BIOMIMICRY AND PARAMETRIC DESIGN: DAYLIGHT OPTIMIZATION OF BUILDING FACADES USING BIOMIMETIC PRINCIPLES

A THESIS SUBMITTED TO
THE FACULTY OF ARCHITECTURE AND ENGINEERING
OF
EPOKA UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ARCHITECTURE

JULY, 2023

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This is to certify that we have read this thesis entitled **“Biomimicry and Parametric Design: Daylight optimization usin biomimetic principles”** and that in our opinion it is fully adequate, in scope and quality, as a thesis forthe degree of Master of Science.

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ABSTRACT

BIOMIMICRY AND PARAMETRIC DESIGN: DAYLIGHT OPTIMIZATION OF BUILDING FACADES USING BIOMIMETIC PRINCIPLES

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The design of the façade determines a building's distinctiveness, as well as its interactions with the micro-climate components, such as sun exposure. Integrating biomimicry and parametricism can lead to an optimal solution to reduce heat gains and visual discomfort. Parametric design tools are the new design methods that emulate Nature's algorithm. This paper provides an understanding of the principles of natural system and develop a design concept outlined by biomimetic principles.

This study applies the biomimicry principles to the interactive and adaptable building facades. The proposed shading system is based on the geometric shape of plants' pollen and the movement of earwigs' wing fold. It is applied at the architectural studio classrooms (of campus building) of Epoka University in Albania. The windows in the classes are located on the south side, which makes it essential to provide the comfortable lighting and to control it due to the complexity of the window system.

The evaluation of different concepts and scenarios of the parametric shading system is based on the simulation of lighting conditions inside of the studios. Based on the analysis, the study proposes the optimal solution which reduces the energy reduction for cooling and heating, increases the use of the natural light and provides the visual comfort facilitating the artistic environment of architectural classes.

Keywords: *Biomimicry, parametric design, kinetic building façade, optimization, visual comfort, shading system, light control*

ABSTRAKT

DIZAJNI BIOMIMIKRI DHE PARAMETRIK: OPTIMIZIMI I DRITËS SË FASADAVE TË NDËRTESAVE DUKE PËRDORUR PARIMET BIOMIMETIKE

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Dizajni i fasadës përcakton dallueshmërinë e një ndërtese, si dhe ndërveprimet e saj me komponentët e mikroklimës, siç është ekspozimi ndaj diellit. Integrimi i natyrës dhe parametrizmit mund të çojë në një zgjidhje optimale për të reduktuar rritjen e nivelit te nxehtesise dhe parehatinë vizuale. Mjetet e projektimit parametrik janë metodat e reja të projektimit që imitojnë algoritmin e natyrës. Kjo tezë ofron një prezantim të parimeve të sistemit natyror dhe zhvillon një koncept fasade të përshkruar nga parimet biomimetike.

Ky studim zbaton parimet e biomimikrisë në fasadat ndërvepruese dhe të adaptueshme të ndërtesave. Sistemi i propozuar i hijezimit bazohet në formën gjeometrike të polenit të bimëve dhe lëvizjen e palosjes së krahëve të insekteve. Aplikohet në klasat e studios arkitekturore (të godinës së kampusit) të Universitetit Epoka në Shqipëri. Dritaret në klasa janë të vendosura në anën jugore, gjë që e bën të domosdoshme sigurimin e ndriçimit komod dhe kontrollin e tij për shkak të kompleksitetit të sistemit të dritareve.

Vlerësimi i koncepteve dhe skenarëve të ndryshëm të sistemit parametrik të hijezimit bazohet në simulimin e kushteve të ndriçimit brenda studiove. Bazuar në analizën, studimi propozon zgjidhjen optimale e cila redukton përdorimin e energjisë për ftohje dhe ngrohje, rrit përdorimin e dritës natyrale dhe siguron komoditetin vizual duke lehtësuar mjedisin artistik të klasave arkitekturore.

Fjalët kyçe: *Biomimikri, dizanj parametrik, fasad*ë kinetike, *optimizim, komoditet vizual, sistem hijezues, kontroll i drites*

To my Grandpa

ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude and appreciation to those who have supported me throughout my thesis journey.

First and foremost, I would like to thank my supervisor, Dr. Anna Yunitsyna for her exceptional mentorship, invaluable insight and dedication. I am truly grateful for the knowledge I have gained under your guidance.

I would like to express my sincere appreciation to the architecture student of Epoka University, who participated in the survey for this thesis.

Lastly, I am deeply grateful to my family and friends for their constant encouragement and support throughout this entire process.

TABLE OF CONTENTS

ABSTRACT 3

ABSTRAKT..4

ACKNOWLEDGEMENTS 6

TABLE OF CONTENTS 7

LIST OF TABLES 10

LIST OF FIGURES 10

CHAPTER 1 INTRODUCTION 1

1.1 Problem Statement 1

1.1 Thesis Objective 2

1.2 Scope of work 3

CHAPTER 2 5

LITERATURE REVIEW 5

2.1Introduction to Biomimicry..5

2.2 Classification and Approaches to Biomimicry 7

2.3 Application in Architecture...9

2.3.1. Application in building facades 12

2.4 Daylighting effects on occupants visual comfort...14

2.4.3 Visual comfort 15

CHAPTER 3 METHODOLOGY 17

3.1 Overview 17

3.2 Biological Solution 18

3.2.1 Organism Level 18

3.2.2 Behavior Level 19

3.2.3 Design principles (grasshopper) 20

3.3 Simulation approach 22

CHAPTER 4 24

DAYLIGHT PERFORMANCE ANALYSIS 24

4.1 Location of the Case Study 24

4.2 Climate Data 25

4.2 Questionnaire 26

4.3 Case Study 33

4.4 Daylighting Scenarios 40

4.5 Results 42

4.5.1 Annual results 43

4.5.2 Hourly results 47

CHAPTER 5 55

DISCUSSIONS AND CONCLUSIONS 55

5.1 Discussion 55

5.2 Conclusions 56

REFERENCES...59

LIST OF TABLES

Table 1. Levels and dimensions of Biomimicry [13] ---8
Table 2. Biomimicry approaches [13] [18] [20] ---9
Table 3. Lighting parameters for activities conducted in studios [39] --------------------------- 16
Table 13. Material properties --- 36
Table 14. Annual Daylight Availability analysis-- 37
Table 18. Annual daylight performance values --- 45
Table 19. Annual best performing scenarios-- 46
Table 24. Hourly illuminance values -- 52
Table 25. Hourly best performing scenarios --- 53

LIST OF FIGURES

Figure 1. Timeline of the field “biomimicry” 6
Figure 2. Matthew Parkes’ Hydrological Center for the University of Namibia and the stenocara beetle. [28] 10
Figure 3. East gate Building in Harare, Zimbabwe natural transmission [30]........................11
Figure 4. Generating complex form triggered by a dynamic transitory-sensitive area (TSA) of attraction point (inspired by Stomata patchy pattern transitory stage) [32].............................13
Figure 5. Flectofin® by ITKE, Institute of Building Structures and Structural Design, University of Stuttgart [33]..13
Figure 6. Parameters of the design [34] 14
Figure 7. Methodology Research diagram...17
Figure 8. Four sets of pollen grains showing the scanning electron microscopy image alongside the simulation of the physical model for the same geometry (Image credit: PalDat.org (SEM image) and Asja Radja (simulation)). [40]...19
Figure 9. Assumptions and FEA simulations describing the self-folding [41]........................20
Figure 10. Biomimetic Design modeled in Grasshopper...21
Figure 11. Grasshopper script..21
Figure 12. South elevation of Epoka University building with the developed kinetic facade.22
Figure 13. Section of the studio classrooms 22

Figure 14. Final design with semi-opened shading devices....22
Figure 15. Location of Epoka University (source: GIS)....24
Figure 16. Top view of Epoka University (source: ASIG)....25
Figure 17. Average temperature and precipitation (left), and the cloudy, sunny, precipitation chart [49]....26
Figure 18. Maximum temperatures [49]....26
Figure 19. Importance of good lighting....27
Figure 20. Preferred type of lighting....28
Figure 21. Experience of discomfort or strain in the eyes due to the lighting....29
Figure 22. Light adjustment....29
Figure 23. Current lighting in the university studios....30
Figure 24. Lighting conditions during winter in the university studios....31
Figure 25. Lighting conditions during summer in the university studios....32
Figure 26. Difficulties in activities due to poor lighting....33
Figure 27. 2nd floor plan of the building with studio classrooms highlighted in red....34
Figure 28. Layout of the studio classrooms....35
Figure 29. Interior of studio classrooms....35
Figure 30. 3D View, section and façade of the studio classrooms....36
Figure 31. Annual Daylight Availability diagrams....37
Figure 32. Point-in-time illuminance chart....39
Figure 33. Point in time Illuminance for Equinoxes and Solstices....39
Figure 34. Facade scenarios....41
Figure 35. Unit 100% and 75% opened....41
Figure 36. Unit 50% and 25% opened....42
Figure 37. Annual DA & Glare chart....43
Figure 38. Annual Average Lux chart....44
Figure 39. Comparison of the base case and best performing scenarios....46
Figure 40. Spring Equinox illuminance chart....48
Figure 41. Summer Solstice illuminance chart....49
Figure 42. Fall Equinox illuminance chart....50
Figure 43. Winter Solstice illuminance chart....51
Figure 44. Best performing scenarios for each year of study....54

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Due to environmental change and sustainability strategies, improving the visual comfort of occupants through adequate daylighting the interior has become an important theme of facade design. Natural light is a renewable and sustainable source of energy, affecting the health of the inhabitants in terms of physical, psychological and mental benefits. In places where people work or study, a good lighting environment does not only improve mental and physical health of the occupants, but also increases work efficiency. [1] Studies have shown that good daylighting in schools' environments provide visual comfort for performing any task. [2] In addition, designing a building skin is important for the quality of its indoor spaces.

A building façade has traditionally been considered to be either a thermal barrier to prevent heat- loss or shade to limit solar gain. Yet, the majority of building envelopes are built to give static design solutions.

Biomimicry is defined as the study of overlapping fields of biology and architecture, demonstrating the potential of innovative architecture in the field of study and is widely used to explore nature to develop unique facade ideas that can adapt easily to contextual issues and requirements. [3] In architectural design, copying nature is not often used as a design strategy, but it can be used to choose alternative materials, such as adhesives and fibers. Biomimicry offers several advantages in architecture, including: structure efficiency, material fabrication, zero-waste systems, water management, control of thermal environment, and energy production. With the current efforts to create sustainable built environments, there should be a database of successful attempts to solve design issues by imitating nature, so that these design techniques can be shared and used to educate others. The databases available today are more conceptual and need to be developed further and given guidelines for implementation. That is why there is a need to take these concept and further develop them into usable designs.

Applying biomimicry principles in existing buildings is challenging considering the condition, structure, orientation, size of the building. The existing building that will be addressed to serve as an example toward finding a solution to improving visual discomfort will be the Epoka University's Social Center and Department of Architecture building, specifically the studio classrooms. The studio's opening face the south side, making them more prone to over-heating and glare effect. A south-facing room can become uncomfortably hot, particularly during the spring and summer months. The intense sunlight that comes with it can cause glare on computer screens and other electronics. This can be frustrating and potentially harmful to the eyes over time. These are the aspect of the space that need to be checked and analysed in order to be improved or better be replaced.

Biomimicry has been proposed as a promising approach for developing adaptive shading systems that can respond to changing environmental conditions. By emulating the design principles and strategies of natural systems, such as …., biomimetic design can provide innovative solutions that are efficient, sustainable, and responsive.

However, the integration of biomimetic principles into the design of adaptive shading systems presents a number of challenges, including the need for sophisticated digital and parametric design tools to facilitate the design process, the lack of standardization and regulation of adaptive shading systems, and the limited understanding of the performance and effectiveness of these systems in real-world applications.

Therefore, the main problem addressed by this thesis is how to develop an adaptive shading façade based on biomimetic principles of design that can be integrated into the process of digital and parametric design, and provide a sustainable and effective solution to reduce energy consumption in buildings. This problem requires an interdisciplinary approach that involves the fields of architecture, engineering, and biology, as well as the use of advanced digital and computational tools to facilitate the design and evaluation of the adaptive shading system.

1.1 Thesis Objective

In this thesis, I will introduce the concept of biomimicry through its various approaches, methodologies, materials from nature, developed materials and systems in architectural applications, explore the principles of biomimicry in relation to adaptive shading systems and apply them to the design of a façade system that can adapt to changing environmental conditions. Digital and parametric design tools to facilitate the design and to evaluate the performance in terms of the ability to regulate light, will be needed. Exploring the potential of digital and parametric design tools will aim to optimize the design of the adaptive shading system, taking into account a range of factors such as building orientation, solar radiation, and occupant preferences.

The research is based on literature study, a bio-inspired design approach and parametric simulation to develop a design for kinetic façade, as well as to evaluate the performance of the adaptive shading system in terms of its ability to reduce glare, maintain a comfortable level of natural light, and minimize the need for artificial lighting. The soft wares and plugins used are Rhino 7, Grasshopper, ClimateStudio, which processes will be explained in detail in the forthcoming chapters.

The main objective is to develop an adaptive shading façade based on biomimetic principles of design that relate to and inform the process of digital and parametric design. Overall, this thesis aims to demonstrate the potential of biomimetic design principles and digital tools to inform and enhance the development of adaptive shading systems, and to promote sustainable design practices that can improving occupants' visual comfort.

1.2 Scope of work

This thesis will provide a complete overview of data collected from research and the approach selected for developing a bio-inspired kinetic façade for daylight performance optimization in Epoka University’s architectural studios. The approach followed is *Problem Based Approach (Top-Down),* as explained in the upcoming chapters, starting with the definition of the problem, reviewing the problem, search for the biological solution, define the biological solution, design principle extraction and applying them. Based on the approach, the thesis is divided in five parts, each consisting of particular subsections: *Literature Review, Methodology, Daylight Performance Analysis and Conclusions.*

The first part uses existing articles and research papers in order to gain a better understanding of what is Biomimicry, its classifications and approaches, and application on architecture and building facades. Further details on the daylighting effects on occupant’s visual comfort and the daylighting requirements for activities conducted in educational spaces can be found in the first chapter. The requirements will help in analyzing the current state of the case study selected, in this case being the Epoka University’s studios.

The methodology chapter is in compliance with Problem Based approach followed for the design of the façade. Data is collected from extensive research to find a biological solution that will best respond to high daylighting values and illuminations. The subjects were selected based on *Levels of Biomimicry*, specifically *Organism Level and Behaviour Level.* The first is inspired by the geometric patterns of plant' pollen, whereas on behaviour level, the design has been inspired by the movement of earwigs' wing fold.

The selected solutions are further elaborated, where the principles of each organism are extracted to design the kinetic façade's alternatives for evaluation and development. By applying this principles, the aim is to produce a sustainable solution that addresses the daylighting problems and meets the needs of the students who work in the studios.

To develop different façade alternatives, a characterization of the base case of Epoka University's studio is given in chapter 4. Simulation were performed using Daylighting Evaluation Criteria: sDA, ASE, Illuminance and Glare. Additionally, a survey was conducted among the students of the Department of Architecture to have their perspective on the daylighting challenges in the studios. Combining the results from the survey and the simulation findings, the basis for defining the stated design problem is formed.

As per the design principle, a total of 16 building façade alternatives were developed using Rhino's plug in, Grasshopper. The building skin scenarios are implemented in the selected case study for evaluation. Daylight performance simulations will be performed on each building skin scenario, in order to gain a deeper understanding of the impact and the effectiveness of the solution. The software tool used for the simulations will be Rhino's plug in *Climate Studio.*

Lastly, results are evaluated and compared to the current state of the base case, in order to find the best scenarios for improving occupants' visual comfort.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Biomimicry

The word Biomimicry derives from two Greek words: “bio” meaning life and “mimesis” meaning imitation. Biomimicry is a relatively new field of study that has been gaining traction in recent years. The term itself has been confused and often used in relation with other field such as *biomimetics and bionics.* Historically, the term biomimetics was first introduced in the 1950s by Otto Schmitt, an American engineer and biophysicist. Schmitt developed the field of biophysics and was the founder of the field of biomedical engineering. [4] The famous biologist and mathematician D'Arcy Thompson published his 1917 book On Growth and Shape, replacing Otto Schmitt. According to him, the influence of physics and mechanics on the creation of shapes and structures of organisms is under-understood. His book aims to demonstrate the relationship between biological and mechanical structures. Thompson's book does not attempt to propose any universal discovery in all biological systems, nor does it mean a causal relationship between the emerging form of engineering and the similar form of nature. [5] The U.S. Air Force Medical Division's Jack Steel introduced the term bionics in 1960 and combined the terms biology and technology. Biomimicry is the youngest field in the field, based on natural design created by John Todd and Nancy Jack-Todd in the 1970s (Figure 1). [6]

According to a research conducted on *Biologically Informed Disciplines,* the findings were able to conclude that the fields of bionics and biomimetics are best suited for biologists, engineers, and designers interested in the technical complexity of projects with a focus on technological innovation, whereas the field of biomimicry is better suited for biologists, designers, architects, economists, and others who are motivated by a nature-focused philosophy and seek minimal technical complexity. [7] While the two terms share similar meanings, we can argue that *biomimicry* is a more holistic approach that emphasizes the importance of sustainable and regenerative solutions. In contrast, *biomimetics* and *bionics* may be more narrowly focused on the development of specific products or technologies.

