University of Constantine 3

Faculty of architecture and urbanism

Department of architecture

BIOMIMICRY: INNOVATIVE METHODOLOGY FOR SOLAR DESIGN

THESIS

submitted for obtaining the degree of doctorate

in Architecture in Bioclimatic Architecture

Presented by

Imene KESKAS

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in front of a jury composed of:

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DEDICATION

The modest research work presented in this thesis is dedicated to my beloved people who always meant to me. Especially, to the memory of those that are no longer of this world,

My Father Mohammed Tahar

My professor Mustapha Samai.

dedicated to My beloved Mother “Yasmina”, My sisters “Sonia” and “Fatima”

My brothers “Sofiane” and “Mohamed”

My dear friend “Nour el Houda Bouchenak”

Sincerely Imene

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NOMENCLATURE

BSM: Building solar morphing

SMA: Shape Memory Alloy

SBE: Segmented building envelope

GSS: Geo-solar segmentation

SUT: Solar Useful Time

MOGA: Multi-objective genetic algorithm

S: Shape coefficient

E: Usable space

I: Total received solar radiation

BBF: Building Back-face

B_H: Building height

BFF: Building front face

SN_A: Azimuthal segment number

$SN_{E:}$ Elevation segment number

CTA: Combined tilt angles

COA: Combined orientation angles

SBE: Segmented building envelope

E/NBF: East-north building face

W/SBF: west-north building face

S_S: Solar state

D_H: Horizontal distance

D_V: Vertical distance

ABSTRACT

Building envelope shape plays a crucial role in determining the building energy performance, by regulating its solar exposure and the incident solar radiation. However, there are limited solar morphing tools that allow the generation of static building envelope based on solar principles. Besides solar potential, additional building shape performance indicators need to be considered, such as space efficiency and shape coefficient. Therefore, the present study proposes the ‘Geo-solar segmentation’ morphing method that would help architects generate a range of optimal solar building shapes in the early design-stage, under different climate conditions. Accordingly, based on the top-bottom biomimetic approach, the solar-induced rock cracking mechanism is adopted as an architectural design concept. It is then, transcribed into a solar design generation and optimisation algorithms using visual programming on Grasshopper, in Rhinoceros. Octopus, an evolutionary solver is used to perform the multi-objective genetic algorithm optimisation. A comparative study is conducted between optimal solar segmented building envelopes and corresponding rectangular-based ones. The results demonstrate that under hot climate, optimally segmented building envelopes are 44.90 % more effective at solar protection than rectangular-based ones, and allow a trade-off between solar protection and collection under temperate climates. Moreover, the method helps reduce the shape coefficient by at least 10.30% for any climatic location, while ensuring a minimum space efficiency of 95%. The suggested method can be used as an early design-stage tool to enhance static envelope energy performance.

Keywords

building solar morphing, geo-inspiration, static building envelope design, multi-objective genetic algorithm-optimisation, building shape performance, design trade-off.

RESUME

La forme architecturale permet d’améliorer l’efficacité énergétique du bâtiment à travers un bon contrôle du rayonnement solaire incident. Cependant, les outils existants de conception architecturale solaire présentent des limites intrinsèques. La présente étude propose une méthode de conception architecturale solaire « segmentation géo-solaire » qui aide à générer des formes optimales sous différentes conditions climatiques, pendant la phase préliminaire de conception architecturale. L’ergonomie de l’espace intérieur et le coefficient de forme représentent deux indicateurs de performance de la forme architecturale qui ont également été évalués. En effet, cinq mécanismes de création et d’optimisation de la forme architecturale ont été dérivés à partir d’un concept de design inspiré par le phénomène de segmentation de la roche sous l’effet de l’énergie solaire. Les algorithmes correspondants ont été par la suite établis dans l’environnement de programmation visuelle « Grasshopper » du logiciel « Rhinoceros ». L’optimisation multi-objectifs a été accomplie en utilisant le plugin Octopus. Finalement, une étude comparative a été menée entre les formes architecturales optimales obtenues et celles rectangulaires de référence. Les résultats montrent que dans les régions chaudes, les formes optimales obtenues sont plus efficaces en termes de protection solaire (+44,90 %). Sous des climats tempérés un compromis entre la protection et l’exposition solaires a été établi. La méthode permet également de réduire le coefficient de forme d’au moins 10,30 % sous différentes conditions climatiques, tout en assurant une ergonomie minimale de l’espace de 95 %. La méthode proposée peut être utilisée au coursde la phase préliminaire de conception architecturale pour améliorer l’efficacité énergétique de l’enveloppe architecturale statique.

Mots-clés

Conception architecturale solaire, géo-inspiration, enveloppe architecturale statique, optimisation multi-objectifs, performance de la forme architecturale.

ملخص

يلعب شكل غلاف المبنى دورًا مهمًا في تحديد أدائه الطاقي، من خلال التحكم في نسبة تعرضه للطاقة الشمسية وكمية الإشعاع الشمسي الوارد. ومع ذلك، تبقى القواعد النظرية التي تمكن المعماري من استغلال الطاقة الشمسية وإنشاء غلاف معماري ثابت جد محدودة. إلى جانب استغلال الطاقة الشمسية، يتوجب على المعماري اخذ مؤشرات إضافية لأداء شكل المبنى بعين الاعتبار، مثل كفاءة الفضاء ومعامل الشكل. لذلك، تقترح هذه الدراسة «التجزئة الجيو-شمسية» وهي طريقة للتصميم الشمسي لشكل الغلاف المعماري والتي من شأنها أن تساعد المهندسين المعماريين على انشاء مجموعة من أشكال أغلفة معمارية شمسية مثالية في مرحلة مبكرة من التصميم، في ظل ظروف مناخية مختلفة. وفقًا لذلك، وبناءً على منهجية المحاكاة الحيوية من أعلى إلى أسفل، تم اعتماد آلية انشطار الصخور الناتجة عن تأثير الطاقة الشمسية كمبدأ تصميمي معماري. تم بعد ذلك نسخه الى خوارزميات لإنشاء والتحسين الغلاف المعماري الشمسي باستخدام البرمجة المرئية على Grasshopper في البرنامج Rhinoceros. استخدم بعد ذلك Octopus باعتباره محلل تطوري لإجراء التحسين متعدد الأهداف بالاعتماد على الخوارزمية الجينية. اجريت بعد ذلك دراسة مقارنة بين اغلفة المباني المثلى المتحصل عليها بتطبيق «التجزئة الجيو-شمسية» والاغلفة المستطيلة المتناسبة معها. تظهر النتائج أنه في ظل المناخ الحار، تكون اغلفة المباني المثلى المتحصل عليها بتطبيق «التجزئة الجيو-شمسية» أكثر فعالية بنسبة 44.90٪ في الحماية الشمسية من تلك المستطيلة، وتسمح بالموازنة بين الحماية والتجميع الشمسيين في ظل المناخ المعتدل. علاوة على ذلك، تساعد الطريقة المقترحة في تقليل معامل الشكل بنسبة 10.30٪ على الأقل تحت اي مناخ، مع ضمان الحد الأدنى من كفاءة الفضاء بنسبة 95٪. يمكن استخدام الطريقة المقترحة كأداة في المرحلة الاولية للتصميم وذلك بغية تعزيز الأداء الطاقي للغلاف المعماري الثابت.

الكلمات المفتاحية

التصميم المعماري الشمسي، الاستلهام من الجيولوجيا، تصميم الغلاف المعماري الثابت، خوارزمية الجينية للتحسين متعدد الأهداف، أداء شكل غلاف المبنى

CHAPTER I INTRODUCTION

I.1 Introduction

The evolution of human life on earth was influenced by successive historical events, related to the discovery of new production systems and environmental adaptation strategies. The industrial revolution is one of the most important events that marked history and human progress. It was the logical result of substituting the physical strength and ability of man and animals in the production process by that of the steam engine (La-Machine-a-Vapeur, //www.maxicours.com). In fact, the use of charcoal facilitated and increased the industrial production, and multiplied wealth. However, it created huge environmental issues, such as pollution in all its forms. Thus, the industrial revolution was a double-edged sword.

Consequently, « the carboniferous city» emerged, and was characterized by its grayish environment due to the smoke released by the factories and trains that crossed its heart. These unhygienic living conditions were behind many public health problems. Since then, industrial and technological development has been at the expense of the environment and the ecosystem. The depletion of fossil energy resources has caused a biological imbalance and serious global upheavals. The effects of climate change can be seen around the world, and it is accelerating and affecting people's health and life.

According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have considerably increased since the 18th century due to the intensity of energy consumption and human activities. According to the current greenhouse gas emissions rates, the global average temperature could increase by 1.4 to 2.6 ◦C above pre-industrial levels by 2065. It is recommended by scientists and policymakers to limit global warming to below 2 ◦C within the present century (IPCC, 2014) to avoid significant and potentially catastrophic impacts to the planet (Keskas *et al.*, 2022).

I.2 Theoretical background of the research study

In order to remedy the current situation, engineers, architects and building planners are working together to reduce buildings' energy consumption and enhance their performance. Embedding solar conscious strategies into the architectural design via solar morphing tools allows achieving energy-efficient buildings and comfortable living environments (He *et al.*, 2021), and consequently, attenuating climate change impacts. In fact, controlling the static building envelope's solar exposure has a significant impact on the building's solar potential and energy efficiency; Indeed, building solar morphing (BSM) strategies give designers the ability to regulate incident solar radiation and to set the ideal indoor environment. Moreover, based on the available solar radiation, physical properties of the building envelope, such as G-values, are defined to help in further optimizing solar heat gains (Ménard and Souviron, 2020). The resulting temperature difference between indoor and outdoor environment can drive convective air flow, thereby assisting in ventilation (Kolokotsa *et al.*, 2012) (Bekkouche *et al.*, 2013), and possibly causing heat losses that can be limited by choosing appropriate U-values of the envelope materials (Lee *et al.*, 2013). Thus, building solar morphing strategies are the major factor in regulating incident solar radiation, defining appropriate envelope materials, and consequently, optimizing the heat transfer between indoor and outdoor spaces (Keskas *et al.*, 2022).

The etymological meaning of the term climate (the main element of the ecosystem) is slope; in reference to solar rays' incidence angle (the sun declination) (Gonzalo Roberto and Karl J. Habermann, 2008) The latter varies throughout the day and the year and impacts all climatic conditions. Consequently, solar energy should be the first climatic factor to be considered in bioclimatic architectural design. It is a promising source of energy that can be collected to generate heat or cold, which makes it useful in numerous sectors. The embedment of solar energy in architectural design can take different forms: it may be achieved by employing active systems and appliance that require operating energy, or by the adoption of energy-free passive strategies. In bioclimatic architecture, it is prudent to implement passive strategies in the design process and active systems for further improvement of the building's energy performance. In imitation of a natural system, the present study aims to facilitate the incorporation of solar energy into the building design process.

In addition, taking inspiration from nature is considered as an effective way to generate innovative design solutions (Tavsan, Tavsan and Sonmez, 2015). Bio-inspiration process is supported by a newly established discipline known as "Biomimicry", which is the science and philosophy of learning from nature (Janine Benyus, 2002). Bio-inspiration process relies on specific approaches, it was first put forward by the writer and scientific observer Janine M. Benyus, who defined it as follows: "Biomimetics is not a construction style, nor an identifiable design product, it is a design process, a way of seeking solutions by which the designer defines a functional challenge (flexibility, tensile force, wind resistance, protection against noise, cooling, warming, etc.,) and then looks for a creature that is the champion of this function, and finally starts a conversion "(Benyus 2008). In fact, natural organisms are in continuous interaction with their natural environment. They are characterized by diverse natural adaptation mechanisms. Several natural organisms rely on the external shape that greatly depends upon the climate type, for instance human physical appearance changes according to the climate type under which people live.

I.3 Problem Statement

Nowadays, the construction sector is considered as one of the most energy-intensive economic sectors. The building's energy consumption depends on several factors in relation to the various systems that ensure its proper functioning and to other factors related to the building shape and its envelope material. In fact, the building envelope represents the skin or the intermediate membrane that manages the several interactions between indoor and outdoor environments. As a result, the energy performance of the building envelope contributes to energy-saving policy. Thus, architects should enhance the building envelope ability to regulate the available solar energy. Building solar morphing (BMS) strategies development reveals that rare are the research studies that dealt with the whole building envelope shape morphing. Furthermore, an examination of the field of building solar morphing (BMS) strategies reveals that research studies that dealt with the whole building envelope shape morphing are uncommon.

I.4 Research Questions

Based on the interconnection of natural systems and organisms: **is it possible to design the building envelope as a living system in constant interaction with climatic factors, especially solar energy?**

On the other hand, biomimicry has been applied in the field of design throughout human history, either consciously or unconsciously, bringing positive results. Indeed, learning from nature is not a new concept, nor are experiences that repeat themselves in the same way. Each designer has defined its own method for taking inspiration from nature. Thus, the methodology of concepts and principles transfer in biomimicry is called into question in order to enhance bio-knowledge transfer and, as a results, the effectiveness of bio-inspired architectural design.

Introduction

- **How can bio-knowledge transfer be enhanced? And to what extent?**

According to (Tavsan, Tavsan and Sonmez, 2015) biomimetics help architects understand that a spider is not merely a spider but a producer of material and a designer. Similarly, an ant is also, a builder of structures similar to sand castles.

Therefore, looking for a natural source of inspiration through the observation of the surrounding world stimulates the designer's senses. Each natural organism performs a distinct function in preserving the ecosystem. For instance: human beings continue to exist on earth due to a series of interactions between other living species. According to Albert Einstein, "If the bee disappeared from the face of the globe, humans would only have four years to live." Thus, bees represent an ecological barometer that we should consider. Their disappearance will cause a severe unbalancing to human life (http://nancyroc.com/sans-abeilles-notre-avenir-en-peril). The building should be designed as a prototype of the ecosystem, and each of its elements should contribute to providing a comfortable living environment. In addition, the design of the building envelope impacts the solar potential of its facades. Consequently, the building shape is the major factor that influences the interior conditions and the building's solar potential. Based on the above discussed ideas:

- **To what extent could a building envelope solar morphing strategy (shape performance indicators) help to enhance its ability to regulate the amount of incident solar radiation? throughout the year in several climate regions?**
- **What is the best procedure to select an appropriate natural model that can inspire the design of a static building envelope that is in constant interaction with solar energy? Moreover, what are the geometric functional features, parameters and performance indicators that must be considered?**

The current situation pushes building designers and engineers to exploit technological and scientific advancements in the creation of new building shapes. This can be considered as an adaptation mode of human life to its natural, economic, social, and cultural settings contributing to a sustainable development strategy.

The implementation of the generative approach in the architectural design process enhances the designer's creativity and allows for the generation of numerous design alternatives. Building shapes can be optimised using generative design software based on specific architectural parameters manipulation such as the façade's elements, window dimensions, shading systems, or materials (Yavuz and Çelik, 2014), (Caldas, 2008). Hence, generative design allows for the testing of multiple combinations of design parameters by fixing one variable and varying the others. It helps architects generate a variety of optimal building shapes, and brainstorm more creative design concepts (Caldas, 2008).

- **Is it useful to examine a wide range of solutions that optimize the building solar potential under several studied locations?**

Solar energy is a natural phenomenon intimately tied to earth's movements around the sun following a non-rectilinear path. Organic and irregular building shapes can be designed based on the solar pathway to better regulate the building envelope's solar exposure. However, designing organic and irregular building forms is more complicated than regular forms. Hence, generative design can bring new design solutions and simplify the process. In addition, solar design parameters, such as the building façade orientation can be more diverse in irregular shapes than in regular ones where only a limited number of orientations can be examined. Due to the tools, it provides, technological progress plays a key part in design creation today.

Given the fact that most of solar morphing strategies are based on dynamic facade systems, which consume energy. Do technology-based tools and static building envelope offer cost-effective solutions?

McDonough & Braungart (2003) acknowledged that through collecting solar energy, all natural systems help in maintaining ecosystem equilibrium. Hence, solar energy interacts with the earth's geochemistry to support all regenerative biological systems.

- **By using computational tools, Are Trade-offs between solar protection, solar collection and shape performance indicators achievable under a temperate climate?**

Our local action as architect researchers entails the establishment of efficient design tools to facilitate the implementation of solar bioclimatic design rules in the architectural design process. These tools can contribute to the improvement of the building's energy performance through solar energy regulation. Furthermore, design tools and methods help establish building design policies and rules that can be applied in Algerian context.

I.5 Motivation

The architect's contribution to energy conservation strategies by increasing renewable energy use is part of his eco-responsibility. In order to provide comfortable living environment, architects must adapt the building design and construction process to economic and environmental considerations. As a result, new design and construction approaches have emerged. These approaches simultaneously meet the complex environmental factors and the needs of modern societies and economies. The limited use of generative architectural design tools in Algeria motivated us to explore this topic in the present thesis in order to provide clarifications and information on generative design and encourage its application.

I.6 The aim and the objectives of the study

Examining the existing literature on bio-inspired building solar morphing BSM strategies shows that most of the BSM studies focused on bio-inspired façade dynamic systems, while bio-inspired static building envelopes are rarely addressed. Accordingly, the present study aims to develop a BSM method that enhances static building envelope solar exposure. This method is versatile, allowing shape exploration in several climatic regions. It can be applied in the early design stage to avoid modifications in the building shape post-construction. Thus, it saves time, energy and resources for future upgrades. Additionally, the geo-inspiration source in this study is a phenomenon observed in nature, which has not been explored previously in building morphing studies. Moreover, the method allows the designer to generate optimal building shape by considering multiple factors of solar geometry and shape performance indicators (Keskas *et al.,* 2022).

Accordingly, the present study objective is to establish an innovative design method for building solar morphing by implementing the top-down bio-inspired design approach. Thus, a natural solar morphing mechanism was selected and transcribed into an architectural design concept. By applying the established method, innovative building shapes will be generated.

