the test box (T0) heats up by being exposed to extremely hot sunlight.

As a result, when weekly indoor temperatures were compared for the test box (T0) and after the integration of all biomimetic envelope system variations (T1 - T2 - T3 - T4 - T5 - T6), it was seen that all biomimetic envelope system variations reduced the indoor temperature. T2 variation is the most efficient that can reduce the indoor temperature the most compared to other variations. When the T2 variation is integrated into the test box, the average indoor temperature drops to 42.1 degrees Celsius. A 30 degree opening angle and double layer ETFE are used in the modules that make up the T2 variation. T5 variation is the most inefficient that reduces the indoor temperature the least compared to other variations. When integrated into the test box of the T5 variation, the average indoor temperature 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.

4. Conclusion

In this study, a biomimetic envelope system was developed with a nature-inspired approach for the south facade of an test box (office unit / T0)) located in a fictitious high-rise office building in Doha, Qatar. Both the design process and the performance of the energy efficiency-based biomimetic envelope system developed within the scope of the study were discussed. Briefly, the main findings from this study are:

- The cooling load value before integrating the envelope variations into the test box (T0) is at least 40 kWh higher than the cooling load value after integrating the biomimetic envelope variations into the test box. This shows that the biomimetic envelope system variations developed within the scope of the study significantly reduce the amount of energy consumed by the test box to reduce the indoor temperature.

- The daylight performance of the test box (T0) without integrating any envelope variations is quite low. Because Doha's disturbing and burning daylight needs to be controlled. Thanks to the biomimetic envelope systems developed within the scope of the study, the controlled daylight gain of the test box increased. Thus, the test box with office function becomes comfortable for its users.

- The The indoor temperature of the test box (T0) decreases by a minimum of 2°C and a maximum of 8°C after the biomimetic envelope systems developed within the scope of the study are integrated. This shows that the developed biomimetic envelope system variations significantly reduce the indoor temperature of the test box and increase indoor comfort.

- T2 variation is the most efficient in terms of cooling load value compared to all other variations. After the T2 variation is integrated into the test box, the energy consumed for cooling decreases by 130 kWh.

- T1 and T2 varieties are the ones that provide the best opportunity for controlled and efficient use of daylight compared to all other varieties. The T1 and T2 biomimetic envelope system variations integrated into the test box best meet the 300-550 Lux range in illuminating office spaces with daylight. When T1 and T2 are compared among themselves, the T1 variation is the most efficient in daylight. The T1 variation ensures that the test box (office unit) requires less artificial lighting sources during working hours compared to all other biomimetic envelope variations.

- T2 variation of biomimetic envelope sysyems reduces indoor temperature more than any other variation. The T2 variation reduces the indoor temperature of the test box into which it is integrated by up to 8°C. Thus, the test box requires less mechanical cooling resources.

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

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