Janine Benyus is responsible for classifying biomimetic as a research field. Biologist and writer Benyus contributed to popularizing the term "biomics" in a broader audience. Benyus's work highlights the idea that nature has already addressed many problems humans are trying to solve, and that by studying natural systems and processes, we can develop creative and sustainable solutions to our own problems. She argues that by imitating the structure, processes and systems of nature, we can build more robust and efficient designs that adapt to changing situations. [8]

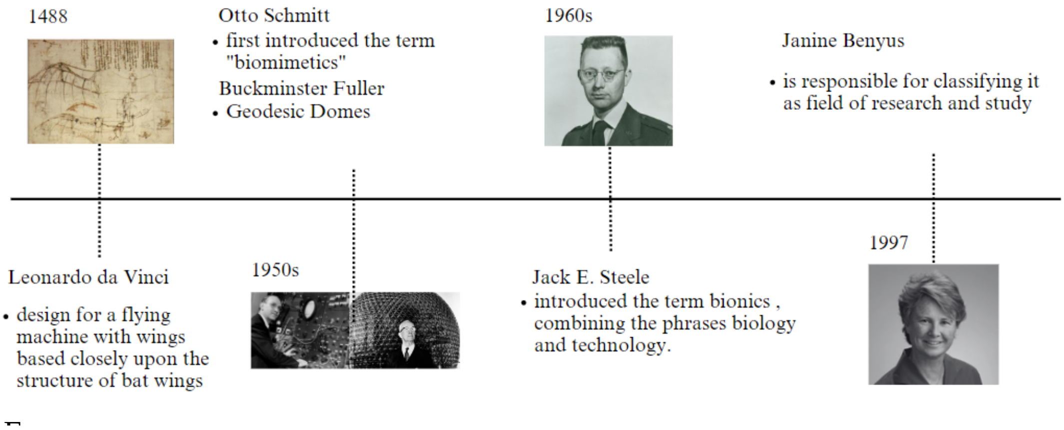


Figure 1. Timeline of the field “biomimicry”

Although the principles and regulations applied to biomimicry in architecture have been introduced relatively late, they have evolved through various biological and architectural successions. Biomimicry is not just a copy of a natural object or system. It is not just about forming something "green" or sustainable. It begins with a careful examination of an organism or ecosystem, and then with a careful use of the basic configuration standards found in natural solutions. Understanding nature is one thing, learning from nature is another. Nature has good patterns and solutions around us, and biomimicry is the exploration and use of natural solutions for design issues.

Lidia Kadri (2014) reports that biomimetics is a rapidly growing design discipline in engineering, and an emerging field in architecture. Morphology and form are most common traits to be transferred from natural systems into architecture. Such traits seldom retain any function of the imitated natural systems, and hardly represent a successful biomimetic design. The application of biomimetics in architecture is still a challenge. [9]

When discussing what can be improved, some limitations to biomimicry methodology were brought up. The main one is that it does not provide a transition from the concept phase to the emulation phase. [10] Another limitation is that if the methodology proposed is not based on reliable and accurate knowledge sources, the generated design concept cannot work properly. Implementing of biomimetic principles can be limited by three obstruction: (1) exploration and selection of strategies from nature, (2) scaling difficulties as some functions work on specific scales (e.g.nano to micro) and (3) conflict of integrated parts of the design concept. [1] Ahmar (2011) pointed out a few problems with biomimicry. [10] Initially, the practice requires a great deal of specific knowledge, abilities, and instruments. In addition, the design process is strongly dependent on computer programming. Furthermore, to determine the right material for a framework, many physical experiments and geometric representations are required. It is important to know the relationship between the components. Hence, the selection of appropriate algorithm development processes and the need to regularly interface with appropriate research applications are some of the problems faced. Finally, continuous assessment and feedback control are also challenges. [10]

2.2 Classification and Approaches to Biomimicry

Based on Benyus's 1997 Biomimicry: Innovation Inspired by Nature, Biomimicry is divided into three categories: form, process and system. The *form* category is the imitation of natural forms, structures and materials, such as the design of airplane wings based on the shape of the bird's wings. *Process* biomimicry is the imitation of natural chemicals and biological processes such as the decomposition of waste using microorganisms. Using natural ecosystem organizational and relational patterns, sustainable *systems* can be produced, such as regenerative agriculture methods are developed. [11]

Due to the complexity of biological systems and many overlaps whining the categories, it is difficult to make a division. This research is based mainly in structures and materials, mechanisms and power, sensors and communication, behaviour and control, and generational biomimetic.

In architecture, Zari (2009) classified the concept of biomimicry on the basis of two results. The first approach focuses on the five design directions inspired by nature: form, what the organism looks like, material, what it is made of, construction, how it is made, process and function, how the organism acts and what it does (Table 1). These dimensions of mimicry are part of a larger division, which leads to the second approach emphasizing the three-level of mimicking the nature: organisms, organisms' behaviour, and ecosystems. The organism level refers to the specific organism (plant or animal), which parts of the whole is being mimicked. Organisms' behaviour is about translating how the organism behaves and referring it to a design. Lastly, the ecosystem level studies the relationships between organisms and organisms to the environment they live in. Some biomimetic design techniques originate from existing ones and literature and produce different results. [12]

Table 1. Levels and dimensions of Biomimicry [13]

Biomimicry Levels	**Biomimicry Dimensions**
Organism (mimicking parts of the whole organism)	Form
	Material
Behavior (behavior simulation of the organism)	Construction
Ecosystem (relationship to others or the environment)	Process
	Function

Depending on the results of research, different directions and classifications are used to implement biomimetic principles into architectural design. Natural systems are a source of inspiration for strategies and mechanisms that organisms use to adapt to different environmental conditions. [13] Based on previous researches there are two primary design methodologies used: *the bottom-up* and *top-down* approach. [14] [15]

The method of the *bottom-up approach*, also known as biometics by inductive or solution-based method, is to transform natural properties into human technology with the help of naturalists or ecologists. This design process focuses on identifying specific characteristics and behaviors of organisms or ecosystems and using them as guidelines for the creation of design plans or industrial products. [16] According to Vincent and Seri, the principles derived from this methodology include adaptation and evolution, self-organization, optimizing instead of maximizing, free energy and the use of materials and processes that are beneficial to life to improve the biosphere. Most of these principles have been applied to industrial products, but some have not been discovered in engineering and have still limitations. [17] An advantage to this methodology is the way it influences humans to resolve predetermined design problems, resulting in new design approaches and technological systems. From the design point of view, the disadvantage of this approach is that biological research must be carried out and then identified as relevant in the design context. Biologists and ecologists therefore need to know the potential of research in innovative application innovation. [18]

The top-down approach is a problem-based biomimetic that starts with identifying a design problem. The designers then find a solution in organisms such as plants or animals, which parameters are applied to the product. According to El Ahmar, this method allows for continuous development of new biological solution without the need of a biologist and a in-depth scientific understanding of the organisms. [10] However, technical issues might appear due to incomplete and shallow levels of scientific comprehensions, affecting the transition from biological data to technical structure. This approach follows a non-linear and dynamic progression scope of work, where later stages of outputs have an impact on earlier stages, providing constant feedback. [19] Each approach is defined through steps as shown in Table 2. :

Table 2. Biomimicry approaches [13] [18] [20]

Biomimicry Approaches	
Bottom-Up Approach (Solution- based)	**Top-Down Approach (Problem- based)**
1. Biological Solution	1. Problem definition
2. Bio. Solution definition	2. Problem reframing
3. Principle extraction	3. Biological Solution search
4. Reframe the solution	4. Bio. Solution definition
5. Problem search	5. Principle extraction
6. Problem definition	6. Principle application
7. Principle application	

2.3 Application in Architecture

Biomimicry is a design methodology that acquires natural solution to building sustainable and efficient technologies and systems. In architecture biomimicry has been used to build structures with minimal environmental effect, that consuming less energy, make less waste and to better fit to the local environment by imitating the way ecosystems and organisms work.

Climate change mitigation and adaption is supported by developed and developing nations, by popularising the low-carbon city and society's plan for growth. [21] However, buildings continuously contribute to the issues we are facing nowadays. According to Ürge-Vorsatz et al. [22], Munaaim et al. [23], and Al-Obaidi et al. [24], roughly 23% of the world energy use and 30% of global electricity consumption is induced by buildings. Moreover space heating and cooling absorbs 60% of total energy utilized in buildings. [25] As Le Corbusier said, the development of architecture has led to changes in design approaches since 1930, when he introduced universal houses for all climates. [26] Today, the relationship between man and nature is strained. As cities move further away from nature, different environmental problems arise and become uninhabited cities. In order to adapt to nature, it is necessary to consider the design of natural and artificial structures and the surrounding vegetation. The biomimetic process, inspired by structures, forms, and ecosystems as a whole, allows us to create sustainable designs based on this new and original perspective called biomimetic architecture. [27] In recent years, biomimicry has been presented in many architectural applications, showing that it can inspire many architects.

One example is the mimicry of the Namibian desert beetle, stenocara, which inspired Matthew Parkes of KSS Architects to design a fog- catcher for the of University of Namibia's Hydrological Center (Figure 2). The beetle's habitat, the desert, provides little to no moisture. However, they turn into the wind whenever there is fog clearing the desert, as they are able to catch moisture from it. From the hydrophilic rough surface of the beetle, the moisture falls in form of droplets into the insect's mouth. This proposal falls into the organism level of biomimicry. [28]

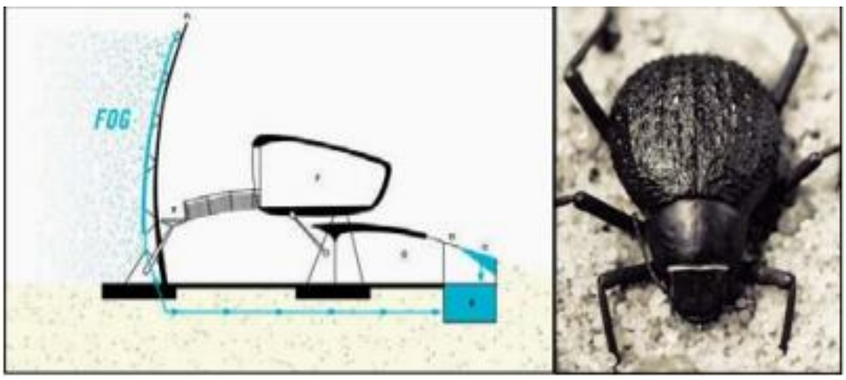


Figure 2. Matthew Parkes' Hydrological Center for the University of Namibia and the stenocara beetle. [28]

The University of Akron came up with a design that was developed for coastal areas affected by drought, and uses glass beads on polystyrene surface water-resistant bumps to provide drinking water. Another method is to use nail polish as a hydrophilic background and then add modified glass beads (OTS and DTS). The aim was to determine in which context the characteristics of the beetle needed to be improved. After all, there were no significant differences in water condensing capacity between the two designs. [29]

In behaviour level biomimicry, Mick Pearce's Eastgate Building in Harare, Zimbabwe can be taken as an example. The Eastgate, a collaboration with Arup engineers, is an innovative design, featuring offices and a shopping center. The ventilation and cooling systems of the buildings are modeled according to the methods used by local termites. The building is not dependent on conventional air conditioning and heating, but on the self-cooling strategies of African termite caves, which maintain a constant temperature of 87 degrees in climates of 35 to 104 degrees. This temperature control is achieved through a shaft that allows ventilation through a convection air flow (Figure 3). The Eastgate Center employs a similar process using a continuous fan to attract air into the cracks of the wall and condition it before being released into the building. The building also benefits from natural air flow and includes a central space between the two buildings that can be opened to allow breeze. [30]

This approach has allowed the building to use less than 10% of the energy, by cutting off the air conditioning unit. [30]

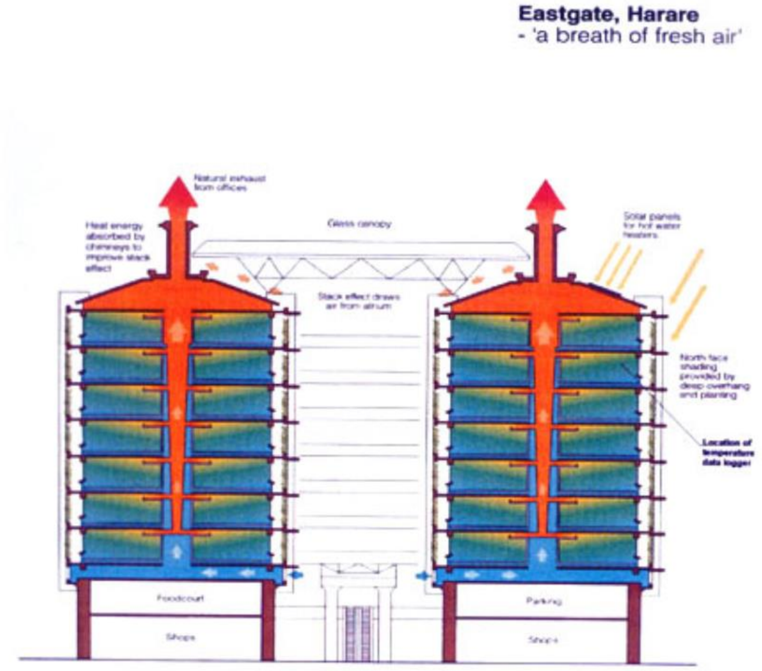


Figure 3. East gate Building in Harare, Zimbabwe natural transmission [30]

As seen from these case studies, nature has proven that it can provide efficient and sustainable ways of minimizing resource consumption, reduce waste and overall promote ecological harmony.

2.3.1. Application in building facades

The design of building facades is a crucial aspect of ensuring energy efficiency and comfort of the occupants. Recognizing the importance of a well-designed building envelope, the application of biomimicry has offered valuable solutions and results. This approach is capable of revolutionizing construction design and construction, bringing innovative solutions such as insulation, shading, and ventilation. Biomimicry can be divided into three categories: physiology, morphology, and behavior. In order to find an effective analogy, it is essential to explore the appropriate level. Many studies have used biomimicry morphological levels to create complex and flexible facades that can adapt to the environment. [31]

The research team from the University of Technology, Eindhoven, Netherlands reported that Biomimicry and biological strategies, like plant adaptions, can help in designing interactive façades that are more adaptable to climatic conditions. They applied the motion principles of plant movement into a larger scale, creating a kinetic shading system. The design strategies included grid forms, symmetrical elements and dynamic TSA sizing and positioning for shifting the shape of the façade (Figure 4). By studying the properties of the plants' stomata, areas that are more sensitive to the sunlight and the occupants were identified, useful in controlling the interactive façade and creating complex forms in real time. This strategy derives from the stomata's ability to filter and use daylight by plants. [32]

Rhino, Grasshopper and Diva 4 were used for the design and daylight evaluation of the façade. Daylight evaluation was based on climate and luminance metrics and the simulations were performed on 810 façade alternatives. The results showed that the kinetic façade with grid division 8x1 performed better on the south direction of a general office building plan. [32]

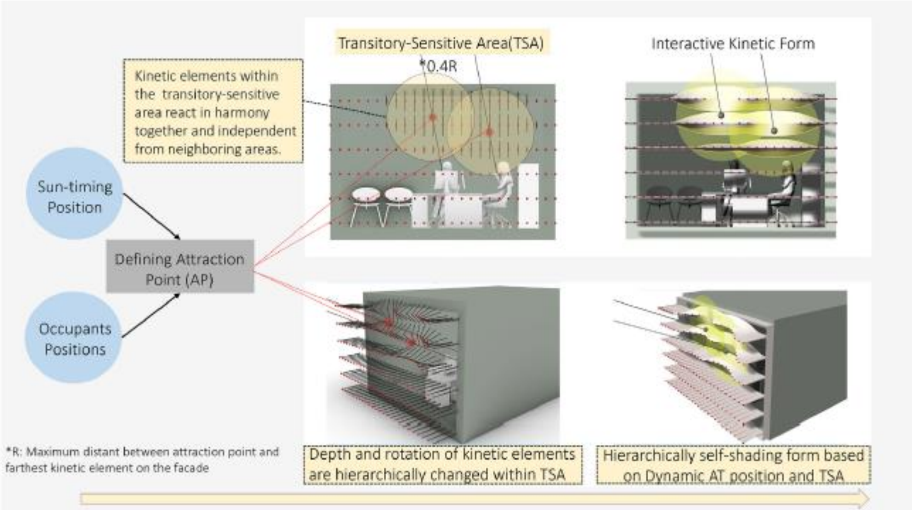


Figure 4. Generating complex form triggered by a dynamic transitory-sensitive area (TSA) of attraction point (inspired by Stomata patchy pattern transitory stage) [32]

Another example of biomimicry in façades of buildings is the "dynamic shading" system developed by researchers at the University of Stuttgart. The system uses flexible panels that move in response to sunlight and provide shade and ventilation when necessary. Flectofin is a helicalless cleavage system that can change the fin by induced spine bending stress caused by the movement of a support or change in laminate temperature. In nature, pollinated sunbirds landed in the flower petals of plants, causing temporary deformation and release of pollen. When the bird's weight is moved, the petals return to their original position and close the pollen. [33]

Figure 5. Flectofin® by ITKE, Institute of Building Structures and Structural Design, University of Stuttgart [33]

Sometimes two or three levels of biomimicry can be incorporated in a design process. Researchers from Assiut University in Egypt adapted two levels: organism level and behavior level. They created a kinetic shading system for a general office plan in Assiut, inspired by snake skin (organism) and plant movement (behavior) (Figure 6). The building skin alternatives were modeled in Rhino and simulated in ClimateStudio based on the LEED rating system. Parameters of the alternatives included the solid to void ratio, the angle of rotation of the units and the number of units in the façade. The results showed nine façade alternatives achieved improvement from 16.69% to 33.73%, with the rotation angle being the most successful parameter. [34]

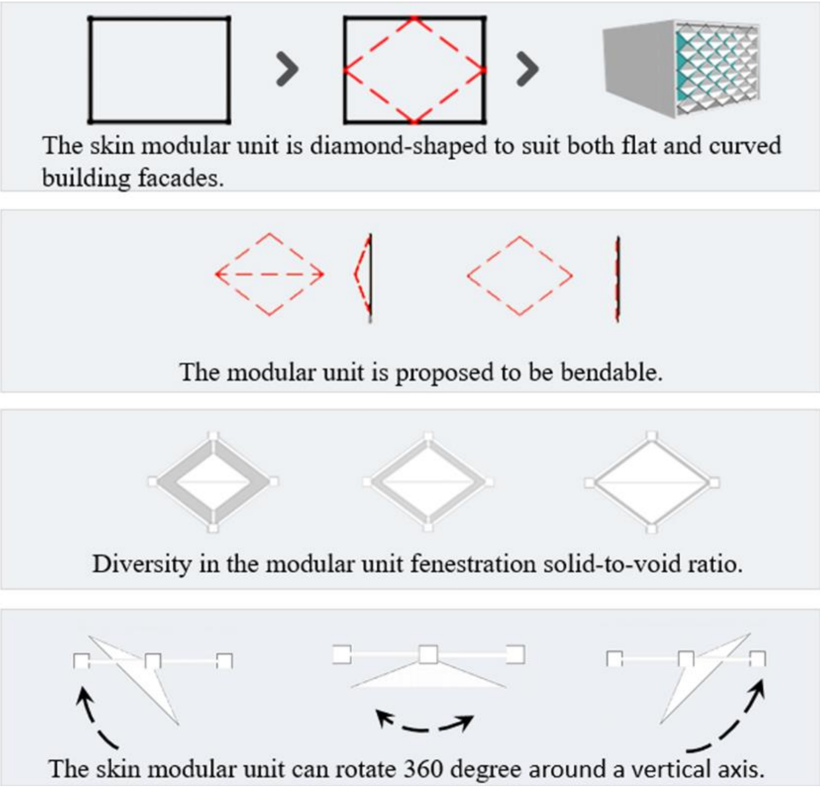


Figure 6. Parameters of the design [34]

2.4 Daylighting effects on occupants visual comfort

The changing qualities and dynamic nature of daylight have a great impact on human visual comfort. As the main source of natural light, it plays an essential role in shaping humans' perception of the world around. The intensity, direction and spectrum composition of sunlight affects human visual experiences, changing the ability to clearly see, to accurately discern colors, and to maintain visual comfort throughout the day. Understanding the influence of daylight on human vision is crucial to creating a harmonious relationship between architecture and natural environment, promoting well-being, productivity and natural surroundings. In this regard, research into how sunlight interacts with the visual system and assesses its impact on visual comfort can provide useful insights into the design of building facades that maximize human visual experiences.