I.7 Research Significance

This study will aid in explaining the variety of options that can be supplied by a single design tool. Also, it will encourage architects to use innovative design tools and come up with more creative building forms.

Introduction

BSM strategies are generally developed to be adapted to the building under specific climate conditions. However, the method developed in this research is a BSM method that can be applied under several climate conditions, even in temperate climates, since it helps set a trade-off between two contradictory objectives in solar design.

Hence, the method presented in our thesis will be helpful to architects, building designers, and engineers. The study findings could inform the researchers on how to implement a natural mechanism in the building solar morphing process. It will also show the diversity of morphing mechanisms and optimal solutions obtained from the combination of the geo-inspired design concept and the multi-objective genetic algorithm optimization (MOGA).

I.8 Methodology

The following research tools are utilized to achieve the intended outcomes and objectives:

- **Documentary research and collecting data:** the use of bio-inspired design approaches has given positive results in several research fields. Hence, a thorough investigation of the field of biomimicry is conducted to understand its basis, methods, principles, and approaches in order to select the most appropriate one for our research. The included and exploited bibliographic resources are mainly: theses, books, journals, and digital databases. This documentary research provided us with a global perspective on the subject matter and the relationship of solar energy to the natural world. The systematic collection of information and subsequent creation of a database allow for the resolution of previous experiment challenges, which have significantly impacted the effectiveness of the bio-inspired process.

- **Modeling and simulation:** in this study, a bio-inspired architectural design algorithm is developed using visual programming tools in Grasshopper, a plugin within Rhinoceros software. The generated models have a specific envelope layout for better solar energy management. According to (Benoit Mandelbrot, 1982) “Clouds are not spheres… the bark is not smooth and does not allow lightning to travel in a straight line.». For this reason, and to give the architectural form a layout resembling natural organic forms, the use of computer-aided design and visual programming tools is vital. Hence, biomimetic design can be explored in novel ways through applying parametric approach (Menges, 2012). In fact, computational design is based on modelling the process rather than the object, modelling behavior rather than designing behavior. This allows for the generation of innovative architectural forms that respond to all design constraints, even contradictory.

I.9 Structure of the thesis

Architectural design is increasingly becoming an interdisciplinary process. Knowledge of several interrelated sciences is required to develop innovative architectural design tools. Accordingly, the theoretical concepts and a literature review of several design approaches are separately explained in the first four chapters of the theoretical part of the thesis. The second part explains the methodology for applying the learned knowledge presented in the first part. It involves two chapters that explain how to establish an innovative bio-inspired design method for architectural solar design.

- **Chapter 1**

Gives an overview of the fundamental elements of the study. First, this chapter introduces the general context of the study. it states the issue treated in the research by asking numerous questions in order to outline the focus of the study and the author's motivations. Furthermore, it emphasises the significance of the research, its goal, and its objectives. Finally, the structure of the thesis is clarified using an explanatory diagram.

- **Chapter 2**

This chapter aims to reduce the complexity of innovative design approaches applied in the present study, such as: computational design approach, generative design approach, and parametric approach, by elucidating their common roots derived from "shapes grammar" theory. Moreover, other innovative design approaches, and traditional and innovative design tools are addressed in order to clarify the basis of an innovative architectural design approach and the needed tools.

- **Chapter 3**

Initially, solar buildings entities are defined in order to distinguish between the different focuses of solar design strategies. Then, the most influential factors and parameters in architectural solar design are explained. The structure of the chapter is designed to provide an inclusive guide to building solar design optimization and the appropriate choice of parameters and variables. At the end of the chapter, numerous combinations of solar design parameters are investigated with a focus on the obtained results and the most suitable combinations.

- **Chapter 4**

Focuses on biomimicry, starting with an historical overview of its development and application in the field of design. Afterwards, bio-inspired design approaches are explained. A successful bio-inspired design approach in architectural design is addressed, outlining the most challenging aspects. The most significant aspect of this chapter is the final section, which explains our vision for a bio-inspired method by describing essential principles of bio-knowledge transfer that assist the derivation of a suitable design concept.

- **Chapter 5**

Presents the steps for implementing the top-down bio-inspired approach in the study process. The source of inspiration is defined then, transcribed into an architectural design concept. The latter is applied in the design process to generate optimal solar building geometries.

- **Chapter 6**

This chapter mainly explains the sequence of steps in the suggested solar morphing method, which is developed based on the derivation of mathematical models and visual programming. The design concept is then embedded into the solar design process applying a computational design approach using plugins in Rhinoceros software, such as: Ladybug and Grasshopper. The developed algorithm is then used to generate and evaluate building solar design under several climatic conditions.

- **General Conclusion:**

This section summarizes the conclusions obtained in each chapter of the thesis. In fact, the contribution of this thesis is not limited to the establishment of a bio-inspired solar design algorithm but also involves a straightforward interpretation of an innovative design approach in architecture presented in the theoretical chapters.

I.10 Framework Limitations

This study presents a further development of the approach and relevant issues addressed by previous papers in the Solar Energy journal, particularly (Zhang et al., 2016). However, the novelty of our study resides in the implementation of an original geo-inspired solar morphing concept, and the corresponding geometric parameters. Additionally, the biomimetic approach is adopted in setting up a static envelope solar morphing tool, contrary to previous studies, which applied the same approach in designing a dynamic solar façade's systems. Moreover, the geo-solar segmentation method can be used under several climate conditions, unlike most studies, which dealt with a specific case study.

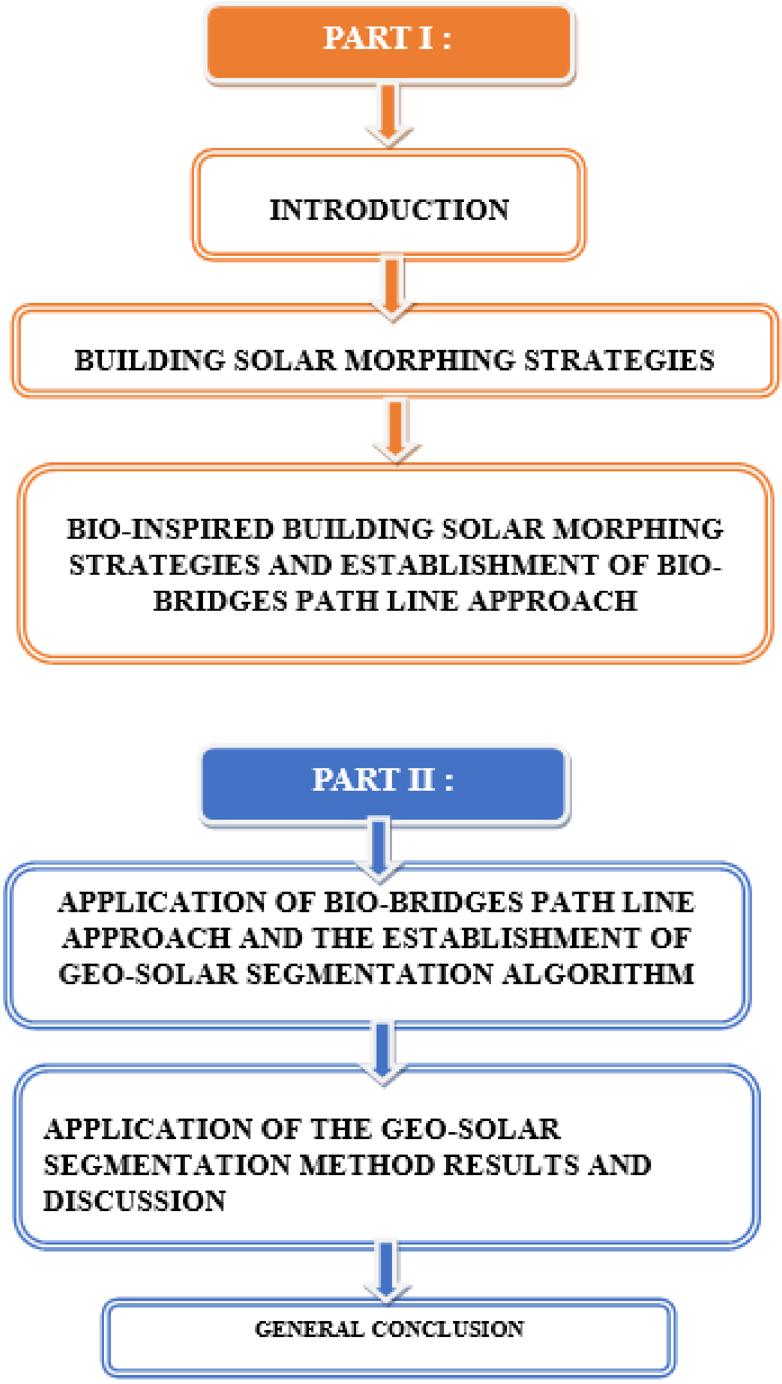

Figure I.1 Structure of the thesis (Author, 2022)

CHAPTER II. THE BASICS OF AN INNOVATIVE ARCHITECTURAL DESIGN APPROACH

II.1 Introduction

The process of morphing relies on geometric composition and undergoes multiple transformations to produce the desired design. The purpose of this chapter is to investigate innovative approaches in the field of architectural design and identify their common origin. the relationships between the architectural design pillars are firstly explained in this chapter, to clarify the form generation process.

The design approaches discussed in this chapter are related to our study objectives (see Chapter 1), and are adopted in the process of establishing innovative architectural solar design methods and tools. The investigated methods are particularly design-deriving methods, such as shape grammar. Thus, the objective of this chapter is to fully explain the basis of computational design tools and algorithmic-based design. Additionally, the relationships between innovative approaches in architectural design and the difference between traditional and innovative design tools are clarified.

In this chapter, the hidden support that ensures the visual style's harmony and beauty is presented in order to explain how to either compose new visual styles or analyse the existing ones to establish a formal identity. It is also behind the several innovative design approaches that are commonly implemented in architectural design, such as: parametric approach, bio-inspired approach, generative approach, and even computational design. Outlining the relationship between these approaches facilitates the establishment of new design methods and tools and helps treat additional constraints in the architectural design process.

II.2 Architectural design pillars and fundamental principles

Self-fulfilment is the highest-level need in Maslow pyramid (Mcleod, 2018), and it can be achieved through several personal practices. Creation and design are considered to be self-fulfilling practises that require an intellectual background. In fact, according to (Agkathidis, 2015) design thinking is strongly related to cognitive ability, and engineering design knowledge. Existing creative design methods help the designer get out of his comfort zone to discover new solution probabilities (Shrestha et al., 2021). Given the large number of variables involved, architectural design is a complicated, non-linear process that integrates several knowledge domains. In the present section, the relationships between the architectural design's main pillars are examined to clarify the process of converting abstract ideas into architectural form. Intention, design concept, and form are the three fundamental pillars of good architectural design. According to (Siret, 1997), architectural design, like other design fields, involves problem-solving process. The solution lies in designing an appropriate building form. The latter is the outcome of the interaction of various design restrictions and elements, which is controlled by the designer's goals. As a result, the designer's references and preferences define architectural design aims. They cover a variety of architectural aspects, such as philosophical, functional, structural, and others (Siret, 1997). Furthermore, (Lianto and Trisno, 2022) confirmed that innovation and creativity can originate from the structural aspect. The latter is basically related to materials that influence the generated form layout and subsequent manipulation options. The design intents result in a fundamental idea that inspires a design concept based on which three-dimensional models are generated (Fig. II-1).

Figure II-1: The process of converting abstract ideas into architectural form (Author, 2022)

Depending on the design objectives, we can find several architectural tendencies. A brief historical overview is presented in the following section to illustrate the main architectural tendencies that influenced the development of architectural form and expression. In addition, (Siret, 1997) emphasizes the value of treating architectural form in accordance with project aims. The building shape greatly depends on the overall design context; it is the formal manifestation of how various design restrictions interact from the initial design idea to the finished built structure (Fig. II-2). Therefore, the building shape represents a trade-off between the various architectural design objectives.

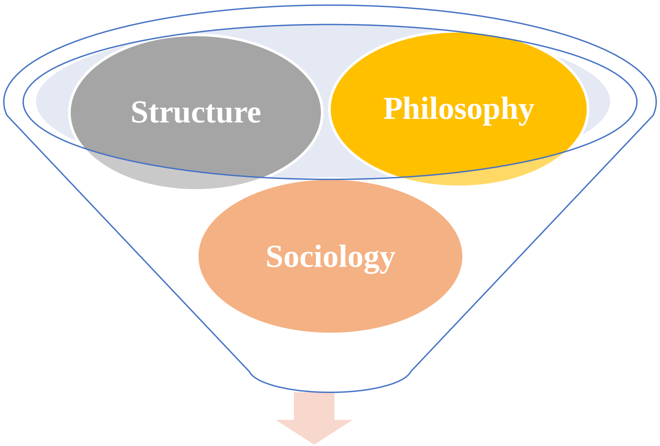

Figure II-2: Architectural form design factors (Author, 2022).

The functional aspect plays a crucial role in the building form evolution. "Form follows function" (https://www.re-thinkingthefuture.com/rtf-architectural-reviews/a3347-theory-in-architecture-form-follows-function/) is one of the most well-known principles of architectural design. Many of architectural styles originated from functional requirements. In recent years, building functionality has been assessed through performance evaluation by analysing the building shape behaviour. This gives a new architecture tendency known as "performative architecture", which represents the rational aspect of architectural design (Dino, 2012). Beyond shape design, the form includes both the building envelope shape and indoor space characteristics. According to (Akin, 2001), architecture is a representation of problem domains through analogy and symbolic modalities. The analogy representation is the visual architectural object perceived from the outdoor, which means the constructed entity. While factors related to the indoor ambiance, such as: light thermal comfort strongly affect the indoor space occupancy and well-being ambient factors. The description of the quality factors of indoor space are basically of symbolic aspect (Dino, 2012).

II.3 A brief overview of form evolution in architectural design

In fact, architectural form evolution results from the vital human need to look for innovation and change. However, there are a number of variables that govern the architectural form's evolution, such as innovative designers' ideas, tendencies, and philosophies. In addition, architectural form's evolution is also reliant on advancements in fields like industry, economy, and technology. **Fundamental principles** of architectural design are influenced by a number of important architectural design ideas. Vitruvius placed a strong emphasis on order and arrangement, considering them the fundamental principles of good architecture (VITRIVUS). Order ensures total harmony between shapes and design elements by adjusting their measures, dimensions, and proportions with respect to the whole. While, arrangement involves putting each of the components in its appropriate place. By harmonizing the measures, dimensions, and proportions of the shape components in relation to the whole, order promotes complete harmony between them. While arranging entails placing each component in its proper location. Several rules of order and arrangement identify and characterize the existing architectural **formal languages** shapes in terms of composition's rules. For instance: in ancient Greek and Roman architecture, specific formal languages are distinguished by their unique characteristics, such as the three column orders (Fig. *II-3*).

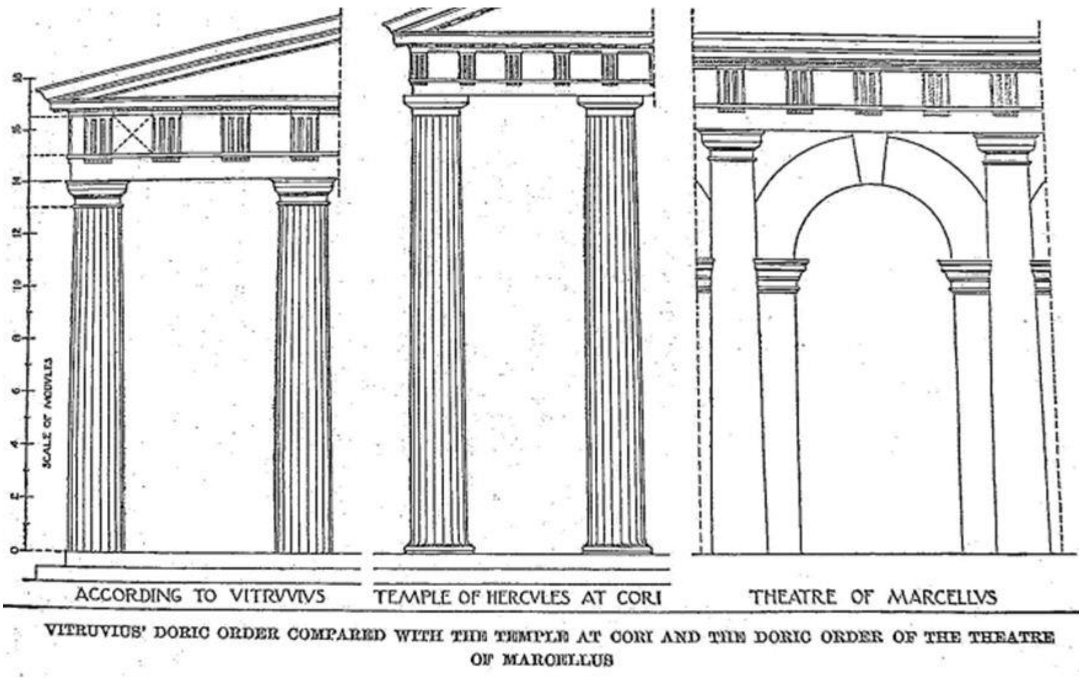

Figure II-3: Arrangement, measures and proportions in Doric order (VITRIVUS).

Therefore, the difference between architectural design pillars and fundamental principles resides in the fact that the first ones dictate the theoretical design ideas, while the second ones help translate those ideas into 3-D shape (Fig. II-4).