Daylight is often used for architectural and energy savings. However, it should also be taken into account the psychological and physiological advantages it offers, such as the comforting atmosphere and the connection with the environment for the building's inhabitants. The different wavelengths of light have different effects on the human body. [35] Full-spectrum fluorescent lighting is near natural light, but most electrical sources lack the spectral distribution required for complete biological functions. The blue light that is most important to humans is most effectively provided by natural light. [36] Full spectrum fluorescent lighting is the electrical source that resembles the light spectrum most closely to natural light. [37]

The effects of daylighting in schools have been shown to be significant for both teachers and students. However, if used correctly, it can cause unpleasant conditions in the building. In order to realize the advantages of daylighting, an appropriate implementation is required. The wrong use of sunlight can have harmful effects such as the reduction in productivity, the increase in student absence due to excessive sunlight, high temperatures and extremely high levels of lighting. Integrated and balanced daylight management can benefit school children and teachers in various ways, such as reducing school waste costs, improving student attendance and academic performance, and creating less stress and learning environments. Inadequate lighting in schools can be harmful to the student's ability to learn and process physiological information. Insufficient spectral light can impede the eye, reduce learning abilities, and increase stress. [38]

2.4.3 Visual comfort

To evaluate a daylighting system, whether it should be applied in a specific building, performance parameters help to define that. Visual function parameters, which are directly linked to the eye’s physiology, determine if the lighting conditions provide sufficient sight or visibility. Good visibility is having enough light for the task, even distribution of light, proper angle of light, no glare, and accurate colour rendering. Two of the most common used parameters for daylight evaluation are Illuminance and Glare.

Illuminance has to do with the amount of light emitted by a source that falls into a surface and it is measured in lux. Discomfort glare is the feeling of being bothered by bright or uneven light in your field of vision. To measure this, the Daylighting Glare Index (DGI) is used and can be calculated for someone facing a large glare source from a window or wall at different distances. This method was introduced by Hopkinson in 1972. [38] Table 3 shows the lighting requirements for the conducted activities in the studio classrooms of Epoka University.

Table 3. Lighting parameters for activities conducted in studios [39]

Parameters	**Activities conducted in Studios**			
	Reading or writing	Using computers or electronic devices	Drawing/ Sketching	Model making
Light Intensity,Lux	500	300	750	500
Light Uniformity (Uo)	0.6	0.6	0.7	0.6
UGR	19	19	16	19

CHAPTER 3
METHODOLOGY

3.1 Overview

The methodology chapter follows the problem-based approach used for facade design (Figure 7). Data from extensive research are collected to find the best biological solution for extensive daylight and lighting values. The first part of the chapter will be an introduction to the two organism selected based on shape and movement. On *Organism Level,* design principles are extracted from the geometric shape of a plant's pollen. The movement is inspired by the self-folding mechanism of the earwig's wings. In the second part, the development process of the Grasshopper model will be described step by step, starting from a single unit to the final parameters of the façade. Additionally, four criteria are selected for evaluation of daylight performance, along with the analysis of the hourly performance of summer and winter solctices, and spring and autumn equinoxes. The simulation will be performed by ClimateStudio, based on the LEED v1.4 requirements.

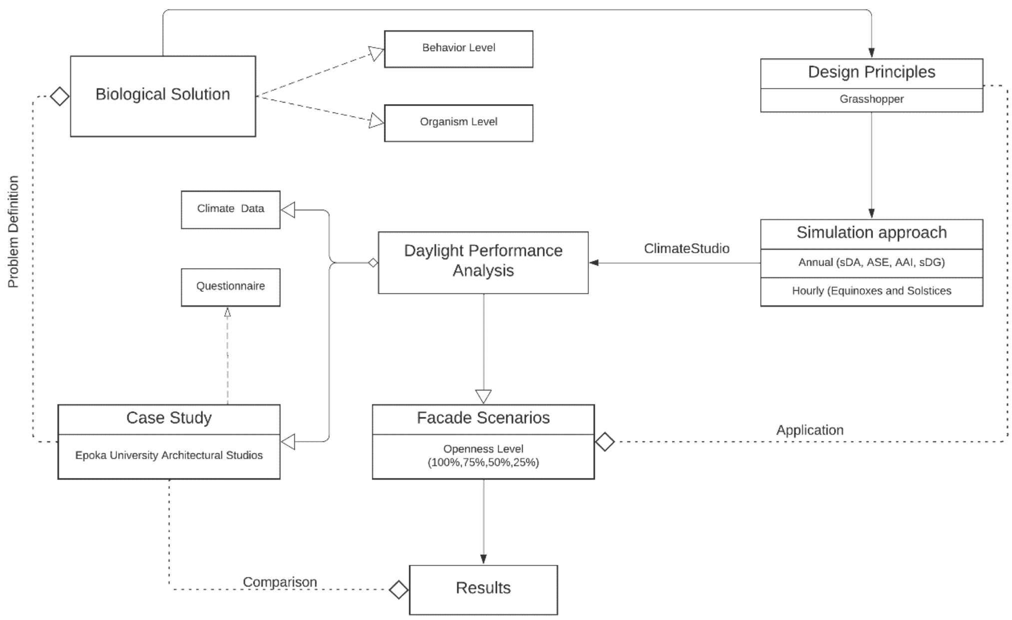


Figure 7. Methodology Research diagram

3.2 Biological Solution

The proposed biological solution consist of two parts. The first one is based on *Organism Level* and it is inspired by the geometric patterns of plant' pollen. The second one, based on *Behavior Level,* is inspired by the movement of earwigs' wing fold. The selected solutions are further elaborated, where the principles of each organism are extracted to design the kinetic façade's alternatives on Rhino's Grasshopper for evaluation and development.

3.2.1 Organism Level

Scientists have long been fascinated by the intricate patterns and designs in the microscopic world, such as the geometric patterns found on individual pollen grains (Figure 8). Despite their fascination, the formation of these patterns, which are smaller than the width of a human hair, remains a mystery. Originally, it was believed that pollen spheres formed due to the buckling mechanism, a process in which the outer layers are tough and the inner layers are pliable, causing "buckles" to form on the surface. However, it is now believed that pollen patterns are the result of phase separation, a process that creates geometric patterns in other systems. As an example, milk naturally separates into cream when allowed to settle at room temperature, without any additional energy or agitation. This process of phase separation leads to detailed geometric patterns that can inspire the initial shape of a parametric building façade. For the initial shape of the façade unit the molecules of Gomphrena Globosa or known as Amaranth flower is taken as an inspiration. [40]

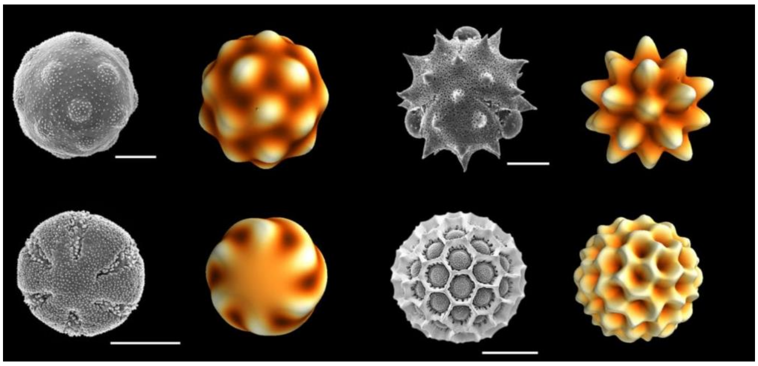


Figure 8. Four sets of pollen grains showing the scanning electron microscopy image alongside the simulation of the physical model for the same geometry (Image credit: PalDat.org (SEM image) and Asja Radja (simulation)). [40]

3.2.2 Behavior Level

Earwig wings are normally stored beneath leathery forewings, but expand more than ten times larger than their folded size when in flight. Their folding pattern is optimized for strength and flexibility, making them a prime example of natural folding Insects wings only have active muscles where they attach to the body, but this doesn't hinder their ability to support weight or to maintain stability when flying. Earwig wings have evolved to fold quickly, without using muscles, but with a joint structure similar to that found in origami.

The wing is divided into a stiff outer and more flexible inner region, with the leading edge providing stiffness from base to tip (Figure 9). This leading edge helps it bear aerodynamic loads and, in addition, a central mechanism allows the wing to snap from a stable folded state to a stable open state. The wing is curved in the middle, which helps it withstand bending forces. Resilin protein strengthens the joint to give the wing a great deal of flexion, which allows it to fly slowly or at a wide range of speeds, with high maneuverability. These wings are incredibly lightweight and can be tucked away for protection. [41] They also have the potential to influence a number of design with their strong and flexible self-folding process.

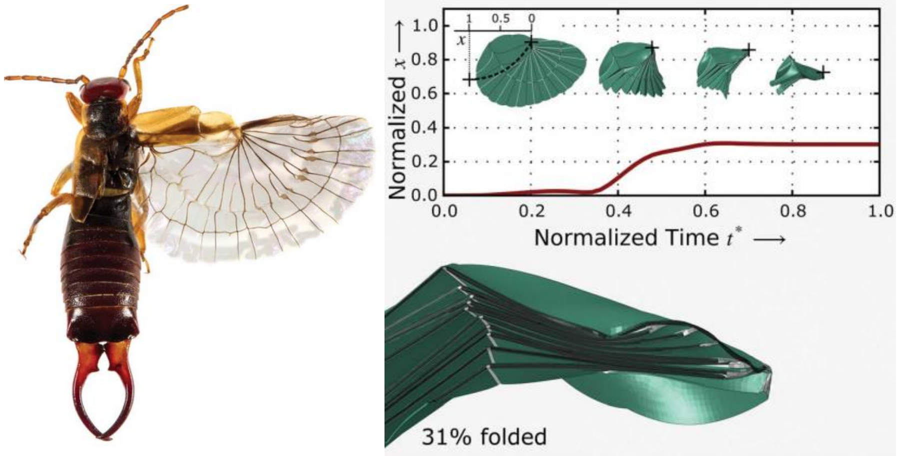


Figure 9. Assumptions and FEA simulations describing the self-folding [41]

3.2.3 Design principles (grasshopper)

Elements inspired by the geometric configuration of plant pollen and the complicated folding mechanism found in earwig wings are included into the architectural design. These ideas served as the foundation for the creation of numerous façade options based on the underlying concepts acquired from these natural sources.

The hexagonal units with a radius of 57 cm serve as the design's fundamental construction block. To maintain consistency, each hexagon's perimeter is split into twelve equidistant points, each of which connects to the hexagon's center, resulting in the production of twelve equal triangles.

The façade is made up of these hexagonal cells, each of which works as an independent shade device, altering its configuration in response to the sun's course. The folding process begins with a 360-degree spin around the hexagon's core axis (Figure 10). Extensive modeling and testing were carried out utilizing Rhino’s plug in, Grasshopper to assess the feasibility and efficacy of the design and its accompanying folding method. In the end 3D models with different level of openness, ranging from completely opened to 25% opened, were generated.

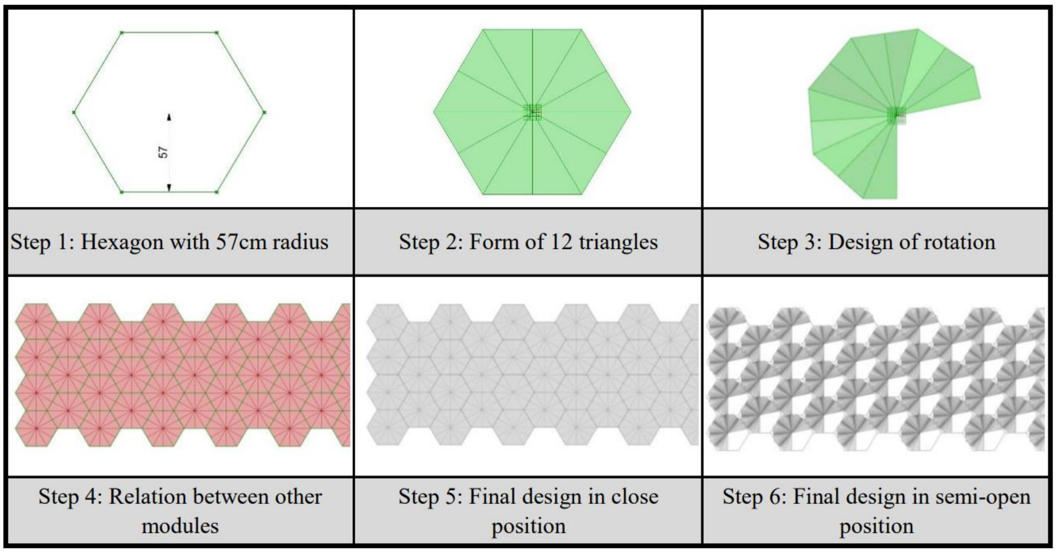


Figure 10. Biomimetic Design modeled in Grasshopper

The development process of the Grasshopper script is divided into three parts (Figure 11). The first part is the designing of one unit parameters and the folding system. Secondly, a screen comprised of hexagonal cells was developed to see the relation between other units. Lastly, to analyze the effects of the proposed design, façade alternatives were developed.

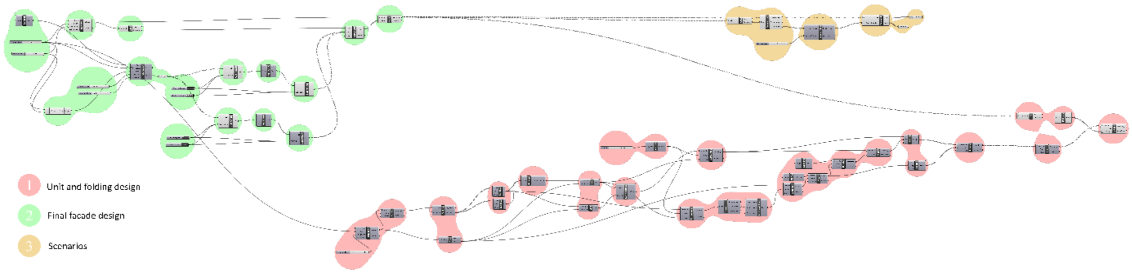


Figure 11. Grasshopper script

The elements of the design consist of *the movable part,* the triangles that resemble the self-folding earwigs' wings, and *the fixed part,* the hexagonal cells similar to the geometric shape of plants' pollen. The kinetic façade is supported by aluminum frames. Simulations were performed by ClimateStudio, thus the material of the panels comprises of Opaque Roller Blinds. The folding shading envelope is grouped according to the layout of the studio area (by each year of study) and can operate manually or automatically in response to the sun's movement. (Figure 12) Each group is comprised of 60 units. An actuator is responsible for the closing and opening of the shading device. Figure 13 shows a section of the building façade and the developed shading device.