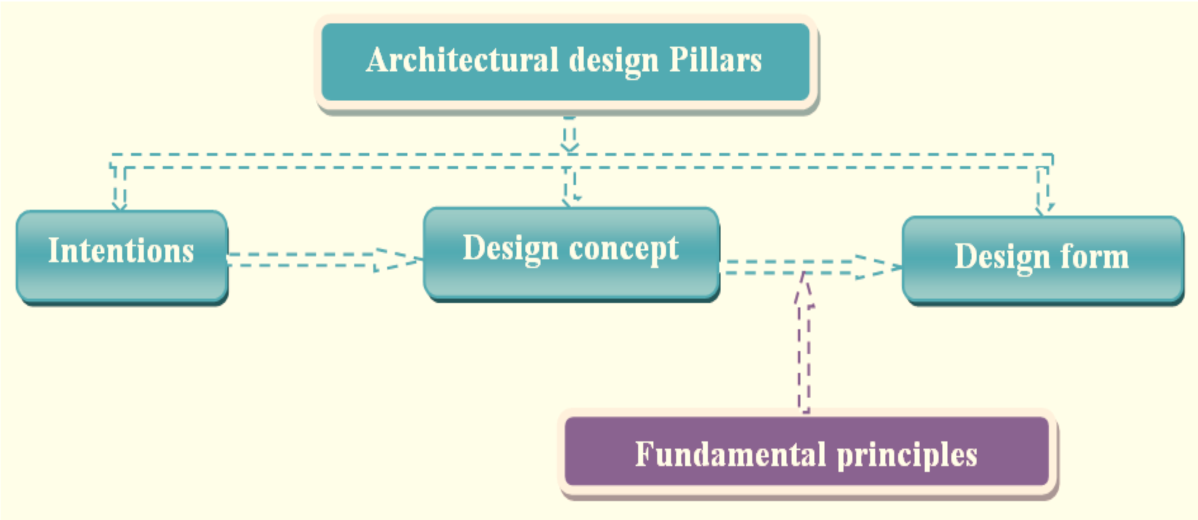

Figure II-4: Architectural design pillars (Author, 2022).

Observing the evolution of architectural formal language throughout history reveals the evolution of building shapes from simple to more complex. The classical and neoclassical formal languages limited the designer's creativity by by setting up a set of rules that couldn't be changed or adjusted (Ian Sutton, 1999). These architectural styles were criticized as being rigid and more rational than emotional (Ian Sutton, 1999). Buildings' shapes were constrained by linearity and right angles (Fig. II-5). Consequently, architects escaped the classical architectural formal language by placing less emphasis on superfluous aesthetic ornamentation, and seeking more simple and flexible forms.

Figure II-5: Packard building No.10. Detroit. Michigan. USA. Albert Khan. Utilitarian style cheap and nasty (Colin Davies, 2017).

The basics of an innovative architectural design approach

In his book published in 1683, Claude Perrault declared that good and expressive architecture relies on mathematical rules and order. He also acknowledged that "architecture is not an art but a science" (Ian Sutton, 1999). While, (Krishan, 2020) admitted that "Good meaningful architecture emerges at the meeting point when art becomes science and science becomes art". The artistic aspect involves the creative design ideas, while science is a technical support that helps concretizing the philosophy behind the building shape.

In the modern era, architectural form design and perception evolved through considering additional aspects; like: the psychological effect of a given building configuration on human perception. Beyond its morphological aspect, Architecture is an environmental component that stimulates feelings and emotions. Consequently, the "expressionism" tendency emerges in architecture in many architects' realizations. Bruno Taut is a key figure that contributed to the evolution of expressionism in architecture. He also shares the same opinion as Henry van der Velde who perceives architecture as a spiritual and emotional art form (Colin Davies, 2017). The dome of the Glass pavilion designed by Taut was constructed with glass to exhibit the German industry's product but also to create a space where light and transparency evoke the visitors' emotions. The spiritual and poetic dimension of architecture leads architects towards less rational forms. After years, a new tendency emerged in the building designs of many architects, such as Norman Foster, Zaha Hadid, and others. Their philosophy was different and represented the inverse approach of "Constructivism" tendency, which is "Deconstructivism". The corresponding formal language is characterised by the combination of symbolism with out-of-control forms (Colin Davies, 2017). Indeed, the main philosophy of modernism consists in believing in the existence of other ways to see the surrounding world that must be discovered and represented through architectural design. Thus, the physical built environment can be changed based on the way we perceive it (Aaron Betsky, 1998). Moreover, in some of Zaha Hadid paintings, gravity has been eliminated and the buildings are suspended. These paintings expressed the architect's preference for free form buildings (Colin Davies, 2017) (Fig. II-6). In fact, even if the building form is out-of-control, every constructed object obeys to geometry and laws of physics. For this reason, the method that helps establish design formal language, and which is behind creative design is addressed in the present chapter. The geometric composition generated applying specific rules and vocabulary constitutes a formal language, which corresponds to a visual style (Eilouti and Al-Jokhadar, 2007a, 2007b)(Eilouti, 2019).

As shown above, each of the architectural styles, has its own formal language. The evolution of architectural design tools affects the ideation process by providing new brainstorming tools using artificial intelligence (AI); this process is named “generative computer-aided ideation” (Zhu and Luo, 2022).

Figure II-6: Zaha Hadid paintings expressing her architectural design philosophy (Aaron Betsky, 1998).

II.4 Architecture design Tools between tradition and innovation

Architectural forms depend not only on the above-mentioned architectural design pillars but also on the tools used in the morphing process. Two main types of architectural design tools can be distinguished: traditional and innovative. The first type includes both manual and digital sketching and drawing tools, such as pencils and CAD software. In fact, the difference between the two design tools is related to the following aspects:

II.4.1 Degree of interactivity between designer, design tool and model

Traditional architectural design tools limit the interaction between the designer and the model, compared to innovative tools that ensure more interactivity between the designer and the model. A paper or digital representation using CAD software allows the production of a drawing, sketch, or physical model in 2D or 3D format. However, programming using software improves the visualization and configuration of the architectural form (Salman, Ravi and Hooker, 2008). Furthermore, the model is automatically generated based on a previously developed algorithm. The Architect's task in the design process has changed from modelling to programming algorithms to explore more design alternatives.

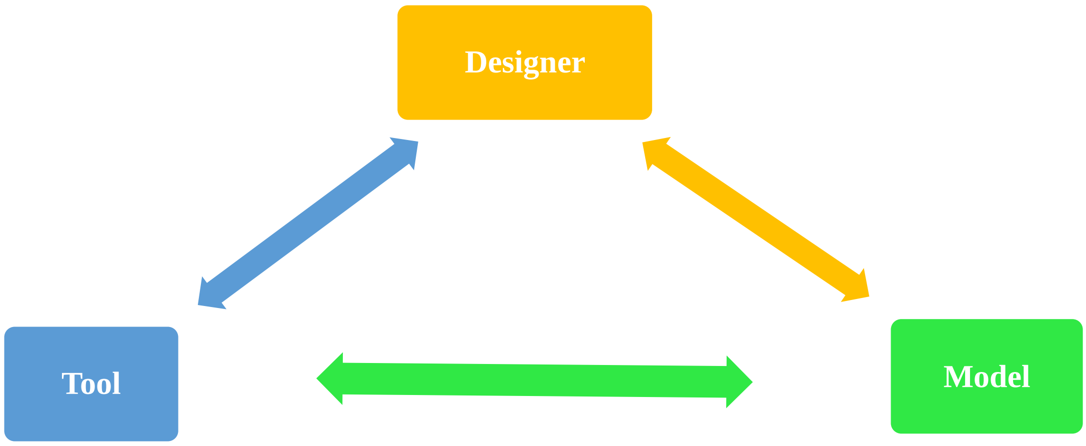

Figure II-7: Interactions in architectural design (Author, 2022).

(Zhu and Luo, 2022) considered the human-computer interaction as a sort of combination. Thus, each of them plays a complementary role in the design process. The start point of the design process can originate from either a human or a computer, and then the process alternates between the two design agents. This helps evolve the design solution, avoiding blank page syndrome and the lack of inspiration (Fig. II-8). Human-computer interaction allows the designer to think outside the box and sparks the designer's creativity.

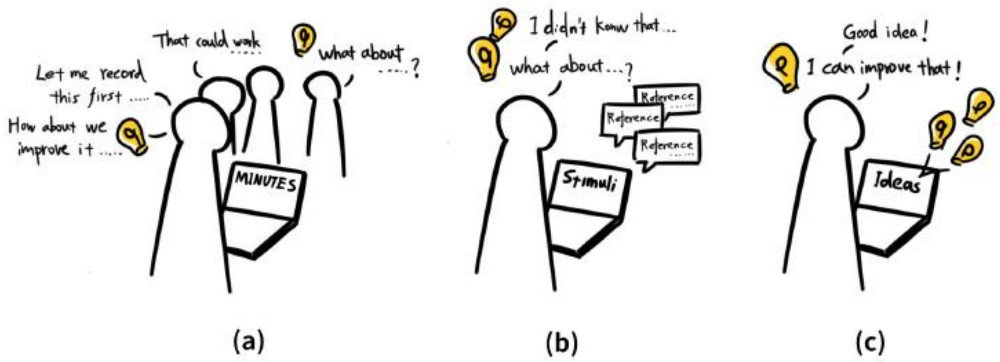

Figure II-8: Human-computer collaboration in design process. (a) brain storming, (b) Stimuli-based approach, (c) Generative approach (Zhu and Luo, 2022)

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II.4.2 The design phase in which the tool is implemented

Both traditional and innovative tools are used, nevertheless within different phases of architectural design process. Traditional architectural tools, such as CAD, are used within the modelling phase, after achieving the building design and defining its geometric features. However, visual programming tools are embedded in the early design stages (design and sketching phases) and help to further enhance the building configuration with respect to the design constraints.

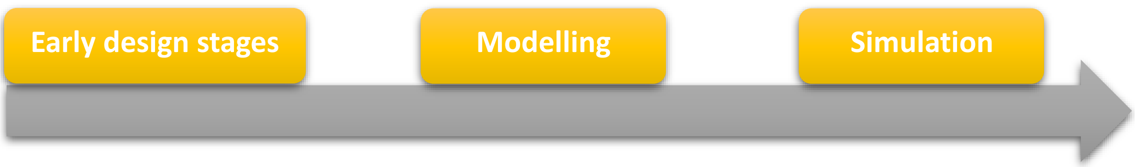


Figure II-9: Phases of computational design process (Author, 2022).

II.4.3 Possibility of transcribing theoretical concepts to morphing mechanisms

Some virtual design environments are endowed with tools that help transcribe theoretical design concepts into algorithms to automatically generate designs, such as visual programming within Rhinoceros software. In this case, the result (3D model) is simultaneously generated and visualized when programming. Thus, all design stages are synchronized.

II.4.4 Designer Skills

Innovative computational design environments rely on algorithm development, which requires the designer’s ability to observe, analyze, and abstract real and natural phenomena. Additional knowledge in mathematics and computer science is required to conduct a successful design process. Therefore, the designer's cognitive competencies impact the quality of the produced design (Agkathidis, 2015). However, traditional architectural design tools include different types of drawing media and instruments, and graphic representation (sketching and drawing). CAD software, including AutoCAD, allow for the editing and the modelling of the final building shape.

Figure II-10: Sky Soho, shanghai, china (Aaron Betsky, 1998).

II.4.5 Relationship between traditional and innovative design tools

The implementation of computation in shape grammars dates from the 1980s. Three early examples marked history: Krishnamurti (1980; 1981), Fleming (1987a; 1987b), and Chase (1989) (Tnpia, 1999). The use of shape grammars helps define the design framework, the design process constraints, transformation rules, and the design step sequence. Each rule generates specific forms; the combination of rules is made according to the designer's desired results. Thus, innovative design tools can be derived by combining the theoretical principles of shape grammars with computer functionalities. Moreover, virtual design environments support parametric and generative design approaches.

The basics of an innovative architectural design approach

Indeed, research and professional fields are inextricably linked; they should be combined to promote greater harmonisation. Accordingly, innovative design methods and tools for bioclimatic architectural design should be established using computational design software. This facilitates the implementation of bioclimatic architecture rules in the architectural design process to produce a sustainable built environment. Computational design programmes and algorithms help generate adapted buildings by simply introducing input values.

Computational design complexity lies in the misunderstanding of its roots and basis. In fact, exploring both shape grammars and computation in this chapter reveals hidden roots of computation that are discovered in shape grammars' rules, and logic. Thus, shape grammars are the basis of all creative design approaches that emerged from the implementation of computation for further design exploration. This reduces computation complexity and clarifies its logic. Accordingly, computation permits a rapid exploration of design alternatives while optimizing their shape performance. The use of traditional design tools does not allow evaluating the resulting shape's performance with respect to numerous design objectives. Subsequently, an algorithmic-based design approach is heavily reliant on shape grammars. As seen above, the successive transformation rules of the same initial shape applied in the same order define **a design algorithm**. Hence, shape grammars' theory is the basis of all computational design approaches, such as parametric approach, generative design approach, shape optimization, and the algorithmic-based design approach. In fact, shape grammar is an open-ended process that can involve an infinite number of transformation operations and rules. The shape performance evaluation process helps make decisions about the optimal design solution. Therefore, it is quite difficult to understand the logic of the computational design tools without understanding shape grammar because they both rely on the same logic but use different tools.

Shape grammar rules, on the other hand, facilitate the manufacturing process because the transformations rules applied to the design process define the geometric relationship between the entire design elements, making the assemblage and fabrication processes of physical product components clearer (Knight and Stiny, 2015).

Shape grammars can be thought of as an algorithmic process that consists of a series of geometric transformations that follow known rules. Exploring design alternatives with simple methods using just pencils and traditional tools is limited and restrained by the designer's imagination. Thus, the use of computational design should be generalized.

II.5 Usefulness of innovative tools in architectural design

The functionalities offered by evolutionary design software allow assessing the design form's performance using simulation plug-ins and tools. Accordingly, the behaviour of the future building is verified in relation to various architectural design constraints, before the building is constructed, which allows for time and energy savings (Prabhakaran, Mahamadu and Mahdjoubi, 2022). Thus, the evaluation process is carried out in the early stages of the architectural design process. This ensures a better adaptation of the architectural form to its context by improving its performance. In advanced software, such as: Rhinoceros, a modelling and simulation process is performed simultaneously, which speeds up the process.

"Architecture is the mirror of a country's civilization," and Algeria is currently suffering from a real crisis of architectural identity. Using innovative architectural design tools helps to improve the quality of architectural production and adapt buildings to their context, especially climate factors. However, these tools remain unknown in Algeria. Furthermore, innovative computational design tools help generate and model free-form surfaces using parametric modelling tools to generate more creative forms (Zboinska, 2015).

In fact, innovative design tools are obtained through the enhancement of computational tools. Computational science is the foundation of innovation in architectural design. Thus, traditional computational architectural design tools, such as AutoCAD, are only used in building shape sketching and drawing. They are called user-driven design tools. The second type of computational design tools includes innovative ones that are implemented early in the design process and are known as computer-driven design tools, such as algorithms. (Zboinska, 2015).

Developing tools for the early-design stage requires programming skills. Consequently, they are difficult to develop, such as Cellular Automata (CA), which is perceived as a difficult tool to use due to interpreting the generated configurations and questions of scale, context, and site. The central challenges of using CA-based processes in their context-free nature can be addressed through the development of a design-related epistemology rather than their science-based deterministic origins (Herr and Ford, 2016) (Chang, Moleta and Park, 2016). Many programming software, such as: c++, Python, MATLAB, and Grasshopper, are used to develop algorithms for parametric design. (Farhadi, Taki and Abdanan Mehdizadeh, 2020) have provided computer code (in Fortran) to compute the solar radiation amount received on a given surface with any function using any solar radiation model. The fundamental idea is based on dividing a curved surface into numerous small flat segments. As a result, computational design makes bio-inspired structures and organic forms a reality and allows for evaluation of their performance.

In this study, we focus on visual programming software, which involves similar components to the tools used in architecture modelling software that facilitate the programming task. For this reason, many architects use it. So, it is admitted that architects have to master computer skills in order to enhance architecture and make building shapes more creative, which improves building performance. Moreover, early design stage tools are developed according to the design functional objective that governs shape definition, such as solar exposure, rainwater gathering, or building structure efficacy. (Kuru *et al.,* 2019) have reviewed research studies that treat the envelope, façade, façade components, and façade sub-component, focusing on efficiency, and have distinguished two kinds of design processes based on the targeted objective: multifunctionality or monofunctionality. Instead of treating more than one functional objective value in this study, we are giving the designer more freedom by generating many optimal shapes that allow him to choose the optimal design that fits the other design constraints. Subsequently, the approach generally followed is a parametric design approach in order to keep parameters constant and only change the function-related parameters. In fact, the Oxford Dictionary defines a parameter as "a numerical or other measurable factor forming one of a set that defines a system or sets the conditions of its operation."(Caetano, Santos and Leitão, 2020).

II.6 Hidden support system of Design “Shape grammars”

Regardless of the innovative and computational design tools used, the theoretical support of the design process is the same. In fact, grammars are the rules that structure natural languages. Meanwhile, each field has its own language, which is established using specific vocabulary and following particular composition rules. For instance: music is a universal language composed of notes following specific composition rules for arranging sounds and rhythms. Similarly, design is a formal language and a means of communicating abstract ideas. The design language vocabulary consists of basic geometric shapes that are arranged following several composition rules to give "shape grammars", which is the hidden support system of design. Accordingly, "shape grammars" is a formal language characterising a visual style.

The first to draw inspiration from language grammar and its rules was Stiny (1980b). He developed "shape grammars" as a theoretical design tool to enhance creativity and help generate alternative shapes. (Çağdaş and Sağlamer, 1995). Knight (1999; Stiny (2006) define "shape grammars" as rule-based systems for describing and generating designs. (Knight and Stiny, 2015). Moreover, "shape grammars" are formal description of design processes that systematically produce similar results based on specific rules (e.g., Stiny, 1977; Duarte, 2001) (Eilouti, 2019). According to (Eilouti, 2012, 2017) shape grammars is a progressive and iterative process of design shape generation based on several aspects, such as morphological, numerical ratios, and topological structures. Moreover, "shape grammars" is the intersection of several fields like linguistics, computation, algebra, and mathematics. (Eilouti, 2019). As in several design fields, shape grammars is used in architecture to define the formal language of several styles and tendencies.