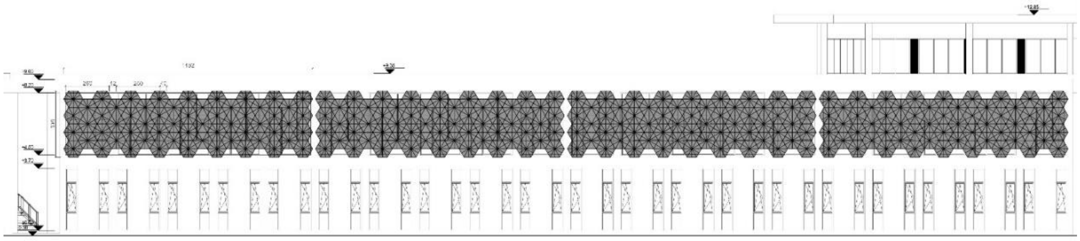


Figure 12. South elevation of Epoka University building with the developed kinetic facade

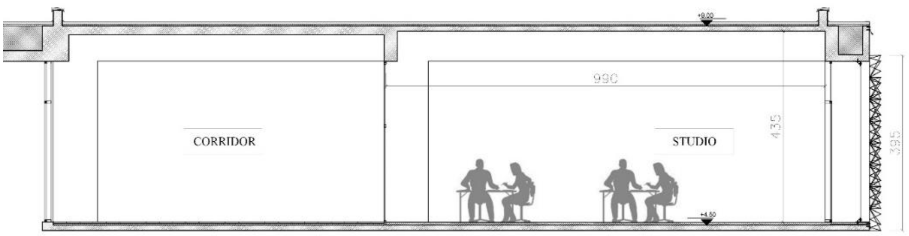


Figure 13. Section of the studio classrooms

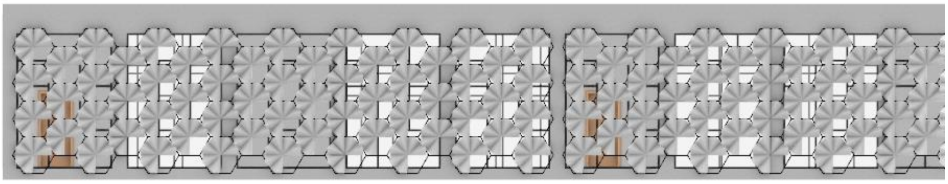


Figure 14. Final design with semi-opened shading devices

3.3 Simulation approach

The building skin alternatives were modeled using Rhino v6 and Grasshopper, with simulations conducted in ClimateStudio (v1.8.8244.25334). ClimateStudio is a platform that uses energy plus and a unique RODANCE-based path tracking technology. Its purpose is to allow users to assess the environmental performance of buildings and urban landscapes. The software can accommodate an unlimited number of sensors and operating/dynamic colors to perform LM-83/LEED calculations. Measurements and validated sources from the real world contribute to a database of thousands of materials, constructions and templates. [42]

All weather data relating to the case study area, including building orientation, room and skin materials used, measurement surface level and occupant's working hours were entered. Simulation results were collected in numerical, report and image forms, providing glare and daylighting performance criteria. To comply with the LEED v4.1 standards for work plane height (no less than 76cm) and calculation grid size (no more than 60x60cm), the work plane height and calculation grid size for all alternatives was set as 80cm from finished floor level and 60x60cm respectively. [43]

As a result, the following four criteria have been selected to evaluate daylighting performance:

- Spatial Daylight Autonomy (sDA 300/50%): The percentage of the floor area that meets the target illumination level (300 lux) is at least 50% of the working time using only daylight.
- Annual Sunlight Exposure (ASE1000/250hr): The percentage of the floor area that receives direct sunlight (more than 1,000 lux directly from the solar disk) over 250 hours of usage.
- Annual Average Lux (AAl) (Mean Illuminance): The average brightness of the ground surface during all occupied hours.
- Spatial Distributing Glare: is the percentage of the view at floor area, affected by disturbing or intolerable glare (DGP > 38%) in at least 5% of the occupied time.

Further, hourly illuminance simulation will be performed for the summer and winter solctices, and spring and autumn equinoxes during these hours: 9:00am, 12:00pm, 15:00pm. According to LEED v4.1 requirements for office and educational spaces, (sDA300/50%) must be ≥ 40%, (ASE1000/250hr) must be <10%. AAl range is assumed to be between 300 lux and 3000 lux. However the analysis will also refer to the lighting requirements for each conducted activity in the studio classrooms of Epoka University. sDG must achieve the lowest possible percentage.[44]

CHAPTER 4

DAYLIGHT
PERFORMANCE ANALYSIS

4.1 Location of the Case Study

Epoka University is located in Tirana, Albania, near Tirane-Rinas Highway (Figure 15). The studio classrooms selected for evaluation are in the university's Social Center and Department of Architecture building (Figure 16).

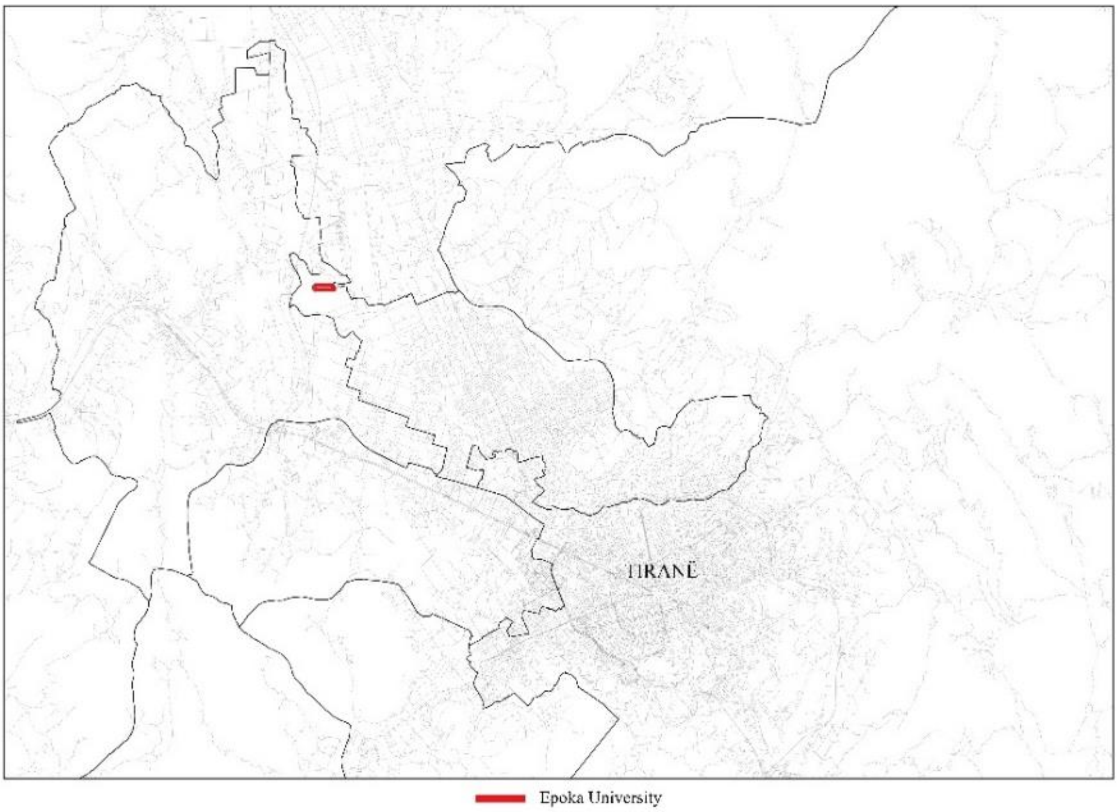


Figure 15. Location of Epoka University (source: GIS)

Figure 16. Top view of Epoka University (source: ASIG)

4.2 Climate Data

Tirana is the capital city of Albania and it is located in the center, around 25 km from the coast. Based on the Köppen classification [45] , Tirana's climate is classified as dry-summer subtropical. The city typically receives plentiful precipitation with a yearly average around 1219 millimetres, most of it occurring during winter months, from November to March and less during June to September. Temperature wise, the average daily temperature ranges from 6.4 °C in January to 24 °C in August. Temperature can exceed 20 °C during summer months. However, during fall and winter months, there is a substantial drop in temperature. [46]

In Albania the solar radiation reaches from 1185 kWh/m2 per year up to 1700 kWh/m2 per year. The average daily solar radiation is 4.1 kWh/m2. [47] The city receives an average of 2500 hours of sunlight per year, the sunniest month being July with an average of 354 hours of sunlight. December has the lowest amount of sunlight with an average of 93 hours. [48]

Figure 17 represents a chart of the average temperature and precipitation (left) and the monthly number of sunny, partly cloudy, overcast and precipitation days in Tirana. The "mean daily maximum and minimum" lines show the average maximum and minimum temperature.

Figure 17. Average temperature and precipitation (left), and the cloudy, sunny, precipitation chart [49]

Figure 18 is a maximum temperature diagram showing how many days per month reach a certain temperature.

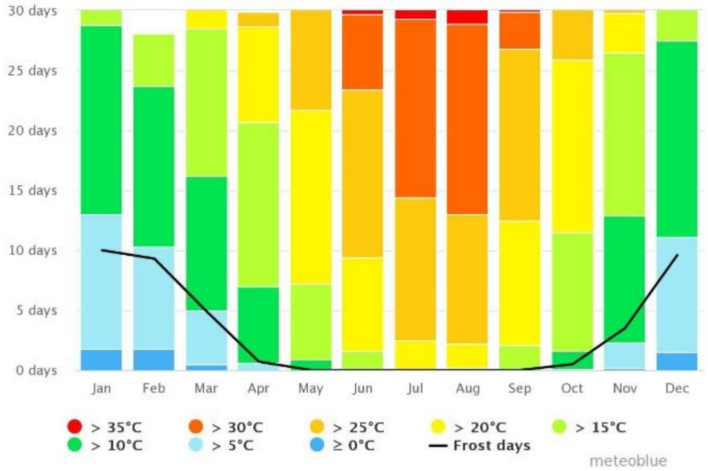


Figure 18. Maximum temperatures [49]

4.2 Questionnaire

A questionnaire was conducted among 84 students of the Department of Architecture to have their perspective on the daylighting challenges in the studios. The main objective of the survey is to obtain detailed feedback from students at various stages of their studies to better understand their needs and preferences. To do this, the questionnaire contains a question about the study year. Thus, an adaptive shading system that meets each year's individual needs and determine students' preferences and needs, is designed. The inclusion of the year of study question helps us to identify potential differences in preferences among students at various academic levels. Insights is gathered into the design and execution of the shading system by requesting comments from a varied group of students.

Question 2: How important is good lighting when working or studying?

Results: The importance of good lighting for studying or working was measured across different years of study. Among 1st-year students, 78.1% considered good lighting extremely important while only 3.1% thought it was not important. Good lighting continued to be highly important for 2nd and 3rd-year students with slight variations in the percentages. Among 3rd-year students, the percentage considering good lighting moderately important increased compared to previous years. Among 4th-year students, 87.5% expressed that good lighting was extremely important (Figure 19).

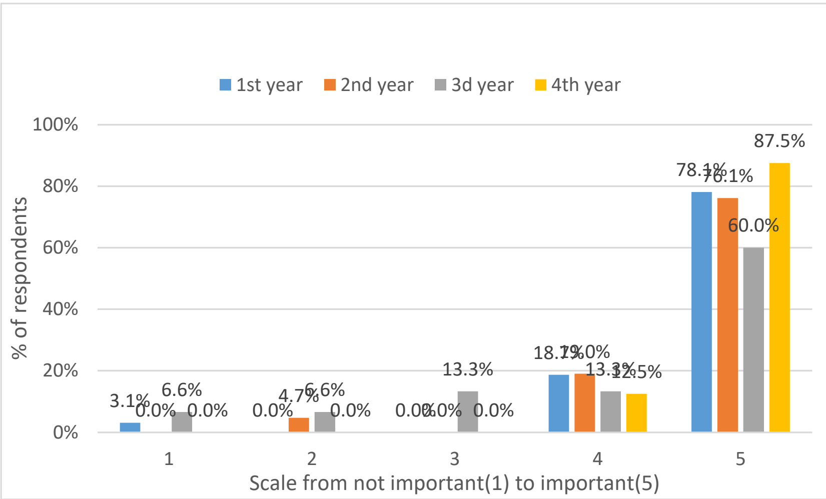


Figure 19. Importance of good lighting

Question 3: What type of lighting do you prefer when studying or working?

Results: These data show that natural light is the most desirable form of lighting for studying and working, and that warm light is the second most popular lighting style among students in the 1st and 2nd years, but the proportion declined as students advanced to the 3d and 4th years. In contrast, students' desire for cold light decreased from the 1st year to the third year, while 4th year students increased slightly. A percentage of respondents, which varied from 9.5% to 20.0% over the years, stated that they were not interested in a particular style of lighting (Figure 20).

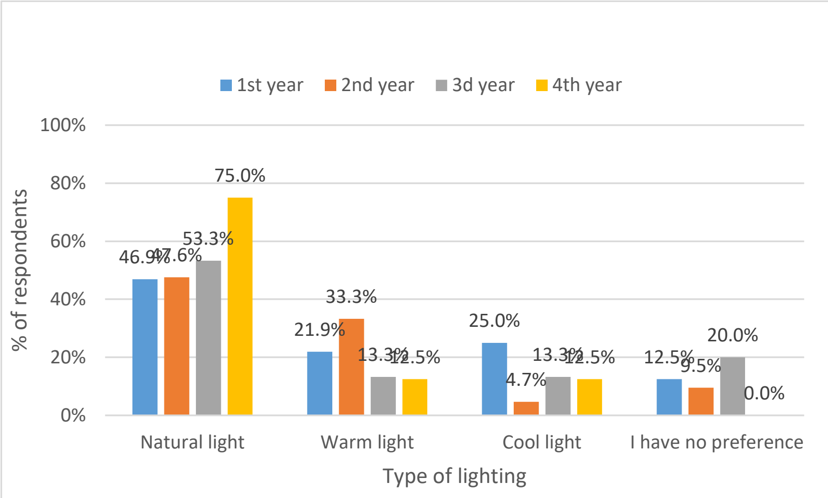


Figure 20. Preferred type of lighting

Question 4: Do you experience any discomfort or strain in your eyes due to the lighting in the university studios?

Results: The study shows that many students in university studios experience eye discomfort or strain due to lighting conditions. The percentage of 1st-year students who reported often experiencing this discomfort was 25%, while the percentage of those who reported occasional discomfort was higher at 34.3%. Only 3.1% of students claimed to never experience any eye discomfort.

The numbers decreased among 2nd and 3rd-year students for often experiencing discomfort, while the percentage of occasional discomfort increased. However, a significant 43.7% of 4th-year students still reported experiencing eye discomfort or strain often. Across all years, the highest percentage of students (53.3%) reported experiencing discomfort occasionally. The percentage of students who reported rare discomfort was consistent across all years (Figure 21).

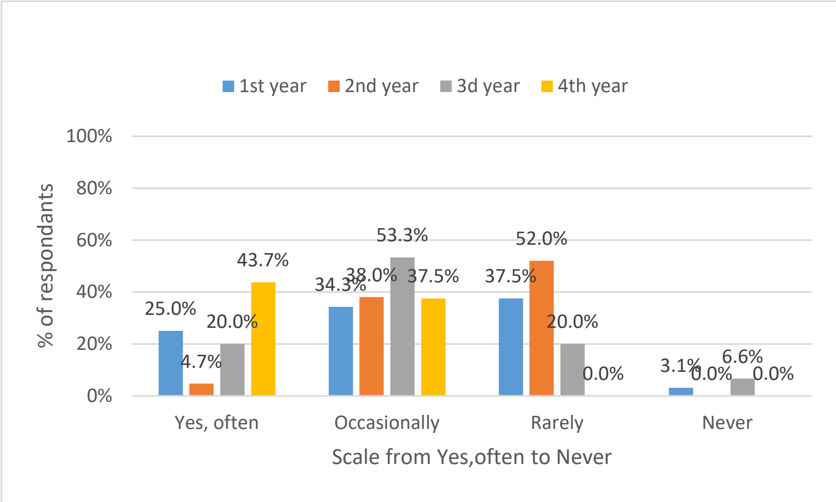


Figure 21. Experience of discomfort or strain in the eyes due to the lighting

Question 5: How do you usually adjust the lighting in the workspace?

Results: The results provide an overview of strategies that students often use to change the lighting on their workstations, by study year. 46.8 per cent of 1st year students considered moving to another location with better lighting conditions to be the preferred adjustment method. This percentage has declined dramatically as students progress through their academic years, becoming the second most popular strategy among 1st year students, accounting for 21.8% and declining in the coming years.

The use of blinds or curtains for managing natural light has little changed over the years, with the 4th year student at the highest percentage (18.7%) (Figure 22).

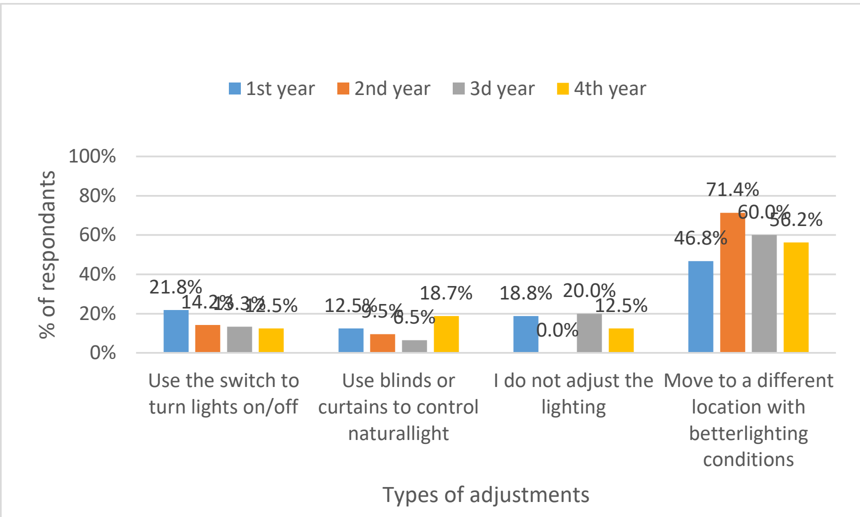


Figure 22. Light adjustment

Question 6: Do you think the current lighting in the university studios is appropriate?

Results: The student perceptions regarding the current lighting in university studios are revealed by the results, segmented by the year of study. The majority of 1st-year students reported concerns with only 15.6% finding the current lighting perfect. The proportion of students who found the lighting too dim increased to 31.2%, while 28.1% perceived it too bright.

As students progressed, a higher percentage found the current lighting perfect, yet significant proportions still expressed concerns. The proportion of students who found the lighting too bright decreased slightly to 23.8%, while 14.3% found it too dim. However, among 3rd-year students, a notable shift occurred, with a majority of 53.3% perceiving the current lighting as too bright. No student indicated the lighting to be too dim among 4th-year students, and the lighting was perceived as too bright by an even higher percentage (68.7%). The results show that evaluating and potentially adjusting the lighting levels to address these concerns is necessary (Figure 23).

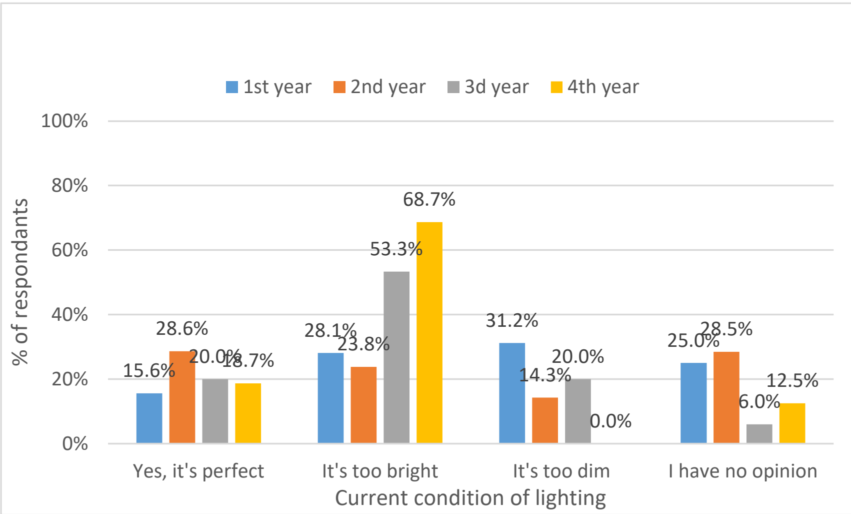


Figure 23. Current lighting in the university studios

Question 7: On a scale of 1 to 5, how would you rate the lighting conditions during winter in the university studios?

Results: The majority of 1st-year students, 53.1%, had a neutral perception of the lighting conditions, as rated by a score of 3. While 28.1% rated the conditions with a score of 2, suggesting room for improvement. A small percentage of students rated the conditions at a score of 1 (6.2%) or 4 (6.2%), and an equally small proportion scored it with a 5.

2nd-year students had 23.8% assigned a rating of 3, while 19.0% and 33.3% gave ratings of 2 and 4, respectively. The majority of 3rd-year students, 46.6%, had a relatively neutral perception, with a rating of 3.

Meanwhile, for 4th-year students, the majority rated the lighting conditions with a score of 2, indicating some dissatisfaction. With 31.2% assigning a rating of 3, and 18.7% and 12.5% giving ratings of 4 and 5, respectively. No 4th year student rated the lighting conditions during winter with 1 (Figure 24).

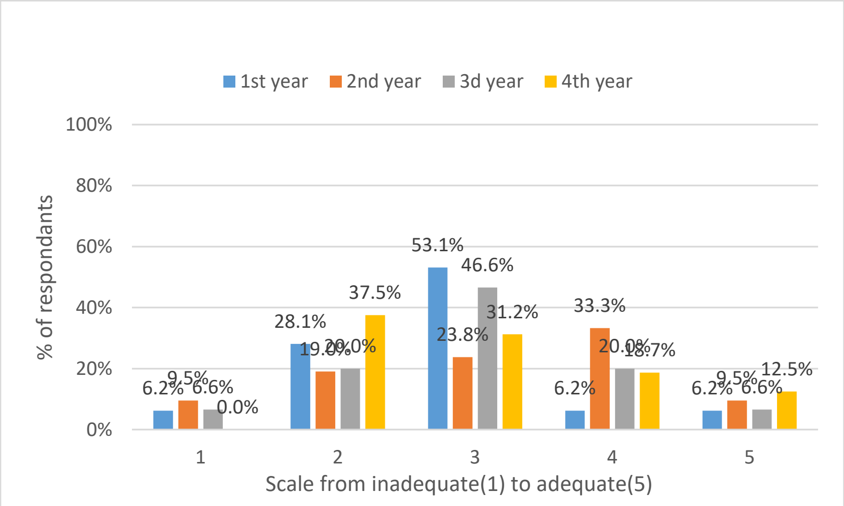


Figure 24. Lighting conditions during winter in the university studios

Question 8: On a scale of 1 to 5, how would you rate the lighting conditions during summer in the university studios?

Results: The lighting conditions during summer were perceived differently across different years of study. Most 1st-year students had a positive perception, with 40.6% giving a rating of 4. For 2nd-year students, the majority had a neutral perception, with 38.0% giving a rating of 3. 3rd-year students had a mix of satisfaction and room for improvement, with 13.3% giving a rating of 3. 4th-year students had a relatively neutral perception with 50.0% giving a rating of 3. These results show that while some students were satisfied, others indicated room for improvement or dissatisfaction (Figure 25).

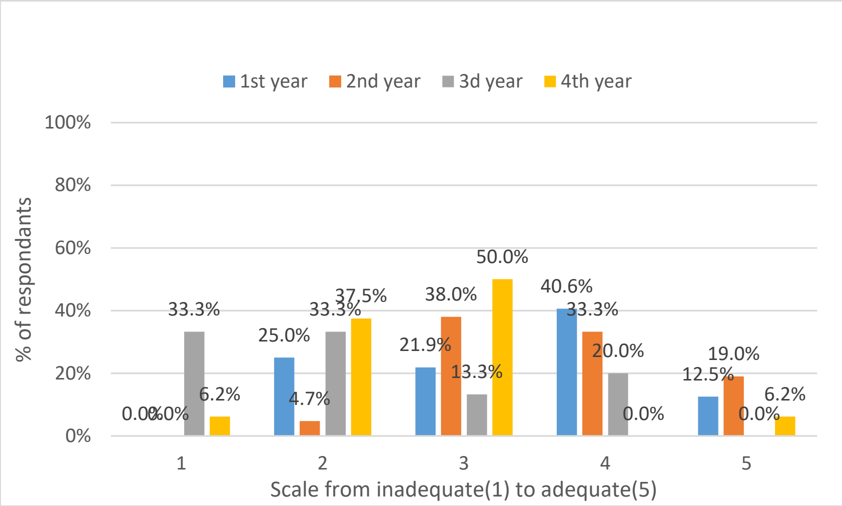


Figure 25. Lighting conditions during summer in the university studios

Question 9: Are there any particular activities or tasks that you find more difficult to do due to poor lighting conditions in the studios?

Results: In various academic years, students face difficulties in different activities due to poor lighting conditions. Working with small or intricate materials seems to be the most affected activity in the 1st year (37.5%), whereas using a computer screen or drawing/sketching are equally challenging (28.1%). Reading small print (15.6%) and writing or taking notes by hand (3.1%) are the least affected activities.

In the 2nd year, using a computer screen becomes the most challenging activity (71.4%), followed by working with small or intricate materials (33.3%), and writing or taking notes by hand (9.5%).

In the 3d year, using a computer screen emerges as the most affected activity (86.6%), followed by drawing or sketching (40.0%), working with small or intricate materials (33.3%), and reading small print (20.0%).

In the 4th year, using a computer screen remains a significant challenge (68.8%), followed by reading small print (25.0%), and drawing or sketching and writing or taking notes by hand are equally challenging (18.8%). "None of the above" accounts for 18.7% of responses (Figure 26).

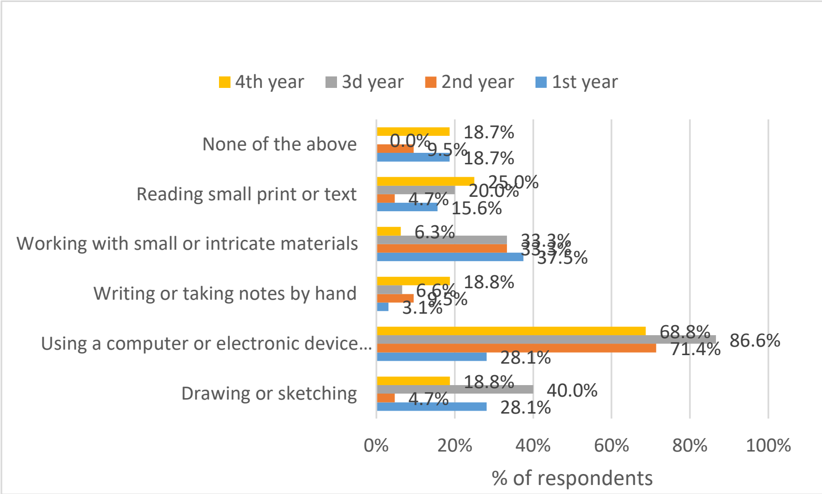


Figure 26. Difficulties in activities due to poor lighting

4.3 Case Study

The zones selected for evaluating the daylight performance are the architectural studio classrooms of the Engineering and Architecture faculty building at Epoka University. The windows in the classes are located on the south side, which makes it essential to provide the comfortable lighting and to control it due to the complexity of the window system. Figure 27 shows the second floor plan of the building where the classrooms are located (highlighted in red), as well as the orientation of the façade.

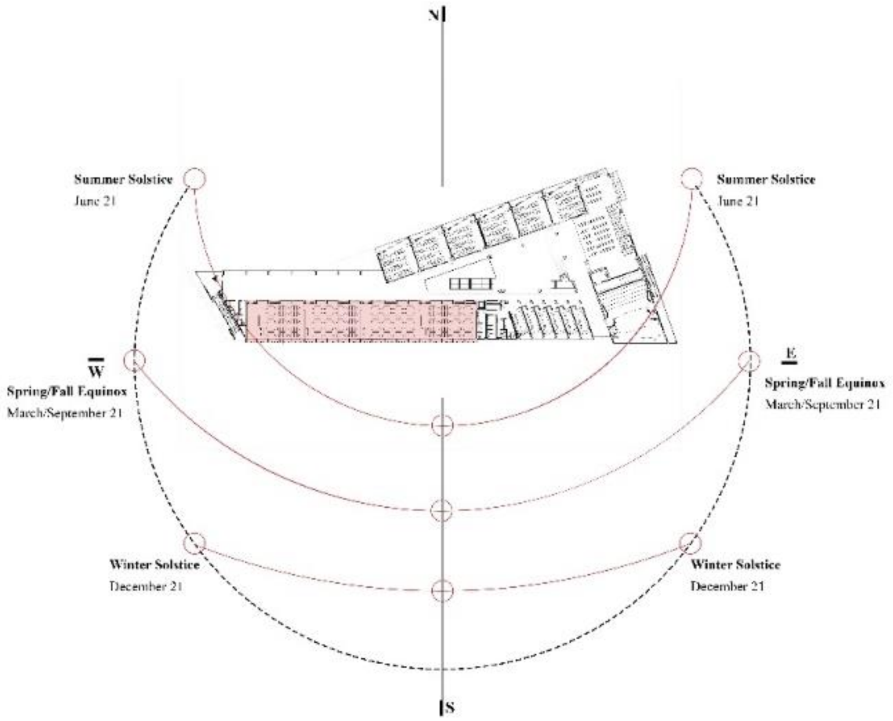


Figure 27. 2nd floor plan of the building with studio classrooms highlighted in red

The window to wall ratio (WWR) of the studio classrooms is 90%. The layout consist of one large longitudinal area designed to provide four classrooms for each year of architecture study, where each is separated through storage partitions. Lately another partition of single pane glass was added to the area, which serves as a laser-cut and maquette making space. The studio classrooms is where the students spent most of their time, where specific activities are conducted based on the curriculum. They include reading or writing, computer and electronic device usage, drawing or sketching and working with small or intricate materials for building maquettes. Figure 28 illustrates the layout design and specifies the year of study of each space.

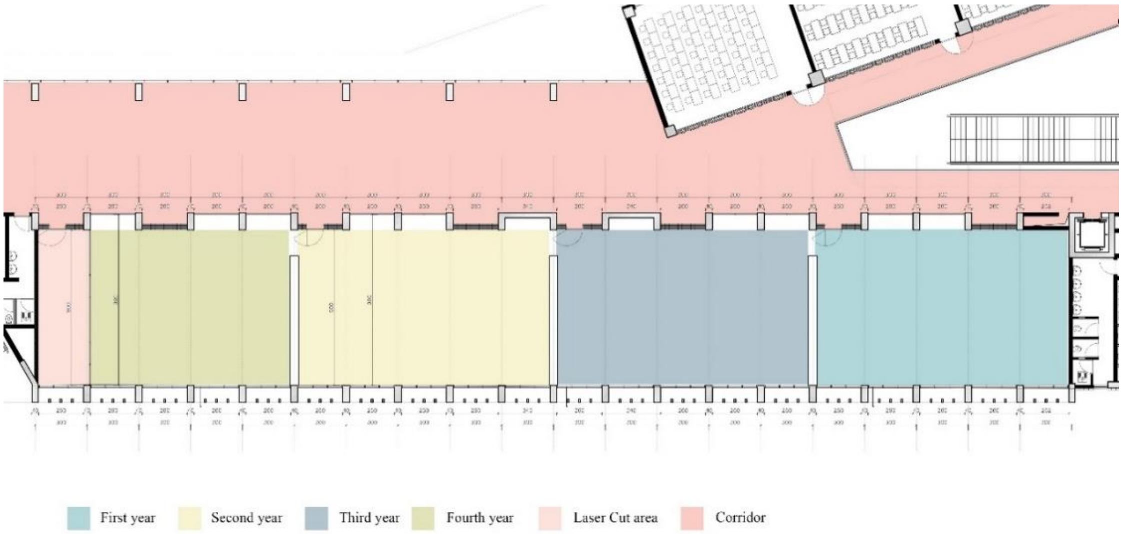


Figure 28. Layout of the studio classrooms

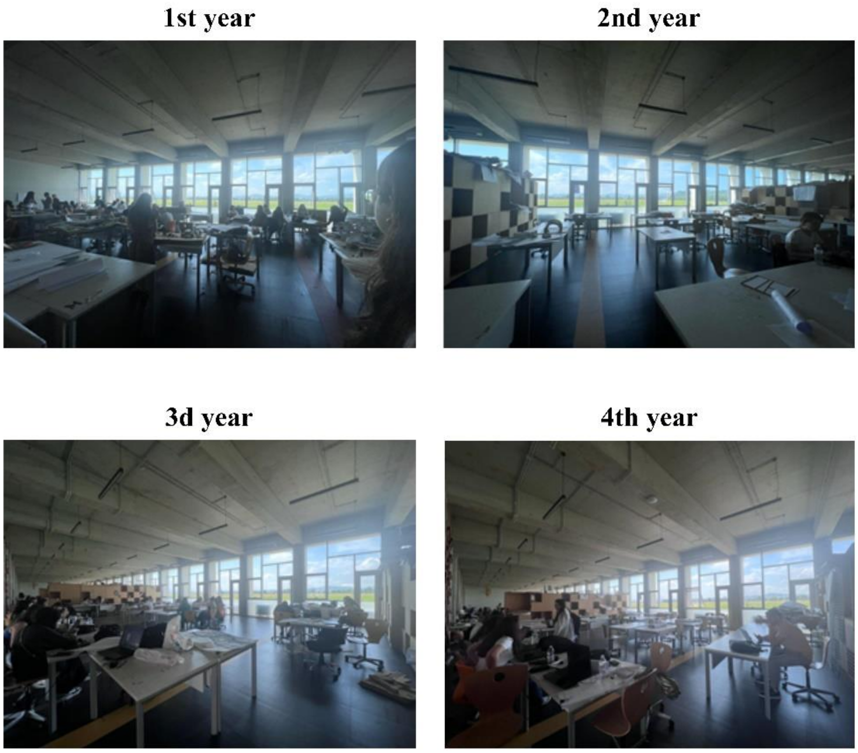


Figure 29. Interior of studio classrooms

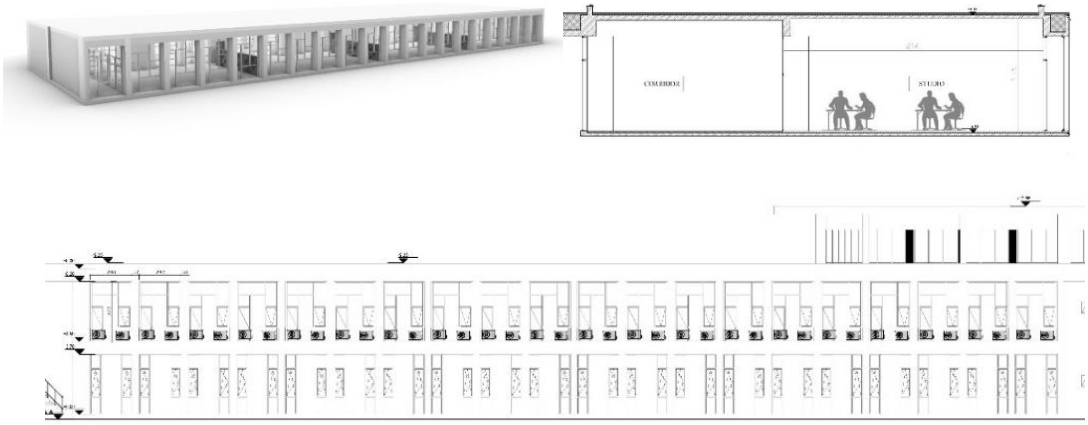


Figure 30. 3D View, section and façade of the studio classrooms

The arrangement and the layout design of the area indicates that the working environment does not provide complete visual comfort for the occupants (Figure 20). However, simulations through Climate Studio were performed to generate quantitative results. Furthermore, materials used for the base case are chosen to accurately give outcomes. Based on a previous study, the glazing of the façade is double pane low E glazing with light transmittance of 70%. [50]

The other material properties are shown in Table 13:

Table 4. Material properties

Parameter	Wall	Floor	Ceiling	Glazing
Reflectance	75%	5%	78%	11%
Tvis	0%	0%	0%	70%

The evaluation of the daylight performance of the base case under normal conditions, using climate-based daylight metrics, reveals the amount of useful daylight provided, falls short with meeting the occupants' needs (Figure 31). The sDA value of 100% (exceeding 50%) indicates that there is presence of sufficient daylight in the studio. However, by switching to the ASE metric, the amount (47.4%) suggests that there is excessive sunlight exposure, quantified as locations where the direct sunlight exceeds 1000 lux for more than

250 hours per year. The Annual Average lux reached the value of 1880 lux . However, a more detailed Point- in- time analysis for the solstices and equinoxes will show the most problematic days and time in terms of Illuminance. In terms of glare, the sDG value (28.1%) shows the occupant are exposed to complete visual discomfort throughout the year. Table 14 shows the average scores achieved by each daylight performance metric, annually.