In the early 1970s, "shape grammars" methods focused on planar shapes and composition generation in artistic fields (Stiny and Gips, 1972, 1978) (Eilouti, 2019). Additionally, "shape grammars" can be used in the visual arts, abstract construction, and object design production. Froebel's building was the first building analysed to set shape grammars rules for three-dimensional shape design. (Stiny, 1980) (Eilouti, 2019). Thus, "shape grammars" are basically inspired by languages; they have their own lexical (vocabulary) and syntactic (grammars) (Eilouti, 2019). Shape composition is the main architect's means of expression. It is present in several existing architectural styles, tendencies, or paradigms. Each of them is characterized by its particular composition rules and principles, which represent unique "shape grammars" and formal languages. The implementation of "shape grammars" in architecture is revealed in many examples, such as: Palladio is a formal language, characterised by circular building plans and domes.

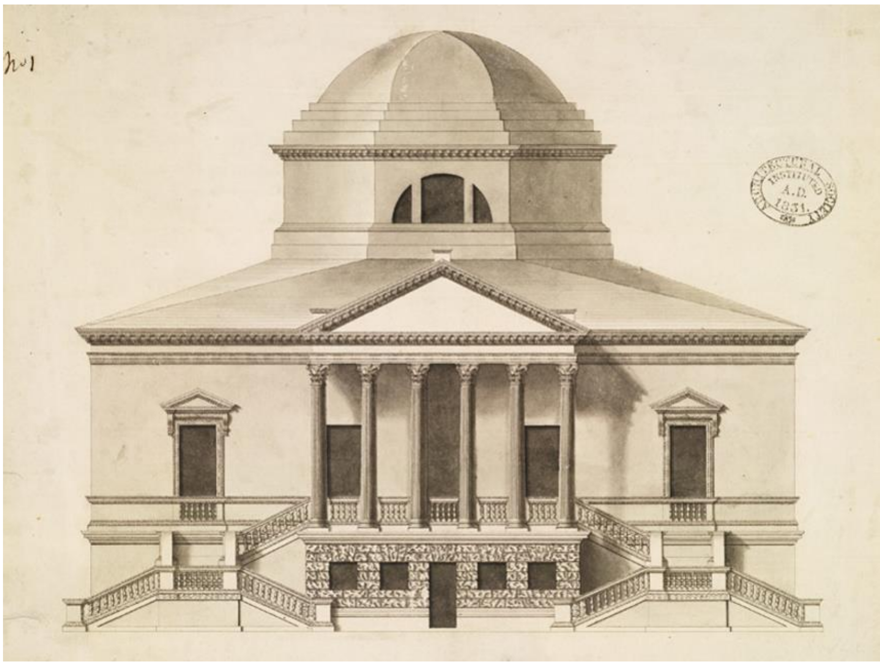


Figure II-11: Architectural Palladian style *(https://www.designcurial.com/news/palladian-design-the-good-the-bad-and-the-unexpected-review-4745749/.)*.

Shape grammars were used not only to come up with new designs, but also to figure out the formal language of buildings that already existed. This reverse approach helps identify the hidden rules of shape composition and syntactical rules behind existing architecture. Shape grammars were used by (Çağdaş and Sağlamer, 1995) to generate the formal language of traditional Turkish houses.

Moreover, using "shape grammars" and establishing the grammars of a given architectural language facilitates the design of new buildings that belong to the same architectural style, as well as the designer's mission. It further gives an alternative vision of creativity and makes the creative process clearer. (Eilouti, 2019) used shape grammar rules in developing an innovative design method that helps architects **analyse buildings' shape and geometry**. The suggested method is based on analysing the formal language of a building façade to outline its geometric composition rules. The latter can be implemented in order to design new buildings. The established method can be applied to contemporary non-rectangular building shapes in formal analysis. Therefore, the process of forming grammars is based on two fundamental operations: composition and its reverse operation, analysis.

II.6.1 “Shape grammars” elements

The main elements of "shape grammars" are: the initial shape, the vocabulary (geometric shapes), the transformation rules and their sequence, and the final design. The effectiveness of "shape grammars" depends upon the compatibility of the selected vocabulary and the transformation rules to achieve the desired design. Thus, original forms can be obtained from "shape grammars.". Stiny (1980) admitted that the elements of shape grammars are: shapes **S**, labels **L**, shaping rules **R** and an initial design **I** (Wortmann and Stouffs, 2018). Shape grammars, in general, rely on schema to explain the intermediate transformation rules as well as the final obtained shape and its geometric features. The initial shape is generally a figure (2D); the transformation rules are then consecutively applied. There exist a variety of geometric entities that can be used in shape grammars as vocabulary. The intermediate configurations that result from the application of a transformation operation are called "sequences." To make describing the transformation process easier, we prefer to call the shapes obtained at the end of each transformation operation intermediate shapes. In fact, the shape transformation operations are computation operations that include rotation, reflection, shift, scale, copy, subtraction, replacement, moving, adding, division, erasing, multiplication, and twisting. (Knight and Stiny, 2015), and other rules at both planar and elevational levels. The isometric or Euclidean transformations act on the position of the shape without changing its dimensions or proportions, whereas the similarity transformation includes the isometric and scaling transformations (Wortmann and Stouffs, 2018). Hence, the transformations are widely constrained by the initial shape configuration (Wortmann and Stouffs, 2018).

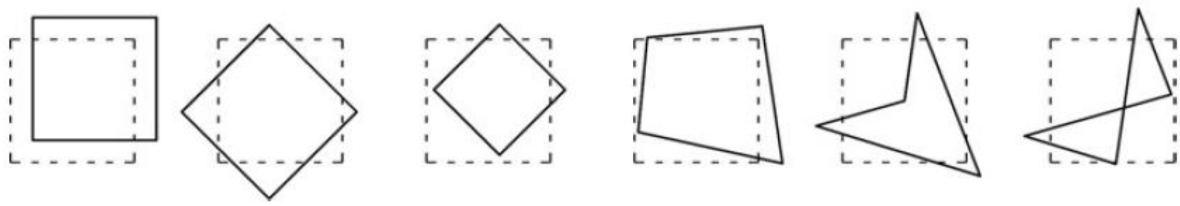


Figure II-12: initial shape and intermediate ones in shape grammars process (Wortmann and Stouffs, 2018).

Additionally, the transformations should be chosen in accordance with the geometric characteristics of the initial shape. This helps explore the possibilities of developing alternative shapes. Furthermore, "shape grammars" elements are defined based on the desired visual aspect of the whole.

Given the fact that some "shape grammars" are developed based on a grid, choosing the appropriate module is of great importance in setting effective "shape grammars". Shape transformation should be made according to the shape's geometric characteristics, such as diagonals in quadrangular-based shapes or diameter in circles (Knight and Stiny, 2015). (Tnpia, 1999) distinguished three stages in the shape grammars process: creation, modification, and further exploration of alternative designs. (Wortmann and Stouffs, 2018) admitted that generally, shape grammars omit the transformation operations that led to the final result. While the vocabulary of the initial shape and the final one can be clearly seen, the embedded transformation operations, their sequence constitute the design algorithm. Furthermore, the more the shapes grammars vocabulary elements are numerous, the more the design algorithm is complex. Subsequently, each visual style is obtained by applying a formal language algorithm. The following example (Tnpia, 1999) showed shape grammars based on the use of an orthogonal grid. This helps maintain shape uniformity and set proportions. Starting from a square shape (/), a set of rule transformations (R) are applied with respect to the initial grid. Thus, the grid is considered the shape support that defines its pattern. The example below explains the process using simple geometric forms that represent entities. Therefore, the process of developing shape grammar starts with identifying the composition support and its module. The initial shape can be chosen with respect to the design support. A series of transformations is performed in order to produce the desired design shape.

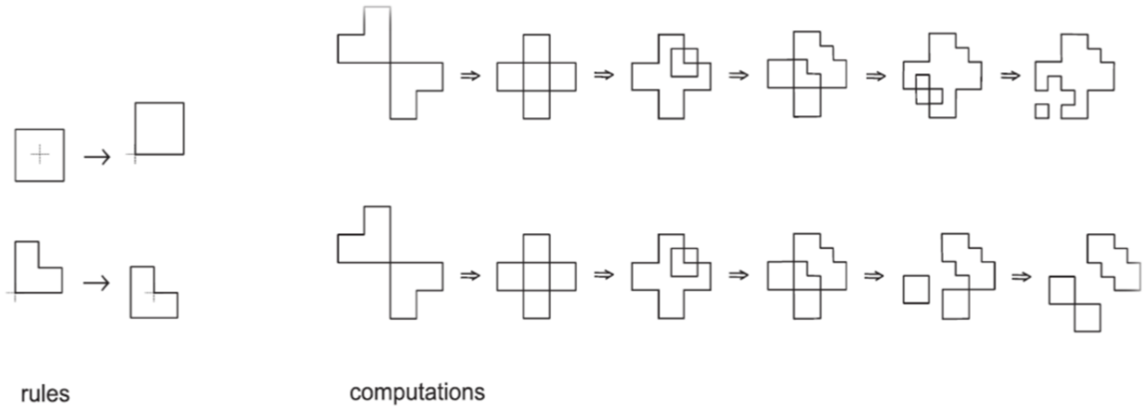


Figure II-13: Two computation process in shape grammar (Knight and Stiny, 2015).

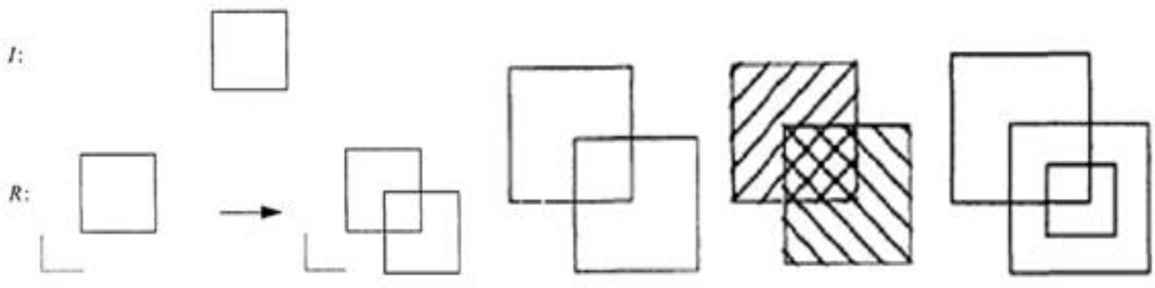


Figure II-14: Simple shape grammar (Tnpia, 1999)

Grammar and syntax form a support system for linguistics. In order to create new complicated designs, shape grammars specify and apply a set of modification rules to an initial object (a shape)(Dino, 2012).

II.7 Computational design approach

Computing is used to solve complex problems in natural sciences and engineering disciplines, specifically to develop mathematical models that describe various phenomena. (Jean-Pierre COUWENBERGH and Mohamed-Anis GALLAS, 2021). This approach is based on computational computation, the origin of the term «Computation». Thus, a computational approach is transdisciplinary. It has rapidly emerged at the intersection of the natural sciences, including computer science and mathematics, as much of the scientific research now includes computer science.

Computational sciences = mathematics + computer science + field of application

The basics of an innovative architectural design approach

The use of computer programming and computational tools to generate new ideas and ways of thinking is known as artificial intelligence. Iterative design, transformation, and modelling operations are conducted based on the resultant design solution. (Shrestha et al., 2021). Artificial intelligence and computer-aided design are both integrated in the new Autodesk product "Fusion 360." The design solution is generated by the simple fact of introducing inputs (parameters). The generation of solutions is based on structural and economic effectiveness (Shrestha et al., 2021).

According to (Daniluk, 2012) computational science generally unifies three distinct elements:

(i) Related disciplines or sciences.

(ii) Software, designed to solve problems in the natural sciences, social sciences, engineering, and medicine.

(iii) Functionality: modelling, algorithms and simulations.

"Digital morphing" is an architectural design tool aids in the creation of a computationally programmed and mathematically modelled architecture whose forms are generated through the calculation and application of algorithms.

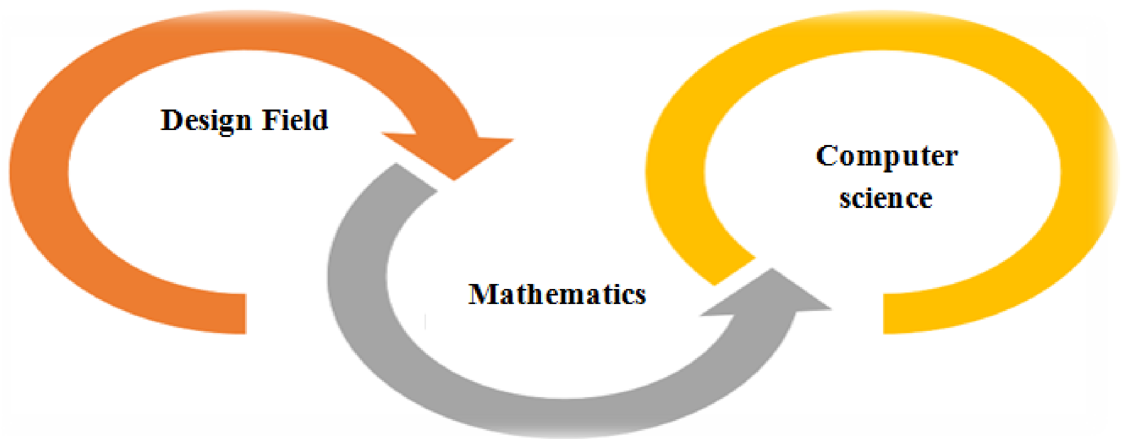


Figure II-15: Computational design process interactions (Author, 2022).

II.8 The combination of Shape grammars and computational design approach

In fact, the evolution and progress of science are based on the previously demonstrated facts. In some domains, such as architectural design, the logic is maintained while traditional tools are replaced with innovative ones, resulting in an innovative approach. The design result depends greatly on the embedded tools and the possibility of exploring and testing the effectiveness of the suggested solution. These are the main advantages of using computation to shape grammar. In fact, creative design approaches are numerous, and the implementation of innovative computational design tools gives different results. In this section, the different creative approaches that are combined with computation and that are related to the objectives of the study are addressed.

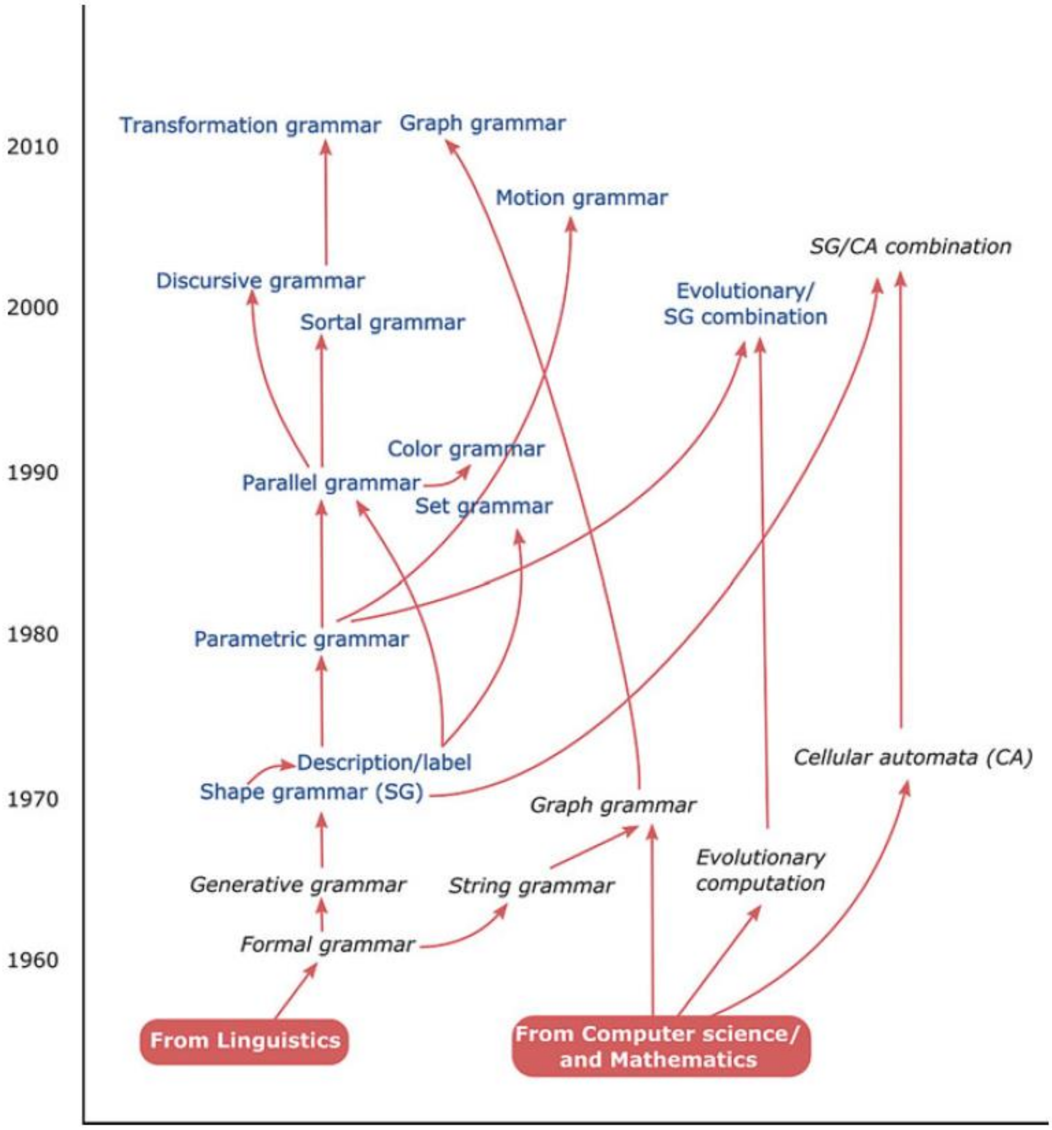


Figure II-16: Shape grammars evolution (Gu and Behbahani, 2018).