Table 5. Annual Daylight Availability analysis

Occupancy	sDA	ASE	Mean Lux	sDG
8am-6pm with DST	100%	47%	1880	28.10%

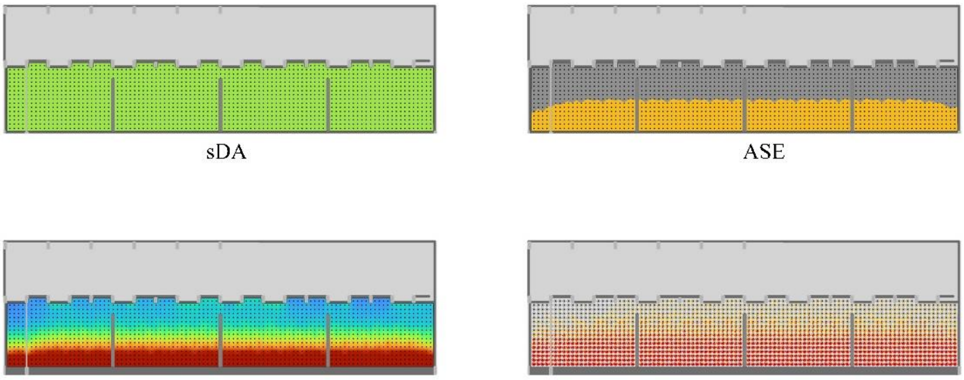


Figure 31. Annual Daylight Availability diagrams

As mentioned, The-point-in-time illuminance analysis was performed for Summer and Winter Solstices, and Spring and Fall Equinoxes. The results for the base case are shown in Figure 32. The most dire scenario in terms of enhanced illuminance may be established by comparing the lux levels across seasons and periods (Figure 33).

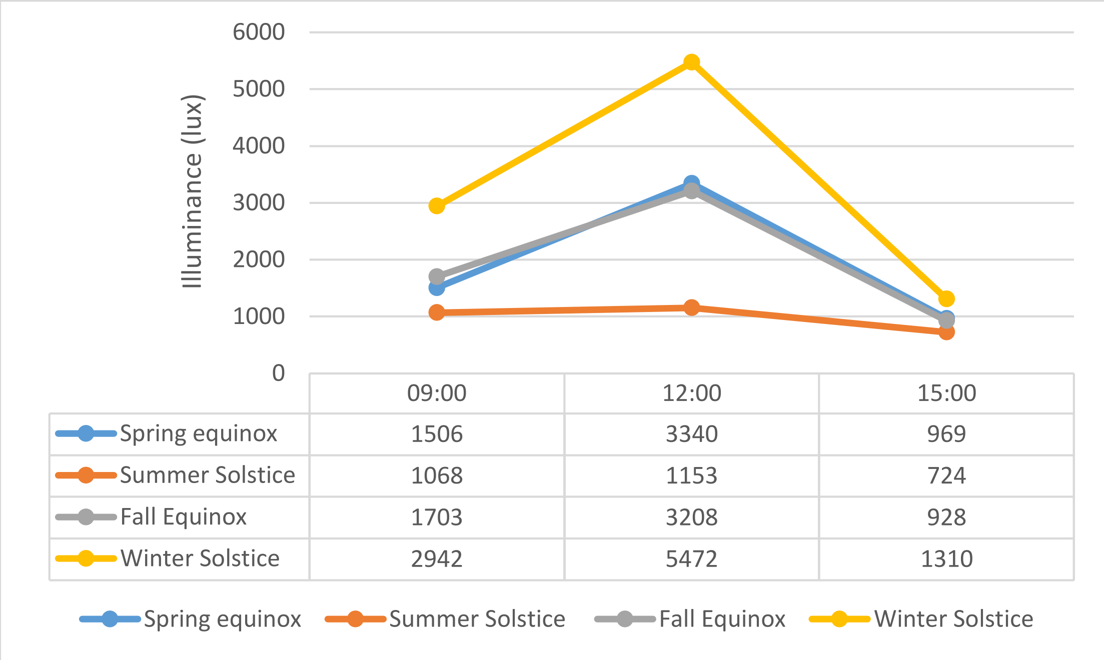
The lux value is 1506 at 09:00 on the spring equinox. The lux number drops to 1068 as we approach the summer solstice. At 09:00, the fall equinox has a slight increase in illuminance, with a lux value of 1703. However, the lux value is substantially greater at 2942 around the winter solstice. The lux readings at 12:00 reveal a considerable rise in illuminance throughout all seasons. The lux value during the spring equinox is 3340, whereas at the summer solstice it is 1153. Although the fall equinox has a greater lux value of 3208, it is exceeded by the winter solstice, which has the maximum value of 5472. Moving on to 15:00, the illuminance levels continue to change seasonally. The lux value during the spring equinox is 969, whereas at the summer solstice it is 724. The autumn equinox has a slightly higher lux value of 928, while the winter solstice has the greatest value of 1310. Considering the worst scenarios in terms of higher illuminance, it can be observed that during solstices and equinoxes at 12:00 pm the lux values can even surpass 3000 lux. During winter solstice, the lux values are worryingly high throughout the day.

The lux levels in the table are affected by the location of the sun throughout the year. The angle at which sunlight reaches the surface is determined by the sun's location, which affects illuminance levels. The sun is directly over the equator at the spring equinox. This season's uniformly distributed sunlight creates a balance between light intensity and shadow, resulting in moderate illuminance levels.

In contrast, the sun is at its highest position in the sky at the summer solstice, and its rays are more directly above in the northern hemisphere. As a result, more sunlight is absorbed and dispersed through the atmosphere before reaching the surface. The extended route length through the atmosphere and the higher angle of the sun both lead to lower illuminance levels.

The sun crosses the equator again at the autumn equinox, resulting in lux values comparable to those measured during the spring equinox. The sun's position at this time of year produces illumination conditions similar to those observed during the spring equinox.

Finally, the sun is at its lowest point in the northern hemisphere at the winter solstice. As a result of the shallower angle of contact and the longer route through the atmosphere, there is higher illuminance levels.



	09:00	12:00	15:00
Spring equinox	1506	3340	969
Summer Solstice	1068	1153	724
Fall Equinox	1703	3208	928
Winter Solstice	2942	5472	1310

Figure 32. Point-in-time illuminance chart

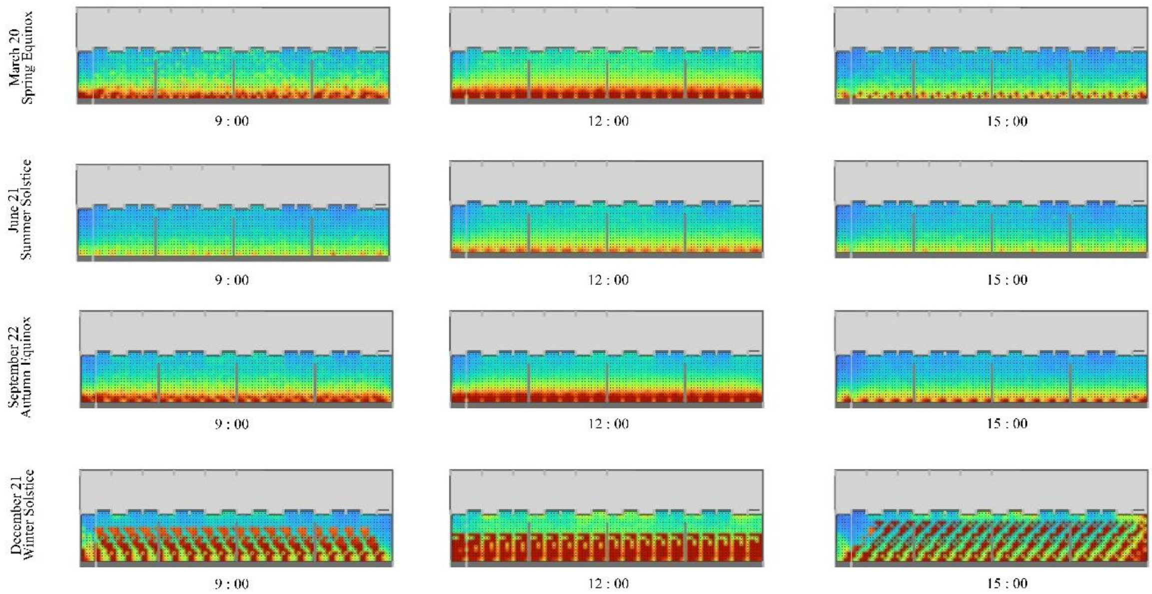


Figure 33. Point in time Illuminance for Equinoxes and Solstices

4.4 Daylighting Scenarios

This project investigates the aesthetic comfort and daylight performance of a customizable kinetic façade in 16 different situations with variable levels of openness. The major goal is to evaluate the influence of various façade layouts on visual comfort and daylighting dependent on sun angle. Four basic façade situations are explored, each with two levels of closeness to the sun's position (100% and 50%). The first scenario entails completely closing the façade. The following three options preserve a 50% openness, but with differences in the exact regions that are opened, which range from the top to the lower and center sections of the façade.

The four main scenarios are divided into four additional sub-scenarios, each depending on the level of openness or folding of the units comprising the entire façade. These levels are expressed as percentages: 100% opened, 75% opened, 50% opened, and 25% opened.

In the end there is a total of 16 façade scenarios as listed below (Figure 34):

- Scenario 1 (S1): The whole façade is 100% opened.
- Scenario 2 (S2): Lower section (50%) is 100% opened
- Scenario 3 (S3): Upper section (50%) is 100% opened
- Scenario 4 (S4): Middle section (50%) is 100% opened
- Scenario 5 (S5): The whole façade is 75% opened.
- Scenario 6 (S6): Lower section (50%) is 75% opened
- Scenario 7 (S7): Upper section (50%) is 75% opened
- Scenario 8 (S8): Middle section (50%) is 75% opened
- Scenario 9 (S9): The whole façade is 50% opened.
- Scenario 10 (S10): Lower section (50%) is 50% opened
- Scenario 11 (S11): Upper section (50%) is 50% opened
- Scenario 12 (S12): Middle section (50%) is 50% opened
- Scenario 13 (S13): The whole façade is 25% opened.
- Scenario 14 (S14): Lower section (50%) is 25% opened
- Scenario 15 (S15) : Upper section (50%) is 50% opened
- Scenario 16 (S16): Middle section (50%) is 50% opened

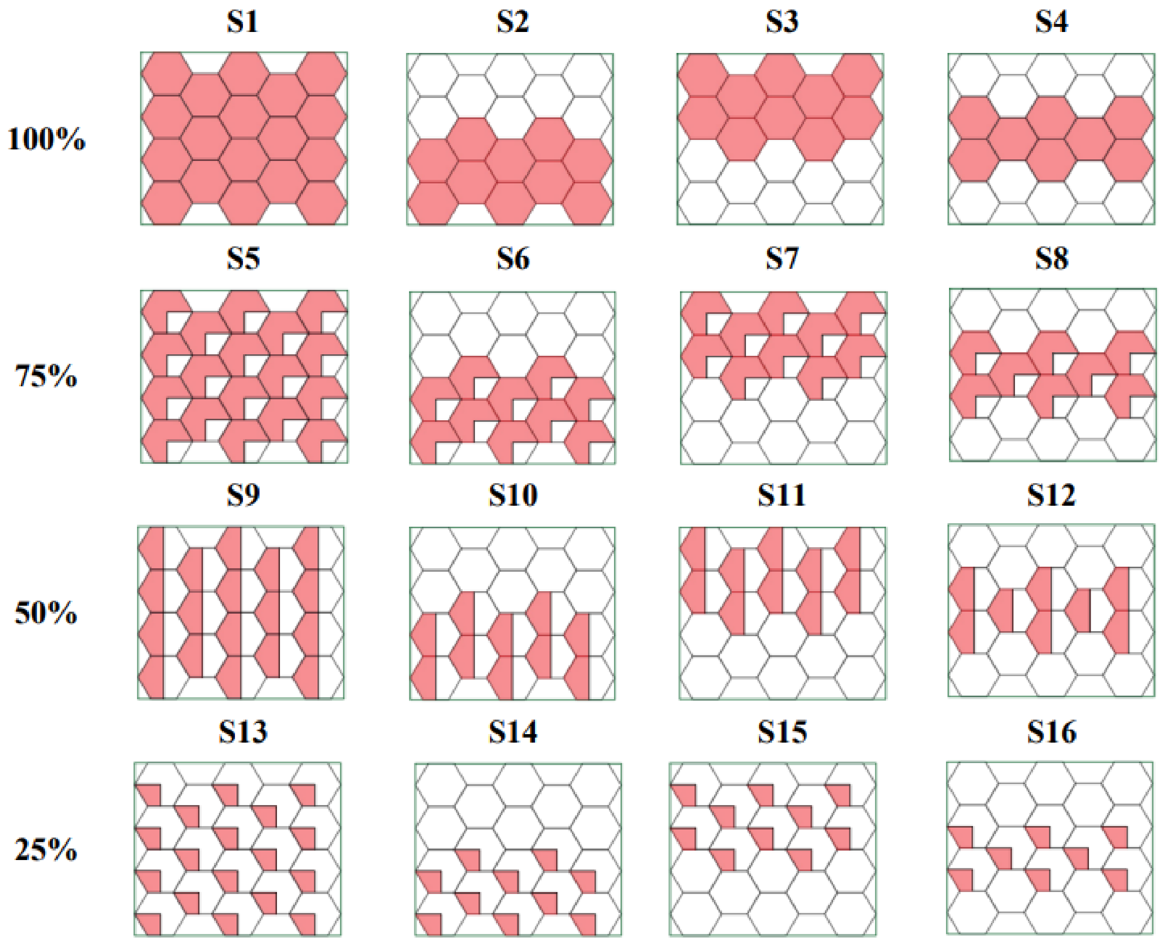


Figure 34. Facade scenarios

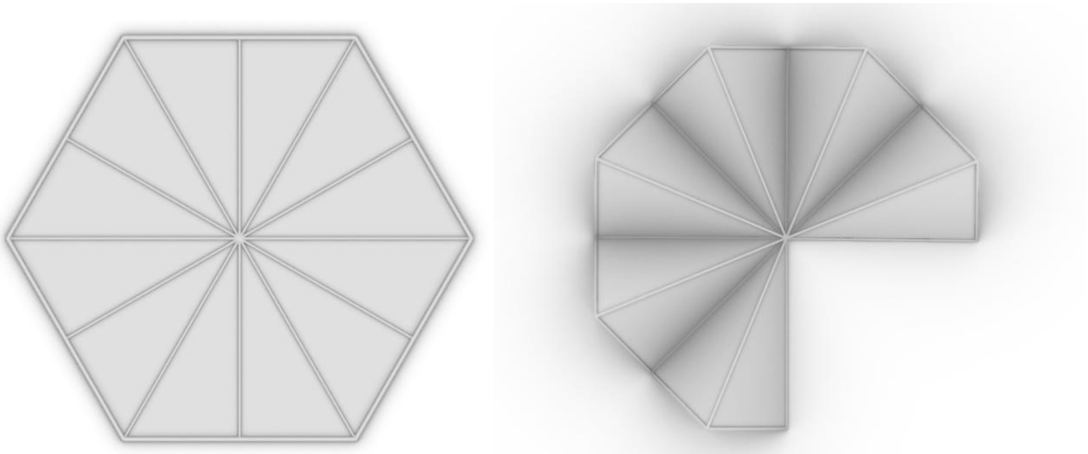


Figure 35. Unit 100% and 75% opened

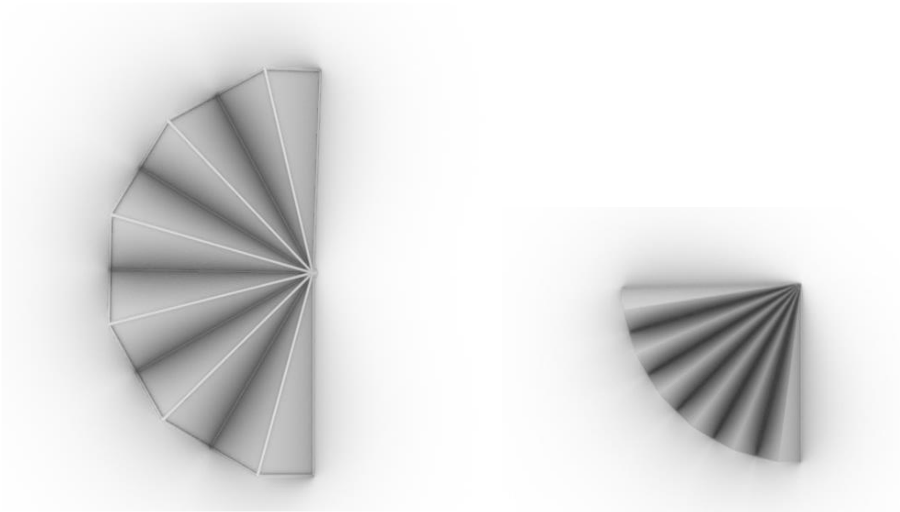


Figure 36. Unit 50% and 25% opened

4.5 Results

In addition to annual and hourly simulations, a detailed investigation was conducted to evaluate the performance of 16 different facade alternatives, characterized by different degrees of folding. The key measurements of daylight, namely spatial daylight autonomy (sDA), annual exposure to sunlight (ASE), annual average lighting (AAI) and spatial distributing glare (sDG), are evaluated annually. In addition, an hourly simulation was performed at 9 a.m., 12 a.m. and 15 a.m. during the days of solstices and equinoxes.

The results of this study demonstrate a substantial improvement in both visual comfort and daytime performance, as a result of the different levels of openness of the facades. In particular, the results have been carefully filtered in accordance with the criteria described in LEED v4.1 and the lighting requirements for each activity carried out in the classroom of the studio.

4.5.1 Annual results

Upon analyzing the annual daylight performance values presented in Table 18, a notable improvement can be observed in the kinetic facade with varying levels of folding, as compared to the base case. The assessment was conducted based on the criteria outlined in LEED v1.4, with 15 out of the 16 facade scenarios meeting these requirements. The only exception was Scenario 1, where the entire facade remained 100% opened, resulting in a decrease in performance values to 0%. Among the scenarios evaluated, three scenarios demonstrated noteworthy results.

It is worth mentioning that there is minimal variation in spatial daylight autonomy (sDA) values compared to the base case, with the exception of Scenario 3, where the upper section of the facade was 100% opened, leading to a decrease in the sDA value from 100% to 79.7%. Additionally, Scenario 1 exhibited an sDA value of 0%.

In terms of annual sunlight exposure (ASE) values, Scenario 3 achieved the most significant improvement, reducing the value from 47% to 2.1%. Notable enhancements were also observed in Scenario 5, where the facade was 75% opened, resulting in an ASE value of 10.3%, as well as Scenario 7, with the upper section being 75% opened and an ASE value of 9%.

Compared to the base case, Scenario 3 successfully reduced the spatial daylight gradient (SDG) value from 28.1% to 1.6%, followed by Scenario 5 and Scenario 7 with SDG values of 8.3% and 9.1% respectively (Figure 37).

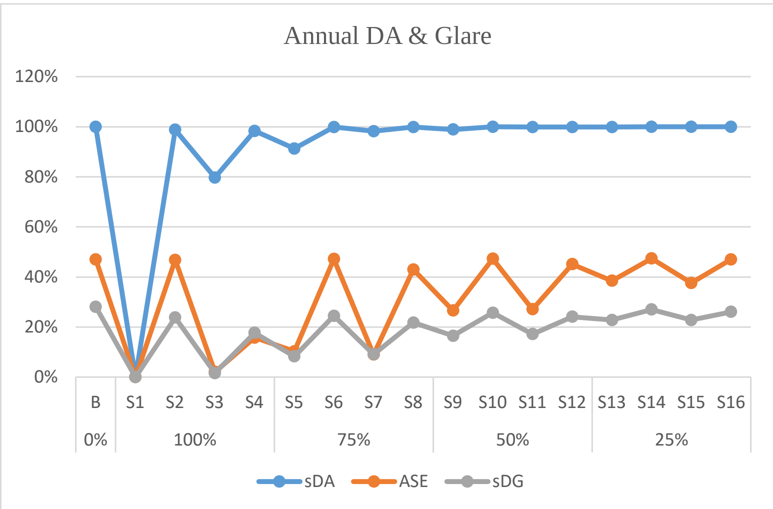


Figure 37. Annual DA & Glare chart

The assumed range for annual ambient illumination (AAI) was set between 300 lux to 3000 lux. All facade scenarios provided mean lux values falling within this range, indicating compliance with the assumed AAI requirements (Figure 38). In comparison to the base case, the highest lux value observed was 1792 lux, down from the current value of 1880 lux- (Table 18). However, considering the lighting requirements for activities conducted in the studio classrooms, Scenario 3 emerged as the most suitable for reading and writing, with an average lux level of 503 lux. This scenario also proved to be suitable for computer and electronic device usage, as well as model making. On the other hand, for technical drawings and sketching, Scenario 5 exhibited a better fit (Table 19).

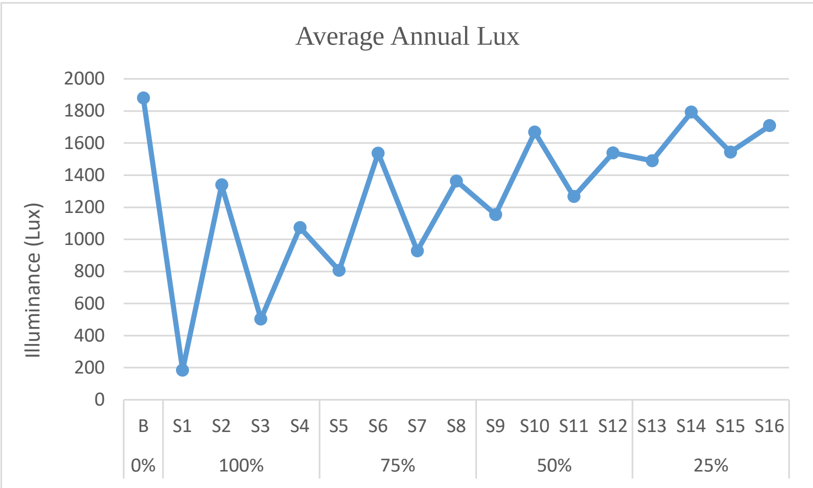


Figure 38. Annual Average Lux chart

Table 6. Annual daylight performance values

Folding Lev.	100%				75%				50%				25%			
DA&Glare	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**
sDA	0%	98.8%	79.7%	98.3%	91.3%	99.9%	98.2%	99.9%	98.9%	100.0%	99.9%	99.9%	99.9%	100.0%	100.0%	100.0%
ASE	0%	46.8%	2.1%	15.8%	10.3%	47.2%	9.0%	43.0%	26.6%	47.3%	27.1%	45.1%	38.5%	47.4%	37.6%	47.0%
Mean Lux	184	1339	503	1073	806	1537	928	1363	1154	1668	1266	1539	1490	1792	1544	1708
sDG	0%	23.8%	1.6%	17.7%	8.3%	24.5%	9.1%	21.8%	16.5%	25.7%	17.2%	24.1%	22.8%	27.0%	22.8%	26.1%

Table 7. Annual best performing scenarios

ACTIVITIES	Reading/Writing	Using a computer or electronic device	Drawing/Sketching	Model making
SCENARIOS	S3	S3	S5	S3

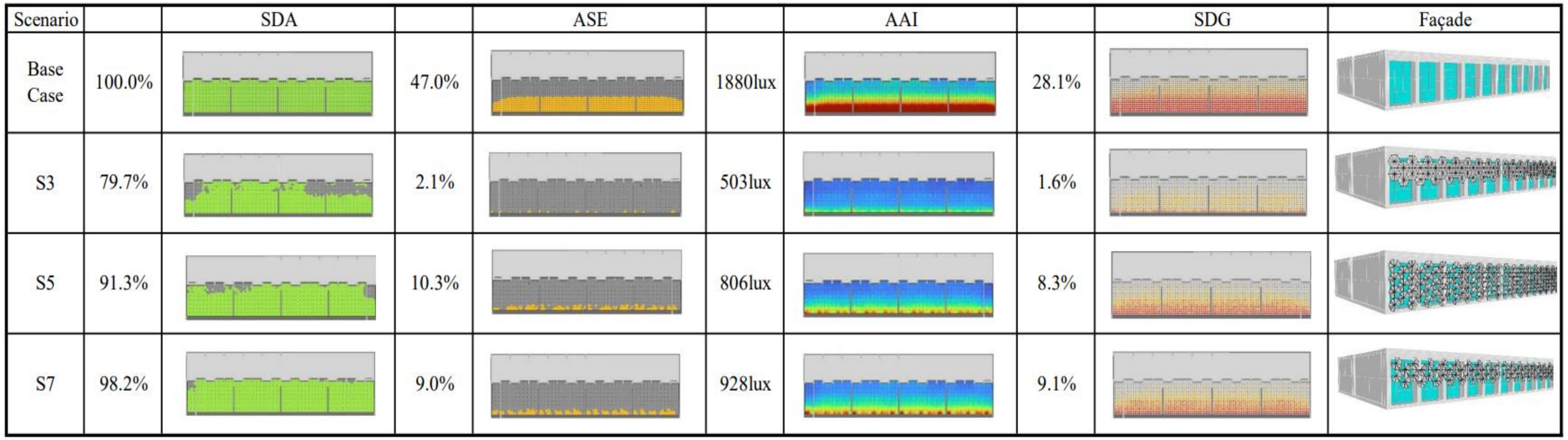


Figure 39. Comparison of the base case and best performing scenarios

4.5.2 Hourly results

Table 24 gives illuminance levels in lux for several facade scenarios at three distinct times of the day during the *Spring Equinox* on March 20th: 09:00, 12:00, and 15:00 (Figure 40).

At *09:00*, S14 (lower section 25% opened) shows the highest illuminance level with 1466 lux, closely followed by Scenario S16 (middle section 50% opened) with 1435 lux. These values indicate a significant amount of light reaching the surfaces, but lower compared to the base case with 1506 lux. On the other hand, Scenario S1 has the lowest illuminance level at this time with only 90 lux, suggesting relatively lower levels of natural light. Considering the lighting requirements for activities conducted in the studio classrooms, S5 (whole façade 75% opened) emerged as the most suitable for reading and writing, as well as model making with 579 lux. S3 proved to be suitable for computer and electronic device usage, with lux value of 330. On the other hand, for technical drawings and sketching, S7 (upper section 75% opened) exhibited a better fit with 811 lux.

Moving to *12:00,* S14 exhibits the highest illuminance level with 3295 lux, indicating abundant daylight. S16 follows closely with 3271 lux. Compared to the base case (3340), these scenarios do not provide much shading. Conversely, S1 has the lowest illuminance levels at this time, with 86 lux. The most suitable scenario for reading and writing is S5 (1065lux), as well as model making and technical drawings and sketching. S3 is suitable for computer and electronic device usage, with lux value of 363.

At 15:00, S14 achieves the highest illuminance level with 948 lux, closely trailed by S16 with 922 lux. These values suggest ample natural lighting, decreasing a little compared to base case (969 lux). Conversely, once again S1 has the lowest illuminance level at this time with only 91 lux, indicating relatively lower levels of daylight. The most suitable scenario for reading and writing is S5 (508lux), as well as model making. For technical drawings and sketching, S2 is a better fit (713 lux). S3 is suitable for computer and electronic device usage, with lux value of 307.

Analyzing the optimal values, scenarios with 25% level of folding consistently appear to provide high illuminance levels at all three time points. Conversely, S1 with the whole façade opened, consistently exhibits lower illuminance levels, falling out of the required range.

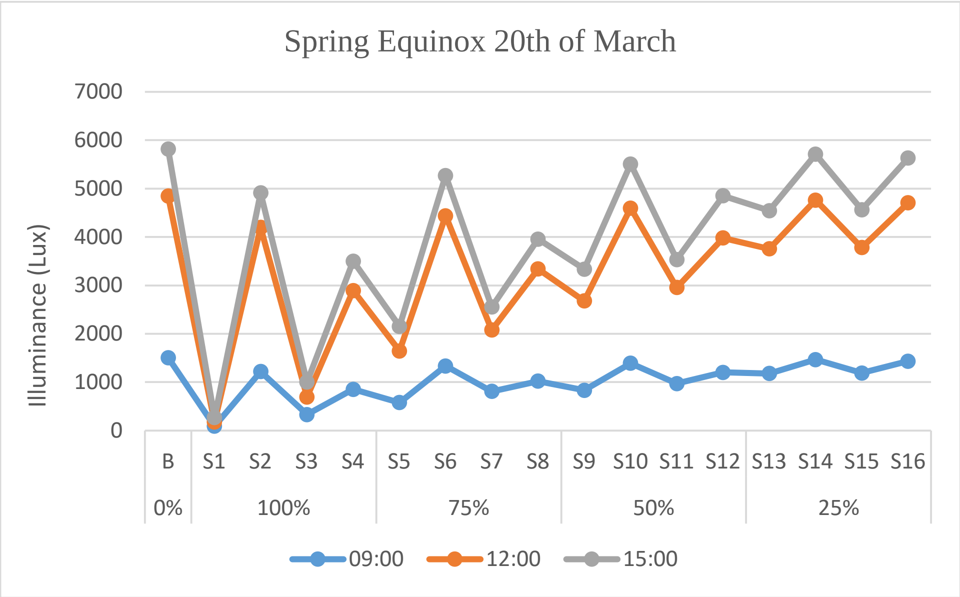


Figure 40. Spring Equinox illuminance chart

During *Summer Solstice* on the 21st of June at 09:00, the highest illuminance value is observed in Scenario S14 with 570 lux, closely followed by Scenario S16 with 556 lux (Figure 41). These values indicate a moderate level of natural light reaching the building's surfaces during the morning hours, compared to the base case (1068 lux). On the other hand, Scenario S1 has the lowest illuminance level at this time with only 72 lux, followed by S3 (258),suggesting relatively lower levels of daylight. The most suitable scenario for reading and writing is S6 (508lux) and S13 (506lux), as well as model making. For technical drawings and sketching, S14 is a better fit (570lux). S4 is suitable for computer and electronic device usage, with lux value of 324.

Moving to 12:00, Scenario S15 exhibits the highest illuminance level with 666 lux, followed by Scenario S16 with 658 lux. These values indicate a significant amount of light available during the midday period. Conversely, Scenario S1 has the lowest illuminance level at this time with 83 lux. The most suitable scenario for reading and writing is S9 (508lux),as well as model making. For technical drawings and sketching, S14 is a better fit (666lux). S4 is suitable for computer and electronic device usage, with lux value of 365.

At 15:00, S15 achieves the highest illuminance level with 507 lux, followed by Scenario S10 with 503 lux. On the other hand, S1, S3 and S4 have the lowest illuminance levels at this time, with 61 lux, 228 lux and 275 lux respectively. The most suitable scenario for reading and writing is S14 (507lux), as well as model making. For technical drawings and sketching, no shading at all is a better fit (724lux). S2 is suitable for computer and electronic device usage, with lux value of 321.

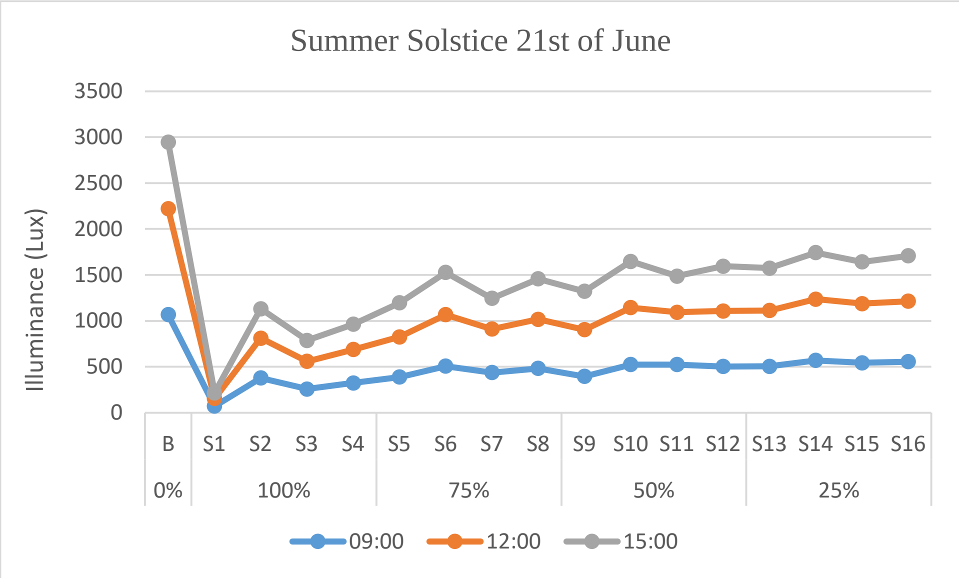


Figure 41. Summer Solstice illuminance chart

During *Fall Equinox* on the 22nd of September, at 09:00, the highest illuminance value is observed in S14 with 1663 lux, followed by S16 with 1631 lux (Figure 42). Conversely, S1 has the lowest illuminance level at this time with only 92 lux, suggesting significantly lower levels of daylight. The most suitable scenario for reading and writing is S5 (672lux), as well as model making. For technical drawings and sketching, S4 is a better fit (841lux). S3 is suitable for computer and electronic device usage, with lux value of 342.

Moving to 12:00, Scenario S14 exhibits the highest illuminance level with 3165 lux, followed by Scenario S16 with 3137 lux. These values indicate a significant amount of light available during the midday period. Conversely, S1 has the lowest illuminance level at this time with 141 lux. The most suitable scenario for reading and writing is S5 (1072lux), as well as model making and technical drawings and sketching. S3 is suitable for computer and electronic device usage, with lux value of 416.

At 15:00, S14 achieves the highest illuminance level with 913 lux, followed by Scenario S16 with 888 lux. These values suggest a moderate level of natural lighting during the afternoon. On the other hand, S1 and S9 have the lowest illuminance levels at this time, with 99 lux and 288 lux, respectively. The most suitable scenario for reading and writing is

S11 (536lux), as well as model making. For technical drawings and sketching, S15 is a better fit (762lux). S4 is suitable for computer and electronic device usage, with lux value of 458.