II.9 Innovative design approaches in architectural design

Art and design basically rely on shapes, materials, and colour composition. Although "shape grammars" support all formal composition approaches, each approach has its specificities. Thus, our objective is to explain the relationship between shape grammars as the basis of the **design thinking process** and innovative computational design approaches such as:

II.9.1 **Algorithmic-based design**

It involves all of the design approaches. In fact, algorithm-based design is a design logic that results in particular step sequences. Algorithmic-based design is the application of successive rules to an initial design to get the final one (Dino, 2012). The design inputs are defined according to the desired output result, and they are specific for each algorithm (Dino, 2012). Algorithms enhance creativity and boost imagination. Burry suggests two motivations for scripting in design: increasing productivity to iterate faster, and gaining control of design to liberate oneself from the limitations of black-box modelling software (Burry, 2011) (Dino, 2012).

II.9.1.1 Stages

In the present section, we explain the logic of the algorithmic design process, which is behind all computational and traditional design processes. The different phases of this process are explained below.

Phase 01: Reflection and brainstorming new ideas

Understanding the phenomenon under study and thoroughly analysing its functional aspects is critical. The designer should have knowledge of the design field.

Phase 02: Simplification and abstraction of functional mechanisms

The knowledge acquired in the previous phase allows a better abstraction of the studied phenomenon and the identification of variables and constants. Hence, it’s a geometric abstraction. The adaptation of a building shape is usually judged based on its functional aspects.

Phase 03: Mathematical modelling

Mathematical language is used to define a mathematical model of a given system or phenomenon. The process of developing a mathematical model is called "mathematical modelling" One of the most well-known and widely used computational methods is parametric modelling, which finds its origins in mathematics using parametric equations. The latter are a series of equations expressing a series of quantities as explicit functions of a number of independent variables, called parameters (exploratory approach).

$X = r\,f(t)$

$Y = r\,g(t)$

X and y = the series of quantities (the performance)

R and t = variables (Jean-Pierre COUWENBERGH and Mohamed-Anis GALLAS, 2021)

Mathematical models come in several forms, including differential equations, dynamic systems, and statistical models. These and other models can overlap, with a given model involving a variety of abstract structures.

Phase 04 Coding: The graphic algorithm development process is often driven by the coding of the mathematical model. This operation allows transcribing the mathematical model into a geometric model by developing an algorithm.

The software's graphical interface offers multiple tools' palettes (components) organized according to their function and nature. The transcription of mathematical models is performed by establishing logical connections between the appropriate components. The parametric modeller consists of two models: the "explicit model," which represents the geometric model, and the "symbolic abstract model," accompanied by an algorithm, while the abstract model allows manipulating the geometric one.

Phase 05: Simulation and selection of optimal solutions

Besides computational simulation's usefulness in exploring undesirable or inaccessible situations, it also permits exploring a wide variety of scenarios, consequently saving money and time. In experimentation and technical design, computational simulation allows a large number of operations to be tested and evaluated much faster, more inexpensively, and safely than traditional experimental and prototyping methods. (Daniluk, 2012).

II.9.1.2 Example: genetic algorithm

Generating Instances through parameters combinations

Optimization is performed in mathematical modelling to select the optimal solutions. It is implemented and applied in visual programming software via evolutionary algorithms that are particularly effective in solving multi-objective problems. The evolutionary process consists in selecting the best solutions based on Darwin's natural selection principles. The principles of genetic algorithms are cited below (Jean-Pierre COUWENBERGH and Mohamed-Anis GALLAS, 2021).

Initial population: It is made up of individuals (solutions), each with their own unique characteristics.

Function of performance: It is a function of evaluating individuals (objective design), also called fitness.

Crossing: consists in crossing the parameters (genes) to enrich the population with individuals of better fitness.

Selection: applied over generations to select the best individuals based on their fitness.

Mutation: By respecting a mutation factor, the peculiarities of each individual are randomly altered.

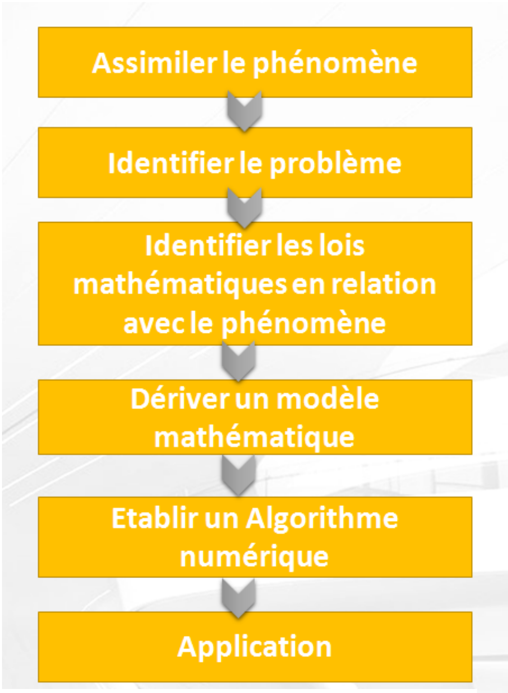


Figure II-17: Genetic alghorithm process
(Author, 2022).

II.9.2 Generative approach in architectural design

Generative design is based on iteration using artificial intelligence (Shrestha *et al.,* 2021). Design refers to both the process of creating an abstract composition, such as in painting, and the operation of making a finished product. However, generative design is particularly embedded in the creation process and aims to transform the design idea into a 3-D object(Dino, 2012). (di Filippo *et al.,* 2021) defined the generative approach as the "ability to produce or create something." In his suggested definition of generative design (di Filippo *et al.,* 2021) reduce the generative design concept to automation by one or a compilation of software tools, but it is still a human-computer interaction process. Precisely, generative design is an automated process controlled by humans. We define generative design as the creation of an abstract or concrete entity based on predefined conditions, context, and constraints. It can be automated or not. However, the computer has more generative ability than the human brain.

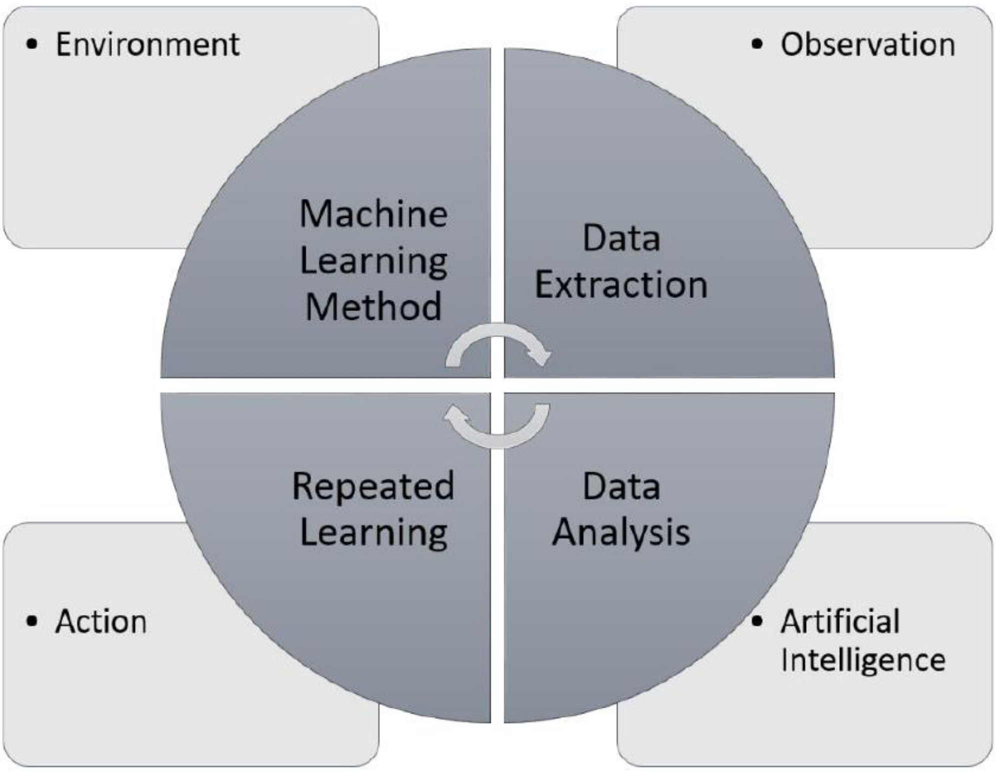


Figure II-18: Operations of artificial intelligence *(Shrestha* et al.*, 2021)*.

Parametric modelling allows the designer to develop a set of geometric models known as "instances" instead of just one, called, by manipulating the links of an associative geometry (Jean-Pierre COUWENBERGH and Mohamed-Anis GALLAS, 2021). The parameters could have different aspects: contextual, functional, or conceptual. The limited modelling environment in traditional software thus becomes an interactive environment for more creative design. A parametric approach is generally accompanied by generative mechanisms (depending on the functional objective of the process) in the simulation phase, when the performances of "instances" are assessed in order to determine the optimal ones. Simulation allows the testing of several combinations of parameters. Therefore, shape grammar can enhance the design-generating potential of basic shapes. Computation is the appropriate tool for alternative designs generation.

1.1.1.1 Elements of generative design process

According to (Dino, 2012), generative design process elements are mainly the initial design context, including (input), transformation rules and mechanisms applied to the first initial design, output generation, and finally optimal design solution selection (Dino, 2012). The advantages of generative design are multiple and apply to several design fields. Despite the fact that the generative design process is constrained by initial design limits and conditions, it produces an infinite number of design solutions that are clearly based on available computer capacity. It also aids the designer's brainstorming by providing atypic creative solutions and contributes to the evolution of expression modes (Agkathidis, 2015). Moreover, it is addressed in academic teaching and research and used in industrial production processes. It actually upgrades the manufacturing process and helps make advanced and high-tech designs (Shrestha et al., 2021).

II.9.3 Shape grammars in parametric design approach

Parametric design is a design process based on transformation operations that only involve the variation of a limited number of design parameters. In fact, parameters represent specific measures or dimensions of the design shape elements. Parametric design approach allows verifying the effects of the variation in the geometric configuration of a part on the whole building's behavior. Furthermore, introducing parameters to the shape grammar process makes it more effective and gives birth to creative design shapes. Accordingly, shape grammars include both parametric and non-parametric design approaches. Contrary to popular belief,(Eilouti, 2019) admitted that shape grammars can be generalized to parametric shape grammars by implementing transformation operations using a set of associated parameters (Knight and Stiny, 2015). Mostly, shape grammars are considered parametric, while the transformation rules in shape grammars are generally not parametric (Wortmann and Stouffs, 2018).

The architect Adams Kara Taylor defined the final roof form of the British Petrol Headquarters based on the generation of a set of variants obtained through parametric design implementation. Parametric design facilitates using computational design tools due to the visual interface and gives synchronised information about shape configuration when programming. Parametric design is a method that frees the designer from traditional formal language rather than a style that generates complex design configuration. (dino, 2012).

The parametric design approach allows testing different combinations of performance metrics through optimization. In performative parametric design, the parametric combinations encourage the divergence of the design space, and the convergence occurs on the basis of performative optimality. Critical concerns for a performance-integrated design process include multidisciplinary thinking. (Dino, 2012).

Parametricism, a recently evolving method of architectural expression Parametricism refers to parametric design as a rebellious architectural creation against modernism(Dino, 2012). Altering and adjusting parameters by adjusting the parameters and their interactions, the PD model of a design enables the production of several design possibilities (Agkathidis, 2015).

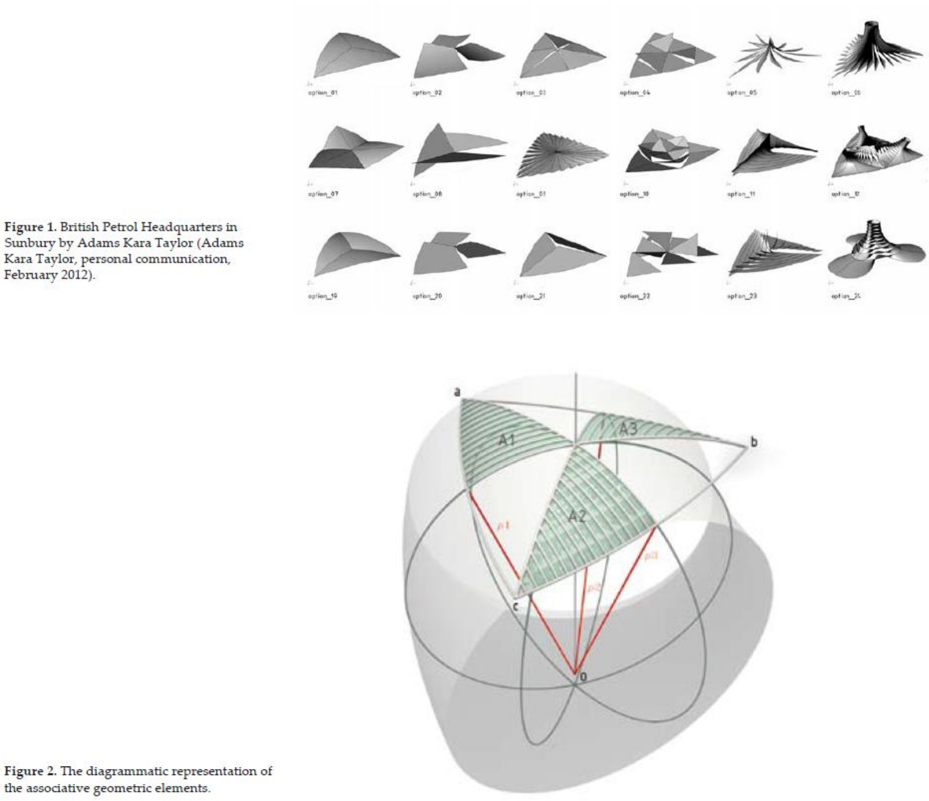


Figure II-19: parametrization of the roof form (Dino, 2012).

II.9.4 Shape grammars in bio-inspired design approach

There are primarily two similarities between shape grammars and the bio-inspired design approach. The first one is about using language or being inspired by its structure to brainstorm new ideas and make connections between the design elements. The second one concerns a crucial phase of the bio-inspired design process, which is abstraction. It relies on deriving the formal language of the design inspiration source and then transcribing it into a 2D or 3D composition.

II.10 Relationship between Parametric design tools

There is a confusion between the several available computational design tools and approaches. It is difficult to distinguish between and relate several commonly used terms and their meanings. In fact, understanding the distinction between design thinking, design methods, and design tools is critical to comprehending the meaning of each of the aforementioned approaches. In fact, the common point between all the approaches is that they are algorithmic-based design processes. Thus, algorithmic-based design includes all the other approaches, even shape grammar theory. Accordingly, shape grammar theory is also a global theory that includes all design approaches, but it concerns the specific configuration and characteristics of the embedded shapes and the final design result. Based on the previously explored studies, in shape grammar theory the term "computation" also designates the transformation operations. Artificial intelligence is the more appropriate term to talk about computer use.

Given that all these approaches involve generating design, they are generative. Others researchers consider generative design to be a design approach based on algorithmic or rule-based processes that generate multiple and potentially complex solutions [24] (di Filippo *et al.,* 2021). However, the computer-generated process is more effective than the human one. These conclusions are in line with previous research conclusions that presume that parametric design is a generative and algorithm-based design process (Dino, 2012). The specificity of parametric approach is that it permits parameter-based control (Dino, 2012). Coding is a way to handle the design logic instead of the design object (Leach, 2009). (Dino, 2012). According to Agkathidis, (2015) parametric design is an evolutionary form of architectural design.

To adapt the thinking concept to the technological evolution and progress in computation, (Agkathidis, 2015) suggested a new design concept, Evolving Design Thinking (EDT), which is considered the enhanced version of traditional design thinking (TDT), which is commonly treated as "Design Thinking".

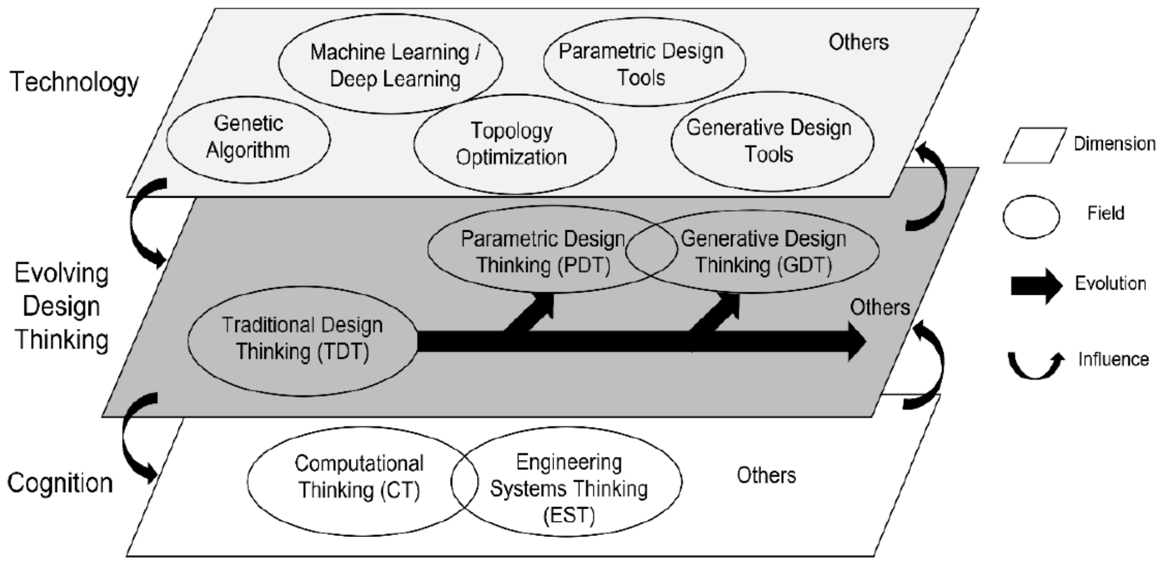


Figure II-20: Evolving design thinking model (Agkathidis, 2015)

Parametric design, a subset of algorithmic design, is totally based on an algorithmic paradigm. From a computational standpoint, algorithmic and parametric approaches are comparable as algorithms by definition deal with parameters and because the algorithm is the core component of a parametric system. Contrary to algorithmic design, parametric systems rely on the manipulation of the numerical values of parameters to transform the design output. This fundamental distinction between a purely algorithmic and parametric design is only apparent throughout the design process, when the designer changes the parameter values to vary the design geometry in search of the ideal design solution. (Dino, 2012). While parametric approach is usually algorithmic, algorithmic is not always parametric. Algorithm-driven design is now considered as generative design. Innovative design tools such as morphology optimization and machine learning-based design are influencing design field approaches (Wu, Qian and Wang, 2019). Computational design enhances algorithm-based design efficiency and the expand the range of possible solutions. Each approach has its own logic, so each has its own algorithm, design line, path, and thinking.

II.11 Conclusion

The logic of each design approach differs due to differences in tools and methods, but they all rely on algorithmic thinking. Shape grammar relies on simple geometric elements composed by following simple transformation rules. "Less is more" is again verified through investigating shape grammar theory, since complex design algorithms result from the application of simple transformation rules.

In the field of architectural design, the rise of computational design tools in general and visual programming in particular is a turning point. This calls into question the linearity of the architectural design process and both the architect's and the software roles. In fact, the roles of the designer and the machine overlap (thinking patterns and tools go hand in hand). Visual programming automates the architectural design process and helps explore a wide range of possible solutions in the early stages, inspiring the designer’s creativity. The use of genetic algorithms allows the building's shape to be tailored to its natural surroundings. It ensures the permanent interaction of the building with climatic factors. Although it is a digital tool, its performance depends on understanding the studied phenomenon.

CHAPTER III.BUILDING SOLAR MORPHING STRATEGIES

Chapter III Building solar morphing strategies

III.1 Introduction

The successive fuel crises that have swept the world show that renewable energy exploitation should be taken more seriously. Architects and building planners are attempting to minimize buildings' energy use and improve their performance in order to mitigate the consequences of climate change. The use of solar as an alternative energy source is one of the best practises that leads towards sustainability in several domains, especially the building and construction sector. The consideration of solar energy in architectural design takes many forms. This can be accomplished through the employment of active devices or passive design measures, which are preferred, especially in the early stages of designing future buildings.

Among the most important passive solar design procedures is the regulation of solar radiation falling on the external faces of the building envelope via the manipulation of its geometry. In fact, the building envelope is in perpetual interaction with the external environment. High building efficiency lies in the building envelope's capacity to manage climatic factors and provide comfortable interior conditions. Consequently, the building's efficiency is assessed by adopting a set of various types of variables that are categorized based on different criteria.

This chapter focuses on building envelope solar morphing strategies (BSM) and examines the embedded design elements. Initially, major stages of developing passive solar strategies are presented based on building envelope entities (BEE). The study is then focused on the first solar design stage, BSM, and the corresponding variables that are classified into categories to help the designer choose the suitable BSM parameter combinations by giving many examples from the existing literature.

III.2 Passive solar design strategies (Previous reviews)

Passive solar design strategies include all free-energy design procedures that aim at enhancing the building envelope's ability to regulate solar exposure and solar gain. This design approach improves the building's energy efficiency and helps achieve eco-friendly architecture. Passive solar design strategies are mostly early-design stage tools and methods that facilitate making design decisions and designing high-performance building envelopes (Zhao and Du, 2020)(Ascione *et al.,* 2019). The building envelope design should be carefully designed since an average of 75% of the heat loss and gain result from its interactions (Aydin and Mihlayanlar, 2020) (Zhao and Du, 2020). Chen et al. showed that considerable energy savings, about 50% can be achieved through envelope design optimization (Ascione *et al.,* 2019).

The aim of literature review articles is not limited to the simple gathering of research data. It also provides a fresh perspective on the research topic under consideration. The researcher's perspectives on solar design strategies differ depending on their background experiences and interests. Firstly, the examination of the review studies is conducted based on the criteria they adopted to review specific solar design strategies, process stages, and methods. Our review study relies on the exploration of the available literature, including: published papers, especially in prestigious journals, books, and conference papers, as illustrated in the histogram below. Therefore, the selected references are representative and the deduced ideas are relevant.

In fact, the present study is established based on two main critical points in solar design that are highlighted through the exploration of the existing literature review in the field of solar design

III.2.1 The overlapping design stages

Stevanović (2013) reviewed passive solar strategies by categorising them into three groups. The first one treats the building form, while the second and third address the opaque envelope components and the properties of glazing and shading systems, respectively. Moreover, the study outlines the adopted methods used in establishing passive solar strategies, especially the parametric approach, the optimization process, and the needed tools. Consequently, the stages of the solar design process overlap and become difficult to distinguish, particularly for beginners who hope to conduct studies in the solar design field. Moreover, it neglects the importance of the initial design stage as well as the necessity of selecting appropriate parameter combinations in determining the performance of future solar buildings. Other researchers structured their review work on the nature of the building envelope surfaces, distinguishing between opaque and transparent surfaces. Quesada *et al* (2012) published two review papers that dealt with solar facades as passive solar design strategies. The publications focused on "opaque solar facades" and "transparent and translucent solar facades," respectively. The first paper examined research studies that addressed the topic of "opaque solar facades" and the progress achieved in the field during the first decade of this century. Specific strategies based on solar facades' design were presented, such as building-integrated solar thermal system (BIST), building-integrated photovoltaic system (BIPV), building-integrated photovoltaic thermal system (BIPV/T), solar dynamic buffer zone (SDBZ) curtain wall, thermal storage wall, and solar chimney. The study of the above-mentioned strategies is done through an exhaustive explanation of the theoretical and experimental study, the development process, the feasibility study, and examples of the application for each strategy. The results show that thermal storage wall strategies are the most developed and allow for a decrease in heating load of 40–50%. The second paper treated the techno-economic feasibility of four categories of transparent and translucent solar facade systems during the first decade of the 21^{st} century. mechanically ventilated facade (MVF), semi-transparent building-integrated photovoltaic system (STBIPV), semi-transparent building-integrated photovoltaic–thermal system (STBIPV/T), and naturally ventilated facade (NVF). For most of them, the performance is either extrapolated, deducted, or calculated from numerical predictions or measurements (Quesada *et al.*, 2012). Therefore, the previous review studies were structured with respect to specific criteria, such as the building envelope components. Subsequently, we started our paper by suggesting a classification of passive solar strategies based on the envelope's entities.

III.2.2 Building envelope entities

The building envelope is a barrier that moderates climatic conditions and provides a comfortable indoor living environment (Ralegaonkar and Gupta, 2010). In each of the architectural stages of solar design, specific building envelope components and their associated roles are treated. A well-thought-out envelope shape allows for managing the total received solar radiation according to the climate type. The envelope materials are then chosen based on their behaviour with regard to solar energy and the desired amounts of its reflected, transmitted, and absorbed components. Moreover, good energy control helps balance indoor comfort requirements such as lighting, thermal conditions, and visual comfort (Li *et al.,* 2021). Accordingly, three building envelope entities (BEE) are distinguished: physical form, materials, and the resulting indoor ambiance (Fig. III-1).

The design of the building envelope is performed in stages, acting on diverse variables to set solar strategies. The first architectural design stage consists in defining the shape of the building envelope (transparent and opaque surfaces) based on the desired performance (Rodrigues *et al.,* 2015). The solar potential of the building envelope is a function of its exposure, which is regulated through the manipulation of geometric control parameters. This process is called building envelope solar morphing (BSM) and involves the building envelope's geometric aspects. Consequently, each of the design stages should be evaluated based on its proper variables (Kheiri, 2018). Indeed, the difference between the design stages is the certainty of the decisions, as the design process evolves, the building envelope features are definitely determined. Consequently, each of the design stages should be evaluated based on its proper variables (Kheiri, 2018).

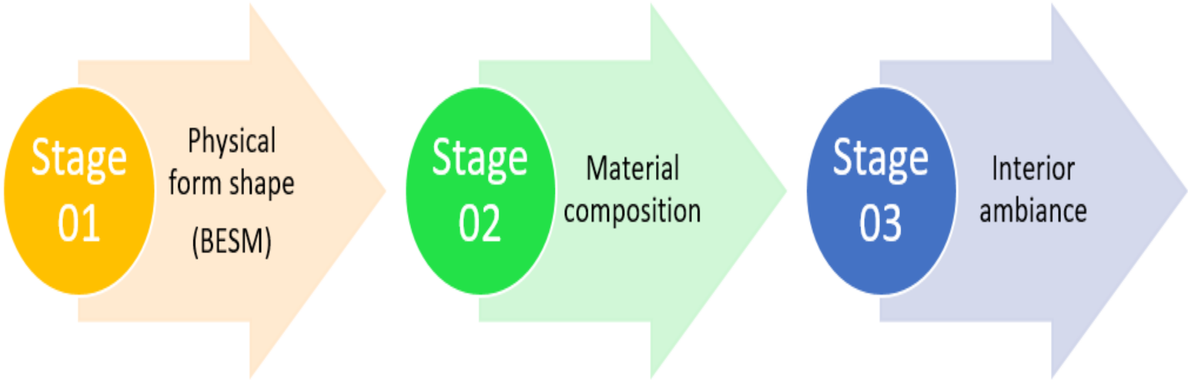


Figure III-1: Solar design stages and building envelope entities BEE (Author, 2022).

The examination of the existing literature showed that the conflicting visions of architectural solar design are related to the perception of the main design element, which is the building envelope's BEE, the related strategy categorization, and the embedded parameters and indicators. Hence, the development of solar design strategies is based on the identified BEE. Kolokotsa *et al* (2012) reviewed all solar strategy categories, which are related to different building envelope entities, to give a complete idea of existing strategies of architectural solar design. Ralegaonkar and Gupta (2010) admitted that BSM strategies should be set regarding lighting, cooling, and heating. while the second BEE should be designed based on thermal and acoustic considerations. while other research teams focused on only one BEE strategy. In this chapter, the main stages of building solar morphing (BSM) strategies are presented.

III.3 Building envelope solar morphing strategies

The term "morphing" indicates the process of manipulating and deforming a given form. In the design process, morphing is the first act performed to produce a given shape. It is generally applied in the early design stages to adapt the building envelope shape to the design functional objectives. Thus, building envelope solar morphing (BSM) is the process of creating or modifying a given building envelope shape based on solar data. It is basically performed according to solar geodesic coordinates to take advantage of its energy. In other words, the BSM process aims at regulating the building envelope's solar exposure through the geometric manipulation of its envelope. The process is done by acting on a set of geometric parameters and indices to define the appropriate dimensions and configuration of the building envelope components based on solar radiation data.

Ralegaonkar and Gupta (2010) presented a review paper on solar design strategies that are particularly developed and involve the following parameters: geographic location and climatic conditions, building shape and orientation, selection of construction materials, building openings (viz. windows), selection of suitable sunshades, etc. The design objectives were limited to the total indoor cooling and heating load. The study results reveal that the most impactful parameters in the solar design process are geometric parameters such as orientation and aspect ratio.

Kheiri (2018) examined the building envelope design methods that rely on the manipulation of geometry-based parameters to evaluate their effectiveness in enhancing the building envelope's energy performance. The results showed that BSM-related parameters, for instance, the length, area, volume, number of floors, and shading systems, significantly contributed to the building's energy performance improvement. Meanwhile, Rodrigues *et al* (2015) recognised that geometry-based parameters are not effective. However, many BSM strategies showed their effectiveness in several climate types. We strongly believe that the question does not need to be addressed because it is dependent on design concerns and priorities. Thus, BSM variables are differently classified by researchers.

In fact, architects need task-oriented design tools (Rodrigues, Gaspar and Gomes, 2014) (Rodrigues, Gaspar and Gomes, 2014) in the several design stages to deal with the different building envelope entities. In fact, this study is focused on the first stage of solar design, which is the BSM process, and the corresponding variables that are classified into categories to help the designer choose the suitable BSM parameter combinations, addressed through the exploration of the existing literature. BSM strategies represent the key to a successful solar design. For this reason, parameters and factors embedded in the BSM process are discussed in the next section to help designers define the most appropriate combination.

BSM strategies are the key to a successful solar design. In fact, architects need task-oriented design tools. In fact, architects need task-oriented design tools (Rodrigues, Gaspar and Gomes, 2014) in several design stages to deal with the different building envelope entities. In fact, numerous details can be addressed at each stage of the solar design process. Thus, the solar design strategies that deal with the manipulation of the building envelope shape are categorized under the BSM process, which is discussed in this chapter.

Indeed, the building envelope shape determines the first reaction of the building to available solar energy. It defines solar exposure time durations and periods, moderates the received energy intensity, and controls the transmitted amount. For these reasons, the building envelope's shape modelling and manipulation during the early design stage help define its solar potential and the resulting indoor temperature and comfort conditions. Consequently, the suggested categorization in this chapter is based on the distinction between the building envelope entities, which include the physical shape, the envelope material composition, and the ambiance factors of the indoor space.

Therefore, each of the building envelope parts and components is responsible for its solar behaviour. Their effectiveness in solar design is tested by manipulating a set of parameters. Accordingly, in this chapter, we particularly focus on the BSM strategies that are based on the manipulation of the first BEE geometric parameters that govern the building envelope solar exposure and the evolution of the BSM process. The geometric features of the building envelope and its elements are outlined in order to help the designer choose the most appropriate ones.

III.4 Building envelope solar morphing variables

The implementation of the geometric parameters and indices in the assessment of the building envelope's energy performance allows the identification of the relationship between them under specific climate conditions (Rodrigues et al., 2015). The geometric manipulation of the building envelope is performed by combining multiple parameter values and evaluating the outcomes of their interactions. In fact, several classifications of the BSM variables have been established. Mirrahimi et al (2016) considered the building envelope as a dual-system entity, composed of an opaque system that includes walls, roofs, floors, and insulation. The transparent one includes all of the following: windows, skylights, and glass doors. This categorization separates the components that should belong to the same BEE, such as: insulation, which can be included within materials. Kheiri (2018) divided BSM variables into two classes: discrete and continuous variables. The building envelope dimensions and volume are considered continuous variables. However, the number of floors, and shading systems are discrete variables. The criteria for this classification are not clear. Moreover Kheiri (2018) admitted that some continuous parameters can be considered discrete in specific cases, which makes the differentiation between the two groups ambiguous. Meanwhile, Lin et al (2016) suggested a solar design strategy using the Office Building Envelope Energy Performance and Configuration Model (OBEM), which integrates two types of parameters: endogenous and exogenous variables. Rodrigues et al (2015) showed that geometry-based parameters have an influence only on certain buildings' thermal performance, and highly impact the resulting solar design.

In this chapter, we suggest two groups of variables based on a review of the literature on BSM strategies. The first varies according to geo-scale, studied location, and surrounding built environment configuration. The second is concerned with architectural scale and related details.

III.4.1 Contextual environmental factors of building solar morphing

BSM factors represent the environmental factors that impact the amount of available solar radiation falling on the building envelope. They vary as a function of geo-location, which defines the climate type. BSM factors are classified into two categories: natural factors, which mainly include: latitude, daytime duration, solar radiation intensity (Blanco *et al.*, 2019) (Wang and Lu, 2020), and the intensity of the hourly incident solar radiation on a given surface(Ralegaonkar and Gupta, 2010). They are beyond the control of the designer and must be taken with their known values (Oral, Yener and Bayazit, 2004). They are beyond the control of the designer and must be taken with their known values (Oral et al., 2004). Moreover, climate conditions significantly impact cooling energy consumption and lighting energy needs (Delgarm *et al.*, 2016).

The second category involves physical factors that characterise the building location and its surrounding physical environment configuration, like: naturel reliefs, vegetation, buildings, and several urban elements. The surrounding surfaces and the ground materials are also included when addressing the second BEE (materials)(Oral, Yener and Bayazit, 2004). These factors play a significant role in determining the building's solar potential. They predicted the laws and regulations that govern architectural design and urban planning. For instance, in the 20th century, urban geometry was defined based on a minimum solar exposure duration of two hours (Qian B, 1995) (Ralegaonkar and Gupta, 2010).

III.4.2 Building solar morphing parameters

In BSM strategies, the building envelope geometry is manipulated in order to generate a responsive building envelope shape that helps meet the design objectives. Contrary to factors, parameters can be changed during the morphing process. Different groups of parameters are defined according to the BSM process's aim and objectives. The BSM parameters are continuous parameters that describe the geometric features and the layout of the building envelope components, such as the shape, size, area, and measurements.

III.5 Main parameters in the building solar morphing process

The exploration of the existing literature on BSM strategies reveals that effective parameter combinations are achieved based on two main parameters: the orientation and tilt angle of the building envelope faces. The BSM main parameters should be initially defined based on their optimal values in order to ensure the effectiveness of secondary ones. Numerous BMS strategies (Hosseini *et al.*, 2019), (Yadav and Chandel, 2013) depend on the variation of building faces' tilt angle and orientation. The manipulation of BMS main parameters aims at establishing a geometric relationship with solar coordinates at given moments, durations, or periods of the year.