Comparing these values with the Spring Equinox and Summer Solstice tables, we observe variations in illuminance levels due to the seasonal changes. The Fall Equinox table generally shows different illuminance values at each time of the day compared to the other seasons, indicating changes in daylight availability and solar position.

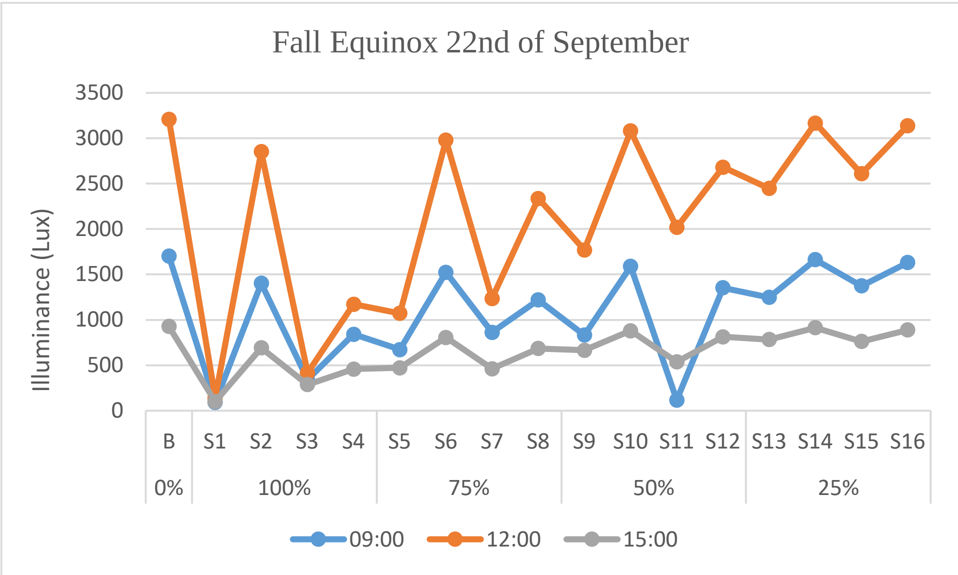


Figure 42. Fall Equinox illuminance chart

During *Winter Solstice* on the 21st of December, at 09:00, the highest illuminance value is observed in Scenario S14 with 2714 lux, closely followed by Scenario S16 with 2521 lux (Figure 43). These values indicate a relatively high level of natural light reaching the building's surfaces during the morning hours. Conversely, Scenario S1 has the lowest illuminance level at this time with only 164 lux, suggesting relatively lower levels of daylight. The most suitable scenario for reading and writing is S3 (773lux), as well as model making, technical drawings and sketching and computer and electronic device usage.

Moving to 12:00, Scenario S14 exhibits the highest illuminance level with 5282 lux, followed by Scenario S16 with 4959 lux. These values indicate a significant amount of light available during the midday period. Conversely, Scenario S1 has the lowest illuminance level at this time with 388 lux, which is suitable for computer and electronic device usage, indicating relatively lower levels of natural light. The most suitable scenario for reading and writing is S3 (1104lux), as well as model making, technical drawings and sketching and computer and electronic device usage.

At 15:00, Scenario S14 achieves the highest illuminance level with 1224 lux, followed by Scenario S16 with 1171 lux. These values suggest a moderate level of natural lighting during the afternoon. On the other hand, Scenario S1 has the lowest illuminance level at this time with 35 lux, indicating much lower levels of daylight. The most suitable scenario for reading and writing is S5 (535lux), as well as model making. For technical drawings and sketching, S11 is a better fit (784lux). S3 is suitable for computer and electronic device usage, with lux value of 361.

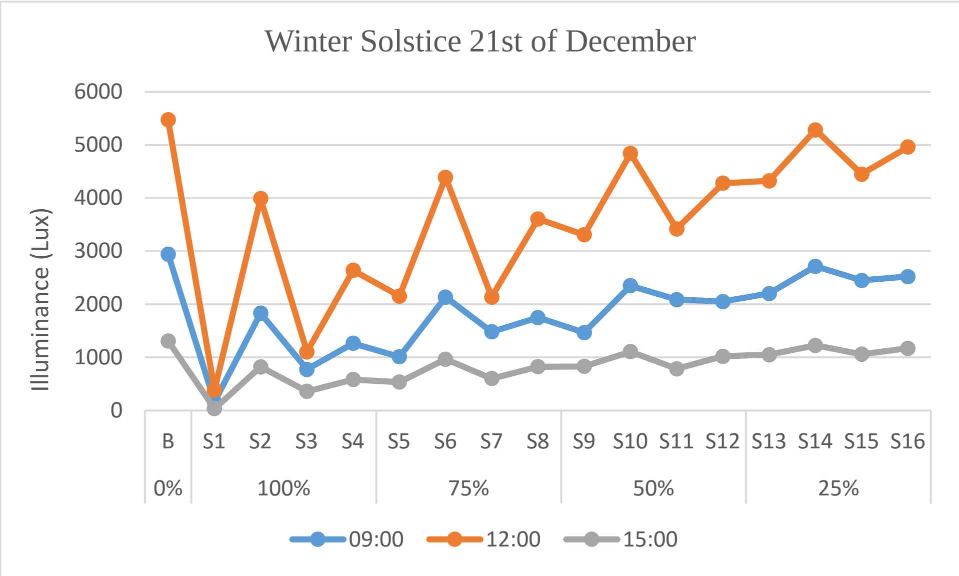


Figure 43. Winter Solstice illuminance chart

The comparison of these values during the Spring Equinox, Summer Solstice, Fall Equinox, and Winter Solstice reveals seasonal variations in daylight availability and solar position (Table 24).

During the Spring Equinox, the optimal facade scenarios consistently demonstrated high illuminance levels,that fall within the range of required lighting. Similarly, the Summer Solstice table showcased lower illuminance values, during the morning and midday hours. However, the Fall Equinox table displayed variations in illuminance levels compared to other seasons, emphasizing the importance of considering seasonal changes in facade design and daylight utilization. Lastly, the Winter Solstice analysis revealed higher illuminance values across all time points, indicating few scenarios that were more suitable for providing shading and visual comfort.

Table 8. Hourly illuminance values

Folding Lev.	100%				75%				50%				25%			
H	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**
Spring Equinox 20th of March																
09:00	90	1218	330	853	579	1335	811	1021	832	1390	970	1202	1179	1466	1188	1435
12:00	86	2978	363	2041	1065	3104	1266	2318	1846	3207	1986	2776	2576	3295	2593	3271
15:00	91	713	307	607	508	830	477	618	657	909	578	871	790	948	783	922
Summer Solstice 21st of June																
09:00	72	378	258	324	388	508	438	483	396	524	525	503	506	570	543	556
12:00	83	433	301	365	438	560	473	535	508	620	568	604	607	666	644	658
15:00	61	321	228	275	371	460	334	439	418	503	394	489	461	507	456	495
Fall Equinox 22nd of September																
09:00	92	1402	342	841	672	1524	862	1219	832	1588	117	1353	1248	1663	1373	1631
12:00	141	2851	416	1172	1072	2978	1235	2335	1770	3079	2017	2680	2447	3165	2608	3137
15:00	99	692	288	458	472	805	462	684	665	879	536	813	783	913	762	888
Winter Solstice 21st of December																
09:00	164	1831	773	1265	1012	2136	1480	1748	1466	2348	2086	2052	2202	2714	2450	2521
12:00	388	3990	1104	2639	2152	4390	2135	3605	3309	4838	3420	4279	4323	5282	4449	4959
15:00	35	821	361	582	535	966	600	823	830	1106	784	1020	1049	1224	1058	1171

Table 9. Hourly best performing scenarios

Spring Equinox 20th of March												
Activ.	Reading/Writing			Using a computer or electronic device			Drawing/Sketching			Model making		
Lux Req.	500			300			750			500		
09:00	S5	75% opened	579	S3	Up 100% opened	330	S7	Up 75% opened	811	S5	75% opened	579
12:00	S5		1065	S3		363	S5	75% opened	1065	S5		1065
15:00	S5		508	S3		307	S2	Low 100% opened	713	S5		508
Summer Solstice 21st of June												
09:00	S6	Low 75% opened	508	S4	Middle 100% opened	324	S14	Low 25% opened	570	S6	Low 75% opened	508
12:00	S9	50% opened.	508	S4		365	S14		666	S9	50% opened	508
15:00	S14	Low 25% opened	507	S2	Low 100% opened	321	BS	no shading	1153	S14	Low 25% opened	507
Fall Equinox 22nd of September												
09:00	S5	75% opened	672	S3	Up 100% opened	342	S4	Mid.100% opened	841	S5	75% opened	672
12:00	S5		1072	S3		416	S5	75% opened	1072	S5		1072
15:00	S11	50% opened	536	S4	Mid.100% opened	458	S15	Up 50% opened	762	S11	50% opened	536
Winter Solstice 21st of December												
09:00	S3				Up 100% opened				773			
12:00	S3				Up 100% opened				1104			
15:00	S5	75% opened	535	S3	Up 100% opened	361	S11	50% opened	784	S5	75% opened	535

Figure 44 shows an overview of how the best performing scenarios would look like on each year of study classroom during solstices and equinoxes. The table is based on the responses from the questionnaire, on which activities each year finds more challenging to conduct.

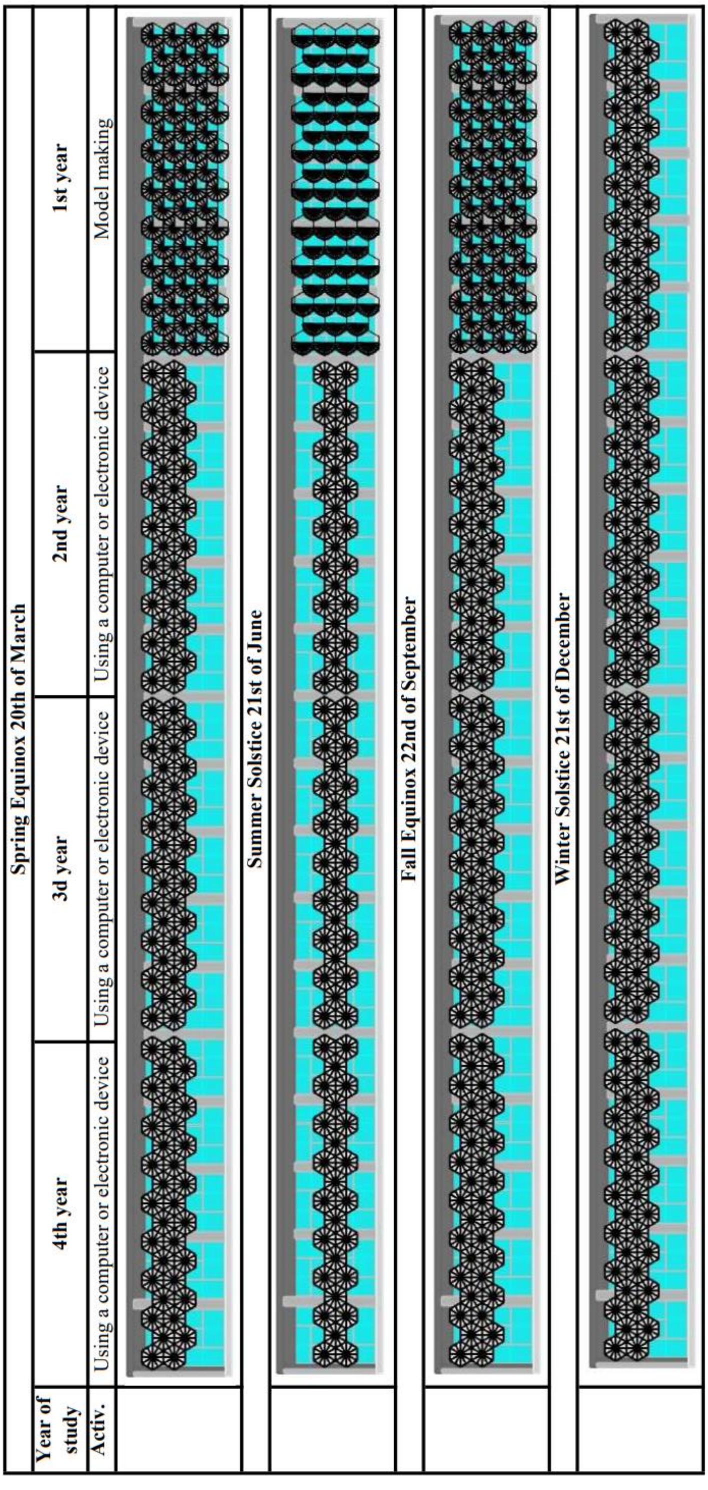


Figure 44. Best performing scenarios for each year of study

CHAPTER 5

DISCUSSIONS AND CONCLUSIONS

5.1 Discussion

The focus on biomimicry approach is due to its high potential for extracting technical solutions and developing real-time form finding logic for the building façade design. The discussion chapter of this research focuses on evaluating the influence of various facade layouts on visual comfort and daylighting performance, with the goal of enhancing these aspects through biomimicry-inspired kinetic building skin alternatives. The study uses geometric patterns of plant pollen and the movement of earwigs' wing fold as sources of inspiration. The base case for the evaluation is the studio classrooms of Epoka University, and 16 different facade scenarios with varying levels of openness are analyzed.

The findings of the research demonstrate that scenarios with a level of openness of 25% provided little to no shading, resulting in insufficient control over daylighting. On the other hand, the scenarios with 100% and 50% levels of openness performed better in terms of daylight performance and visual comfort. Specifically, Scenario 3, which has an upper section with 50% openness, and Scenario 5, where the entire facade is 75% opened, provided the best results.

During the Winter Solstice, controlling lighting conditions proved to be the most challenging, particularly at 12:00 pm. From Scenario 6 to Scenario 16, the illuminance values exceeded the required range and were similar to those of the base case. However, at 9:00 am and 3:00 pm, some values were considerably high.

This research serves as a fundamental study that highlights the benefits of employing a biomimicry morphological approach to design interactive facades that improve visual comfort and communication between dynamic parameters.

However, certain limitations should be acknowledged. The evaluation of daylight performance focused solely on the level of openness of each facade scenario, and future research should consider incorporating the structural aspects and materials of the facade into the analysis.
Additionally, the study utilized parametric daylight simulation based on guidelines for visual comfort prediction, which is consistent with ongoing research practices. However, since the perception of glare is subjective and depends on human sensation, further investigation through experimental studies is necessary to fully understand the functionality of the interactive kinetic facade.
In conclusion, this research demonstrates the potential of biomimicry-inspired kinetic building skin alternatives in enhancing daylighting performance and visual comfort. The findings highlight the importance of facade design and level of openness in achieving optimal daylight conditions. Future studies can build upon these results by considering additional factors such as structural elements and conducting experimental investigations to refine and validate the findings.

5.2 Conclusions

The research conducted in this thesis explored the application of biomimicry principles in building facades to enhance daylighting performance and visual comfort. Through a comprehensive literature review, it was evident that nature has provided efficient and sustainable ways of minimizing resource consumption, making it a valuable source of inspiration for architectural design. The dynamic nature of daylight was identified as a crucial factor affecting human visual comfort, highlighting the need for adaptive shading systems that can respond to changing environmental conditions.

The specific focus of this research was on educational buildings located in dry-summer subtropical climate areas. The goal was to improve daylighting conditions in studio classrooms at Epoka University. Two levels of biomimicry, inspired by the geometric patterns of plant pollen and the movement of earwigs' wing fold, were integrated into the facade design. Sixteen different facade scenarios were developed, each with varying levels of openness, to assess their impact on daylighting performance and visual comfort.

The evaluation process involved a combination of climate data analysis, questionnaires, and daylight performance metrics. Simulations were performed annually and at specific hours during solstices and equinoxes using Rhino v6, Grasshopper, and ClimateStudio. The key measurements of daylight evaluated annually were sDA, ASE, AAI and sDG. The questionnaire results provided valuable insights, indicating that students experienced visual discomfort during winter and summer seasons, which affected their ability to conduct activities effectively.

The simulations conducted on the base case revealed significant visual discomfort throughout the year, particularly during winter equinoxes at 12:00 pm. This highlighted the necessity for improvement in lighting conditions and the potential benefits of biomimicry-inspired facade designs. The analysis of the different facade scenarios showed promising results, with notable improvements in visual comfort and daylight performance.

In the annual analysis, three scenarios showed remarkable results: scenario 3, scenario 5 and scenario 7. Among them, the 3rd and 5th scenarios are more suitable for studio activities. Among the various scenarios evaluated, Scenario 3 (upper section with 50% openness) and Scenario 5 (the entire facade with 75% openness) exhibited the best daylight results and visual comfort, for the hourly daylight analysis.

These findings indicate that the integration of biomimicry principles can effectively enhance the daylighting performance of building facades. The use of nature-inspired adaptation strategies derived from living organisms and plants has the potential to improve occupants' well-being and comfort.

While this research provides significant insights, it also has some limitations. The evaluation of daylight performance focused primarily on the level of openness of the facade units, neglecting the structural aspects and materials. Future studies should consider incorporating these factors to gain a more comprehensive understanding of the performance of biomimicry-inspired building skins.

Additionally, the methodology employed in this research utilized parametric daylight simulation based on established guidelines for visual comfort prediction. However, the subjective nature of glare perception suggests that further experimental studies should be conducted to investigate the functionality of the interactive kinetic facade.

Finally, this study demonstrated the potential of biomimicry principles to improve the performance of light-time and visual comfort in façades. The findings highlight the importance of integrating biomimicry at different levels to create adaptive and responsive design. The study contributes to sustainable architecture and emphasizes the importance of natural inspired solutions for improving building performance. Future research should explore other parameters such as structural considerations and materials to further refine and validate the proposed biomimicry approach. Overall, the study demonstrated the value of biomimicry in creating a sustainable and occupant-oriented building environment.

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