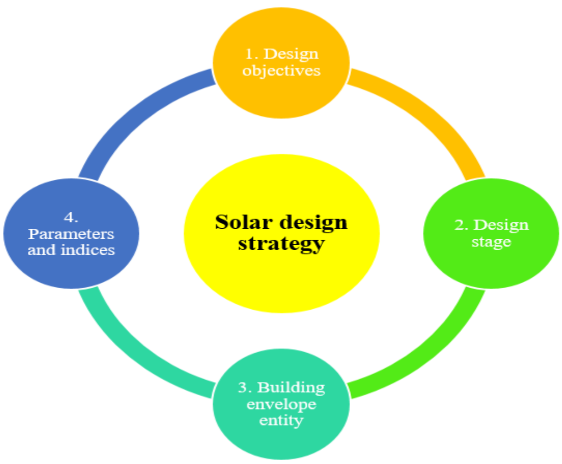


Figure III-2: Solar design strategy's elements (Author, 2022)

III.5.1 Building envelope orientation and tilt angle:

Within the context of environmental sustainability, the effectiveness of the building envelope shape is affected by its orientation(Hosseini *et al.*, 2019) (Blanco *et al.*, 2019). It is the first parameter to be considered in establishing BSM strategies to regulate the building envelope's solar exposure and control solar gain. The building orientation geometrically represents the angle compromised between the north orientation and the normal to the building façade, ranging between 0° and 360° (Ralegaonkar and Gupta, 2010). In BSM strategies, the optimal orientation of the building is initially verified and then fixed. Each of the building envelopes has its own optimal orientation. Therefore, irregular building envelope shapes are characterised by several orientations compared to regular ones (Fig. III-4).

The optimal orientation is not constant; it changes according to the geo-location of the studied site. A south-facing orientation in the northern hemisphere allows to enhance solar heat gain in winter and reduce it during summer (Ralegaonkar and Gupta, 2010). For quadrangular building shapes, it is generally recommended to set east-west axis elongated shapes (Kolokotsa *et al.*, 2012). However, north orientation is considered as the most suitable for residential buildings in southern hemisphere like in Malaysia (AL-Tamimi, 2011) (Mirrahimi, Farid and Chin, 2016). Therefore, setting an optimal orientation helps improve energy and thermal comfort performance while taking advantage of available solar radiation throughout the year. It is easier to set a trade-off between thermal and daylighting for the south, east, and west orientations than for the northern one (Futrell, Ozelkan and Brentrup, 2015). Furthermore, the building orientation influences the zoning of interior spaces based on their heating and lighting energy requirements. Living spaces are mostly located in a way to face the sun (Kolokotsa *et al.*, 2012).

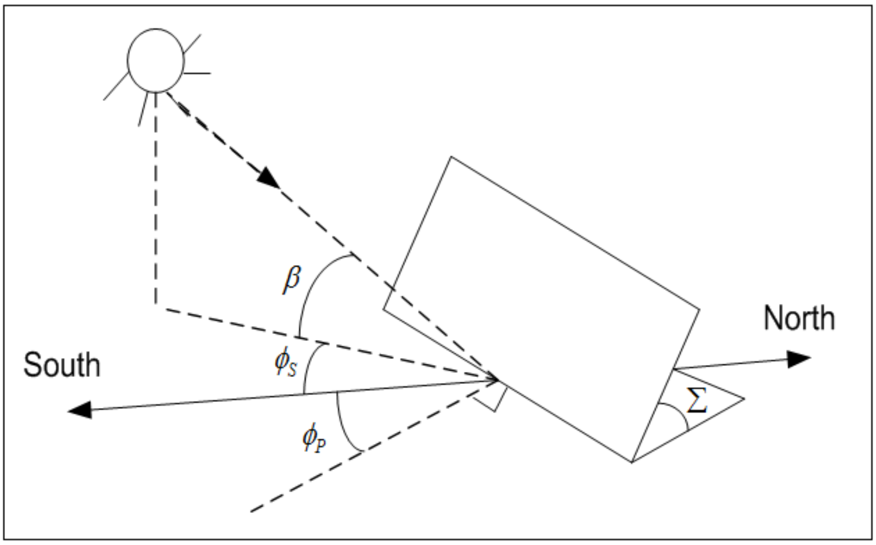


Figure III-3: the geometric relationship between tilt angle and the angle of orientation (Irwanto, 2015).

III.6 Secondary parameters in the building solar morphing process

The building envelope is composed of different parts that are exposed to solar radiation, such as: walls, windows, glazing surfaces, the roof, facades' panels or screens, and shading systems. These components are characterized by specific geometric features that generally include measures and ratios. Ratios represent the proportion between two measures to describe the building envelope shape. While measurements separately give the dimensions of the building envelope's components. The most adopted secondary parameters are addressed in the following sub-sections.

III.6.1 Building envelope walls, surfaces or faces

represent the main components of the building envelope that receive solar energy. Under the solar radiation effect, the surface temperature of the walls rises due to energy accumulation that enhances the indoor comfort conditions (Chenvidyakarn, 2007). The geometric features of the building envelope's walls are mainly the length, the height, the orientation, and the tilt angle. They are constructed of walls and openings that include opaque and transparent surfaces. Their number varies according to the functional and energy requirements of indoor spaces Azmi and Ibrahim (2020). Okeil (2010) demonstrated that, morphing the profiles of conventional rectangular blocks enhances the received solar energy amount on their façades and reduces it on the roof during winter. Furthermore, the building's wing configuration (L, U, H, and T) determines its solar potential and ability to generate electricity according to the wings' shadow and light zones projected on the building envelope (Hachem, Athienitis and Fazio, 2011). Irregular building envelope shapes are characterised by a high number of faces that have different geometric features (Fig. III. 4). Contrary to regular ones, which are generally composed of four vertical facades, other studies dealt with curved building shapes and solar morphing. Adamski (2007) conducted optimisation study of the southern part of a cylindrical building. Moreover, specific walls are designed to enhance solar direct gain, such as the solar wall and Trombe wall. (Kolokotsa *et al.*, 2012).

Figure III-4: Regular and irregular building envelope shapes. (www.lombardodier.com, 2022.) (s3.amazonaws.com, 2022.)

III.6.2 Windows characteristics

Windows are important building envelope components that impact its solar potential and, consequently, its energy efficiency. The window is primarily responsible for the direct gain management of the building (Ralegaonkar and Gupta, 2010). For this reason, specific glazing systems, such as sunspaces, are installed to maximise solar radiation interception surfaces and direct gain (Ralegaonkar and Gupta, 2010). About 15–30% of the received solar energy is transmitted into the indoor living space. Moreover, the sunspace offers a spatial extension for the building's internal spaces with ameliorated thermal comfort conditions compared with the external ones (Kolokotsa *et al.*, 2012). Meanwhile, the window is considered the most vulnerable part of the building envelope because it significantly affects thermal comfort, particularly in hot climates (Azmi and Ibrahim, 2020). The window is a multi-role component that is mostly transparent, so it ensures visual contact between outdoor and indoor environments. It contributes to providing lighting and thermal comfort by reducing heating and cooling energy needs (Zhao and Du, 2020) (Grynning, Time and Matusiak, 2014). In fact, solar-induced ventilation (Mirrahimi, Farid and Chin, 2016) results from the difference between outdoor and indoor temperatures, which creates a natural air flow and contributes to the natural ventilation and passive cooling of the building (Kolokotsa *et al.*, 2012).

Effective window design basically depends on its geometric features, which define its roles in managing solar energy intensity and amount. In fact, a window's size has a significant impact on solar gains and influences energy gains and losses (Futrell, Ozelkan and Brentrup, 2015). The window's orientation, placement, and size should be well- thought out. A proper design, adequate placement, and an appropriate number of windows and doors can be the key factors to creating the necessary air flow to enhance thermal comfort (Mirrahimi, Farid and Chin, 2016). These measures allow for the achievement of the solar design targets without using additional building envelope components, such as shading systems (Kolokotsa *et al.*, 2012). Window placement and size contribute to managing both direct and indirect solar gains (Azmi and Ibrahim, 2020). It has been shown that window size does not have a major influence on heating or cooling demand in cold, temperate, or hot climates, respectively, when using adequate glazing type (Rodrigues *et al.*, 2015). Furthermore, highly glazed buildings or the building envelope with double-skin facades, sunspaces, or solar greenhouses are characterised by a glazing system instead of windows. Consequently, the building envelope geometric features change and affect the indoor comfort conditions, with respect to direct and indirect gains (Kolokotsa *et al.*, 2012). Large south-facing glazing on the façade transmits solar energy into the internal space, where it strikes thermal mass materials in the house (Lin *et al.*, 2016). In addition, a large window area indicates a high opening rate of the building envelope and frequently leads to high solar heat gain through windows.

III.6.3 Shading systems

Windows are fitted with shading devices to enhance their performance while protecting the building from overheating, particularly during hot periods of the year. Shading systems are either natural or architectural. Natural reliefs and vegetation are exploited in building façade shading, since trees provide protection to the building facades from about 70–85% of the received solar radiation (Kolokotsa *et al.*, 2012). In fact, the installation of shading systems follows one of two recognised methods. The first one is widely adopted; it consists of suggesting a shading device and manipulating its geometry to assess its effectiveness. The second method is the inverse one, or building self-shading, which involves the effect of the sunlight and shadow area distribution on its energy performance (Krishan, 2020). Dark and light spots on the building envelope result from the manipulation of its geometry. Subsequently, implementing external solar shading strategies aims to govern sunlit and dark areas. In other words, graphical determination of the sunlit area is helpful to set responsive solutions (Ralegaonkar and Gupta, 2010).

Many building envelope elements, such as projecting and recessed parts, set-backs, and eaves, contribute to shading (Filippín *et al.*, 2005). In hot climates, adding whole built-up volumes and exterior spaces, such as arcades, porticos, or shaded balconies, can also ensure building facade shading (Azmi and Ibrahim, 2020). There are many shading devices that can be added to the windows, like: venetian blinds and Californian blinds, which can be manually handled. Blinds are the simplest shading devices; their configuration varies as a function of the window orientation. Numerous research models deal with venetian blinds and screens as moveable envelope components (Kim and Clayton, 2020). Mirrahimi, Farid and Chin (2016) admitted that the use of an external static sunshade is the best strategy for solar radiation control, given the fact that their geometry can be customised with respect to the seasonal sun path. Moreover, Futrell, Ozelkan and Brentrup (2015) implemented specific shading geometry parameters in the BSM process, such as exterior shade length (ESL), light-shelf length (LL), and window width (WW). As a result, while shading elements and techniques are numerous, their application is determined by the study objectives.

III.6.4 Facades Panels and Screens

represent specific shading systems widely treated as solar strategies. They are several and characterised by different forms and functional principles. Facades' screens ensure the required shading from direct solar radiation while permitting the air to penetrate into the indoor living space. Blanco *et al* (2019) examined the effect of changing perforation size on thermal comfort and daylight, testing different perforation rates: 100, 70, 55, 40, 25, and 10%. The results showed that acting on perforation rate, approximately 15% and 48% of energy consumption savings were achieved in cold and hot climates, respectively. Chi, Moreno and Navarro (2017) suggested a perforated shading system based on the variation of the perforation percentage, matrix, and shape. Furthermore, traditional mashrabiya is a traditional perforated façade screen that greatly enhances the building's thermal performance. Ben Bacha & Bourbia (2016) assessed the performance of a dynamic façade shading system with respect to the performance of the same façade without solar protection. The study aims to reduce energy consumption by reducing solar exposure in Biskra, Algeria's hot climate. The simulation results show that the use of the shading system helped reduce both solar exposure and energy consumption by 17.9% and 43%, respectively.

III.6.5 Building roof

The conventional building envelope shape is rectangular or generally quadrangular, which exposes the roof to solar radiation throughout the day. In this case, the roof is considered the main contributor to heat gain. Hence, its shape needs to be well thought out regarding incident solar radiation regulation, which is a major concern in the BSM process, particularly in hot climates (Azmi and Ibrahim, 2020). As a result, tilted and vaulted roofs are commonly used in such climate zones. Numerous roof forms are introduced in BSM, such as: compact cellular roof layouts with reduced exposure to the sun; high roofs; double roofs; vaulted roofs or roofs with domes; ventilated and micro ventilated roofs (Mirrahimi, Farid and Chin, 2016). In Malaysia, flat roofs are not recommended due to heavy rain (Karim,1988) (Mirrahimi, Farid and Chin, 2016). Shading of the roof is an aspect that is barely discussed in the literature; and innovative solutions can be set up to avoid high solar radiation (Azmi and Ibrahim, 2020). The conventional roof form is deformed to further enhance their solar potential. Kämpf and Robinson (2010) maximised annual solar radiation by manipulating roof orientation and tilt angle. Similarly, Lobaccaro, Chatzichristos and Leon (2016) varied the traditional Norwegian house roof shape depending on its size and inclination.

III.6.6 Building geometric ratios, Indices and coefficient

Different indices may be used in the BSM stages to treat several building envelope entities and facilitate design decision-making. Similarly, legislators frequently define BSM indices such as prospect as legal requirements (Rodrigues *et al.*, 2015), There are mainly three types of indices: shape-based, window-based, and hybrid ones. The shape-based indices are centred on the relationship between the exterior surface area of the building envelope and its interior volume. They provide accurate results when applied in regions with cold climates where the preservation of heat in the interior of the building is important. On the other hand, window-based indices focus on the contribution of solar gains through the transparent envelope areas of the building. Finally, the hybrid indices consist of combining several design variables, in addition to those mentioned above, like the site factors, physical properties of the building envelope materials, climate data, solar radiation, and solar heat gains (Rodrigues *et al.*, 2015). The calculation of ratios such as Cf, Cs, and RC considers the building volume while neglecting the opening's characteristics. However, the use of the wall-window ratio (WWR) does not allow for taking the whole building shape into consideration (Mirrahimi, Farid and Chin, 2016).

III.6.6.1 Volume-based indices

They describe the geometric relationship between the building's internal volume and its external envelope area to estimate heat exchange between the exterior environment and the interior building space. They are more effective under cold climate conditions (Rodrigues *et al.*, 2015). The use of volume-based indices allows one to describe the building volume regardless of the building's shape.

- **Aspect ratio** is the ratio of the width (W) of the facade facing the equator to that of the lateral one (L) (Hachem, Athienitis and Fazio, 2011). It helps establish a relationship between the building envelope sunlight area and the total one, indicating the contribution of the envelope to passive solar heating and cooling (Ralegaonkar and Gupta, 2010) and building solar access (Hachem, Athienitis and Fazio, 2011). Feng *et al* (2021) calculated the aspect ratio of the bounding rectangle of several studied shapes, such as: trapezoid, cross, T, U, L, and H shapes, to evaluate their aspect ratio.

$$W/L$$

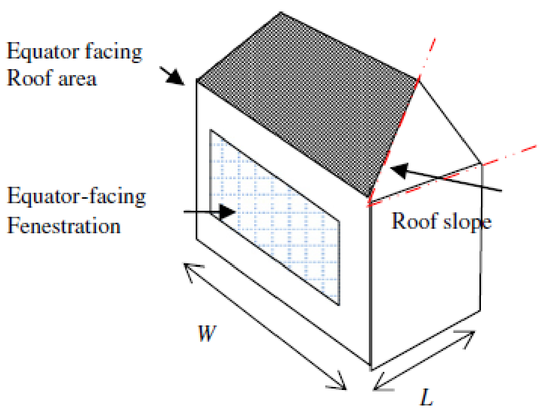


Figure III-5 Aspect ratio (Hachem, Athienitis and Fazio, 2011)

- **The shape coefficient** is the ratio of the building envelope area (S) to its volume (V). (Zhang et al., 2016). The BSM process aims constantly to reduce the shape coefficient, or, in other words, to minimise the external building envelope area while increasing the internal building volume. Designing building forms with a reduced shape coefficient is difficult to achieve, especially when treating additional indices, such as space efficiency (Zhang et al., 2016). Reducing shape coefficient decreases heat transfer between indoor and outdoor environments (Filippín *et al.,* 2005). Although Rodrigues *et al* (2015) found that the shape coefficient is not a relevant energy efficiency index in temperate and sunny regions. Moreover, it reduces the material needs by reducing the building volume. It can give an approximate idea of comfort conditions since the building energy consumption is correlated with the shape coefficient in cold, severe, and barely sunny winter regions (Depecker et al., 2001). Furthermore, the building's form and its shape coefficient impact the limit U value (Zhang et al., 2016). Solar direct exposure has a strong influence on the shape coefficient. Consequently, Albatici and Passerini (2011) replaced the shape coefficient with the south exposure coefficient (Cs) Eq. (2). which emphasizes the best oriented facade and impacts the building volume's passive solar heating and cooling needs (Rodrigues *et al.,* 2015).

$$C_f = \frac{S}{V}$$ (Zhang et al., 2016)

$$C_s = \frac{S^S_{wall}}{V}$$

III.6.6.2 Façade-based indices:

Window-based indices, are specifically set to govern direct solar gain through the opening of particularly large windows (transparent envelope) (Rodrigues *et al.,* 2015). Many indices are related to the facades and window layout, since windows' area critically impacts heating and cooling energy needs (Rodrigues *et al.,* 2015).

- **Window-to-Wall Ratio (WWR)**

It helps evaluate the proportion of the windows or glazing area (Swin) compared to the opaque one of the same facade (Swall)(Albatayneh, 2021). it allows control direct solar incident radiation and the transmitted energy gain (Ralegaonkar and Gupta, 2010)

(Mirrahimi, Farid and Chin, 2016). The window size, is a mandatory factor that helps achieve a trade-off between lighting, ventilation, and thermal comfort. The decrease in WWR induces an increase in yearly thermal comfort hours (WWR). The WWR oppositely correlates with solar direct gain, and heat transfer, which are important thermal comfort indicators (Mirrahimi, Farid and Chin, 2016). WWR is significantly impacted by heat gain related factors, such as solar heat gain coefficient (SHGC), shading, sky cloudiness, and building orientation (Foli, 2016). The optimal Southern WWR in cold climates must be larger to decrease the heating load for single-objective optimization (Harkouss, Fardoun and Henry, 2018). It is calculated using the following formula:

$$WWR=S_{win}/S_{wall}$$ (Rodrigues *et al.,* 2015)

In order to facilitate the calculation of WWR of a set of urban facades, Szcześniak *et al* (2022) used street view imagery to automatically extract façade openings' layouts for each building adjacent to a Google Street View route. The application of the method to 1057 buildings in Manhattan shows that manual and automated methods were within a 20% error in 90% of all cases.

- **Window-to-Floor Ratio (WFR)** gives the proportion between the window surface area (Swin) and the total floor area (Sfloor). The use of WFR provides information about the building volume when the floor height is constant, and it positively correlates with yearly cooling energy needs (Rodrigues *et al.,* 2015).

$$WFR=S_{win}/S_{floor}$$ (Rodrigues *et al.,* 2015)

Implementing WFR Atan and Ibrahim (2019) suggested calculation rules for average illuminance derived from the thumb rule applicable for a light well typology of 1.8 m width, 2.5 m length, and 4.0 m height in single-story terrace houses, with standard clear glass covering its opening. The results show that an average illuminance of about 250 lux and 325 lux could be achieved by applying a window-to-surface area ratio of 70% and a window-to-floor area ratio of 10% under an overcast sky, respectively. Accordingly, the rules of thumb set forth and presented in this study help predict daylight levels inside light-well spaces. Moreover, it can be used as a simple guide for local authorities and architects in designing light wells in Melaka, Malaysia.

$$E_{avg}=18Ag/As+130$$

Eavg : average illuminance

Ag light well's aperture size (m2)

As light well's floor area (m2)

E_{avg}=1.5 Ag/Af+140

Eavg: average illuminance

Ag light well's aperture size (m2)

Af light well's floor area (m2)

DF_{avg}=0.1Ag/Af+1(R2=0.8658)

DF avg average daylight factor

Ag light well's aperture size(m2)

Af light well's floor area (m2)

(Rodrigues *et al.*, 2015)

Combined window-to-floor area ratio and window-to-surface area ratio to optimize illuminance inside the light wells. In fact, the WFR is calculated for each of the building facades separately, while the WWR gives an idea of the proportion between the building envelope window area compared to its exterior area. Additionally, Rodrigues *et al* (2015) suggested the Window-to-Surface Ratio (WSR) index, which describes the proportion between the total building envelope area and the window area. Eq. (7) helps evaluate the WSR value. WSR High values increase the achieved UDI (Narangerel, Lee and Stouffs, 2016).

WSR=Swin/S

WSR is considered an energy-saving measure, since it permits savings of up to 55% (Friess and Rakhshan, 2017a). It precisely affects natural ventilation, which significantly reduces energy needs; the lower the ratio of window area to the wall, the lower the energy needs (Rahsepar Monfared and Azemati, 2021).

Shading coefficient

The facade shading ratio (FSR) is defined as the ratio of the usual shaded area by shading components to the total area of the façade (Fan, Liu and Tang, 2022). It is also called the sunshade coefficient (Ki) (Mirrahimi, Farid and Chin, 2016). The FSR is used to define the proportion of a shaded surface to the non-shaded one (Hachem, Athienitis and Fazio, 2011), which depends upon the building plan and elevation configurations, set-back shape, and the building's depth. The higher is the sunshade coefficient, the lower is solar protection, the FSR for totally sun exposed window is 01(Chen, Yang and Sun, 2016). Thus, it describes the quality of solar protection. It varies depending on the geo-location, for instance: in Malaysia, a shading coefficient of between 0.4 and 0.96 is recommended (Fan, Liu and Tang, 2022).

$FSR = (d1*h1 + d2*h2 + \ldots + dn*hn)/D*H$, (Fan, Liu and Tang, 2022)

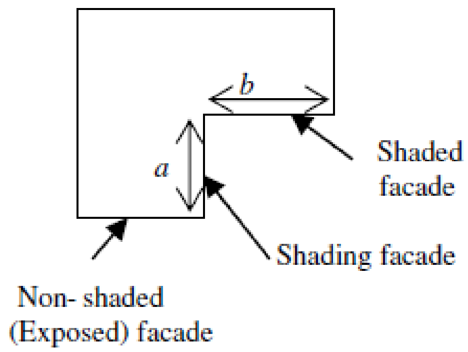


Figure III-6 shade distribution (Hachem, Athienitis and Fazio, 2011)

Fan, Liu and Tang (2022) attempted to enhance the natural daylight and the energy consumption in a gymnasium through manipulating the facade shading ratio (FSR). The results show that increasing the FSR value leads to a reduction in energy needs due to a decrease in hourly radiation of 54% and daylight glare probability (DGP) of 38.5%.

III.7 Parameters combination in building solar morphing process:

BSM process is a part of the architectural design process that aims at achieving energy-related objectives. Both architectural design and BSM processes are nonlinear, not straight-forward (Kheiri, 2018). Energy performance is treated simultaneously with several architectural design constraints, such as cultural, social, and economic. In fact, the architectural design process is generally performed based on a design concept (idea). Consequently, BSM objectives must be fixed in line with the initial design concept. This adaptation makes some energy-related objectives not possible to achieve (Ciardiello *et al.*, 2020) (Azmi and Ibrahim, 2020), specifically in certain building designs, for instance mosques, which are mostly characterised by a high WWR without taking into account energy concerns. Therefore, the design process is a series of cumulative adaptations applied with respect to the priority order of the design objectives and the desired functional features of the final design. It is important to notice that some design decisions cannot be made at the early design stage (Chen, Yang and Sun, 2016).

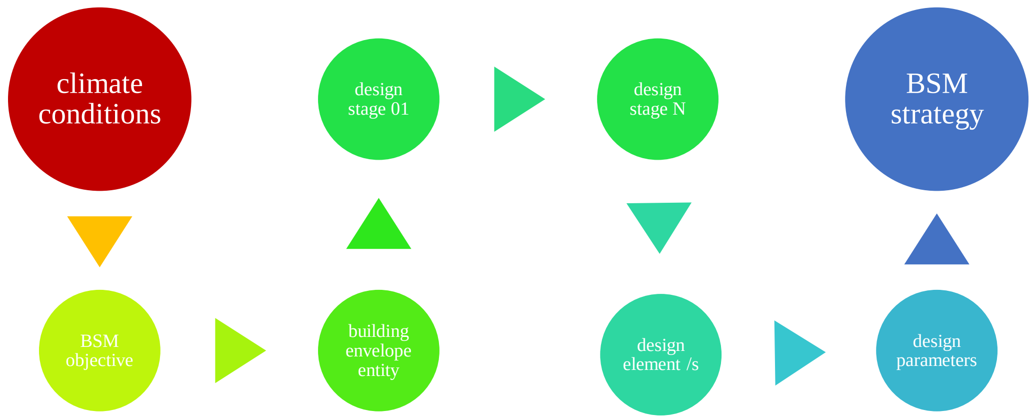


Figure III-7: The process of establishing BSM strategy (Author, 2022).

The effectiveness of the BSM process relies on the appropriate parameters' combination that is initially fixed, taking into account the paramount design elements, which are mainly: objectives, the building envelope entity, the design stages (adaptation series), and parameter categories. The implementation of the optimal parameter combination of envelope passive design leads to considerable energy savings (Harkouss, Fardoun and Henry, 2018).

Significant correlations can only be encountered in specific design programmes or climate regions (Rodrigues *et al.*, 2015). Therefore, the BSM objective must be defined according to the climate type and dominant weather conditions, since they are the most important factors to be considered (Haase and Amato, 2009). Delgarm *et al* (2016) admitted that building energy efficiency can be greatly enhanced by choosing appropriate building parameters based on climate type. Indeed, solar collection and protection optimization are sought in cold and hot climate regions, respectively. In a temperate climate, a trade-off between solar exposure and protection should be established in a temperate climate. The chosen indices are also related to the treated solar component, whether direct or indirect radiation (gains). Accordingly, several BSM parameter combinations are possible. However, a given parameter combination or BSM strategy may be effective only under specific climate conditions. The design objectives can be related to the third BEE parameter, which should be defined based on the building's interior ambiance needs.

The main BSM parameters should be addressed afterwards in order to ensure the effectiveness of secondary ones, especially in certain types of buildings. The influence of building orientation on tilt angle and secondary parameters makes it important in the BSM process (Ralegaonkar and Gupta, 2010). For instance, in mosques, where thermal comfort greatly depends upon the building orientation (Azmi and Ibrahim, 2020).

Overall view on previous research works allows designer to select the most suitable parameters following researchers' recommendations and results. For instance: natural ventilation is a suitable strategy under tropical and temperate climates energy needs contrary to subtropical one, particularly in the hottest period (summer) (Haase and Amato, 2009). On the other hand, windows are characterised by several variables, which cannot always be the most important study variables (Rodrigues *et al.*, 2015). Ascione *et al* (2019) asserted that under cold climate windows geometric features do not significantly influence the building energy efficiency.

Hence, BSM strategies are often based on making trade-offs between main and secondary parameters, and ratios. Ralegaonkar and Gupta (2010) and Mirrahimi, Farid and Chin (2016) considered that the aspect ratio of walls, the orientation of the building, window details (size and location), and a proper sun shading device to control the amount of incident solar radiation were the most impactful BSM variables and significantly affected the solar contribution to the total cooling and heating loads. Rodrigues *et al* (2015) encouraged researchers to investigate the combined effects of WWR and WFR on thermal comfort further. Thus, various building components that are directly exposed to the sun include walls, doors, windows, ventilators, roofs, etc. The window is the most important component that contributes to enhancing direct solar gains. Ralegaonkar and Gupta (2010) admitted that fenestration type, area, and orientation are the most impactful BSM parameters. Haase and Amato (2009) or Gossard, Lartigue and Thellier (2013) outlined the seven most important design variables in the BSM process, which are: window size, transmittance, external obstruction condition, shading ratio, building orientation, window heat transfer coefficient, and wall thermal resistance.

Although there have been numerous studies on the optimization of window or shading design, the majority of these studies have concentrated on the separation of the topics of windows and shading. Few studies have treated windows and shading, including heating, cooling, lighting energy consumption, and thermal comfort (Zhao and Du, 2020). By increasing the window-to-wall ratio, the cooling energy consumption rises. It indicates that increasing the window area leads to cumulative solar energy, especially during the summer. Absorbed solar energy leads to higher cooling energy consumption (Rahsepar Monfared and Azemati, 2021). Specific BSM strategies, such as a double-skin façade, can ensure contradictory design objectives like passive heating and natural ventilation (Ding et al., 2003) (Haase and Amato, 2009).

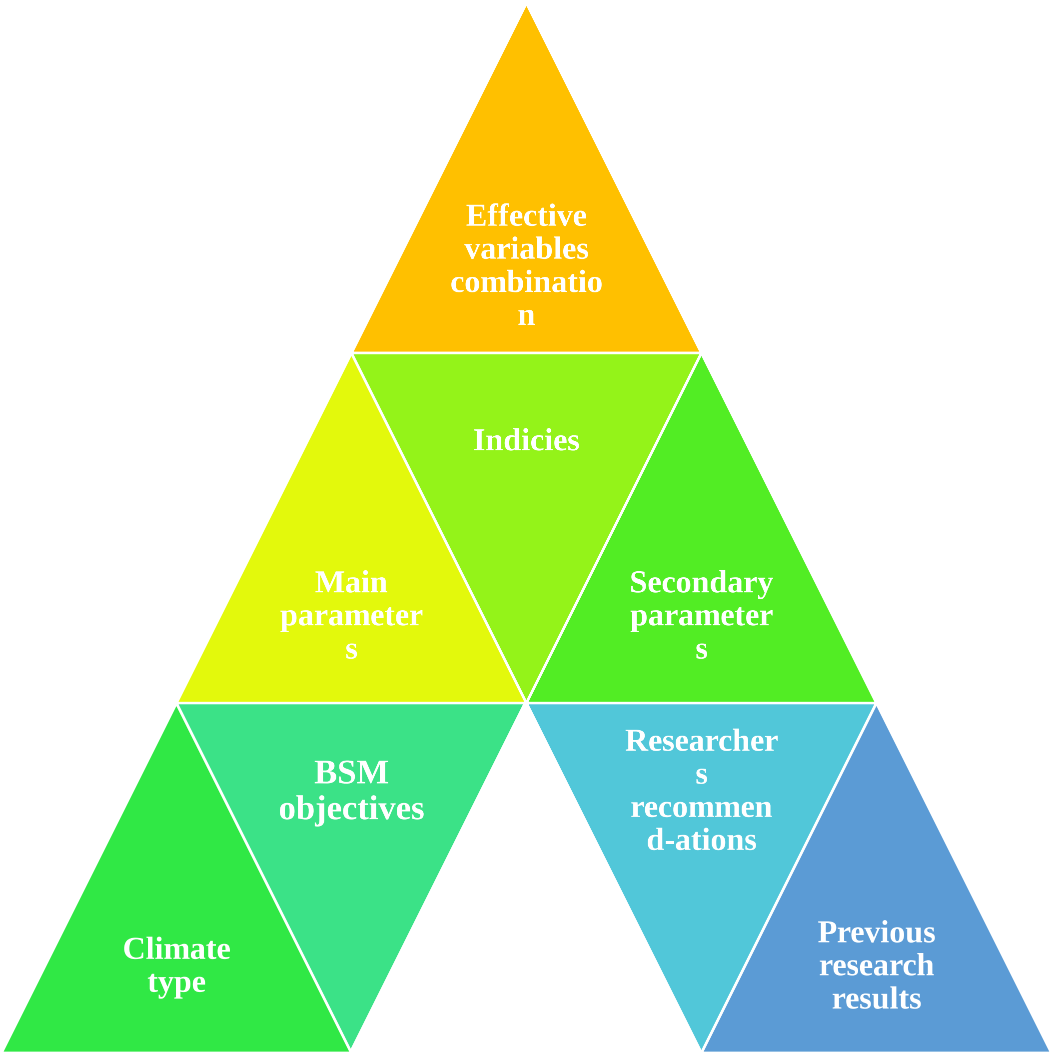


Figure III-8: design elements defining effective BSM variables combination (Author, 2022).

Remark

According to the BSM index categorization suggested by (Rodrigues *et al.,* 2015), the third index type is hybrid. However, in our classification, we just adopted two types and noticed that the parameter combinations can be either homogeneous, which includes parameters of the same building envelope entity (BEE), or hybrid, which involves indexes of different building envelope entities.

III.8 3. Examples of effective BSM variables combinations:

As mentioned above and according to BSM objectives, many combinations are possible. However, their effectiveness must be explored during the design process. In this section, we expose selected relevant examples of BSM parameter combinations based on the designed building envelope parts or elements.

Numerous studies have suggested BSM strategies for rectangular-based building shapes. In this case, the whole building shape is kept, while the geometry of the envelope elements, such as: windows and shading devices, is manipulated to optimize the building's performance. The geometric parameters associated with windows are numerous; they are typically treated in conjunction with the other geometric features of the building envelope. Shan (2014) tried to find a compromise between indoor thermal comfort and natural lighting in a single office room throughout the year. The design generation is based on the window grid dimensions and the shading system depth variation. The results demonstrate that a 500-lux illuminance level is achievable in the early design stage. Konis, Gamas and Kensek (2016) established a building shape optimization method by adjusting the building orientation and windows' shapes to meet daylight requirements. The results show that the suggested method reduces energy use intensity (EUI) by 17% and enhances daylight performance by 65%. Fang and Cho (2019) optimized the day-lighting quality and energy performance of a small office building by manipulating skylights and window dimensions, building depth, and roof ridge location. This optimization strategy is tested in the Miami, Atlanta, and Chicago climates. The results show that the most impactful geometric variable is skylight width and length, Foli (2016) optimized indoor illumination quality and daylight intensity inside office buildings in a temperate climate with high annual temperature fluctuation by adjusting window to wall ratio (WWR), window geometry (WG), and window heights. Thus, three window geometries were investigated: horizontal rectangle, vertical rectangle, and square, associated with four WWR values: 20%, 25%, 30%, and the reference model's 50%. The results show that the vertical, rectangular window geometry gives the best results in terms of annual energy demand; since the window height allows a deep penetration of solar rays into the indoor space.

Beyond rectangular-based building shapes, the solar potential of other orthogonal building shapes was assessed. Okeil (2010) proved that morphing the profiles of conventional rectangular blocks enhances the received solar energy amount on their façades and reduces it on their roofs during the winter. Furthermore, the building's wing configuration (L, U, H, and T forms) determines its solar potential and ability to generate electricity according to the wings' shadow and light zones, projected on the building envelope (Hachem, Athienitis and Fazio, 2011). Friess and Rakhshan (2017a) explored the effectiveness of different building envelope forms (rectangle, trapezoid, T, H, L, and U shapes) in minimising energy needs in residential buildings under five climate types. Besides the whole building shape, additional BSM parameters were embedded, such as orientation, window area and type, foundation, insulation of both wall and roof, infiltration level, and thermal mass. The results show that the best results are achieved by trapezoid and rectangle forms. Ciardiello *et al* (2020) achieved a building envelope solar design in two stages. Geometric features including: the building shape, shape proportion, WWR, and orientation were treated in the first design stage to help get preliminary guidance for designers by selecting the most efficient building envelope shape. Dealing with additional objective functions in the first stage is regarded as insignificant. While keeping the building volume fixed at 9000 m^3 (±10%) the BSM variables are changed. They include: Floor number ranges between 4 and 8, and the building shape was explored starting from a linear shape (I). Various shapes were explored: L, O, C, T, H, X, and Y shapes. The optimization allows for savings of up to 60.6% of annual energy needs. Beyond classic window shapes Barea, Ganem and Esteves (2017) suggested a multi-azimuthal window (bay window) manipulation based on changing: horizontal plan shape, the angle of the side panels, and the area of the glass panel by orientation in order to enhance passive solar gains. The amount of transmitted solar energy through the MW against the same dimension FW is expressed using the "multi-azimuthal/flat solar gain factor" (M/FSGF) ratio. The results show that a MW with 45° inclination side panels increases daily average solar gain by 20%, and it increases to 27% in temperate climates with a 90° inclination angle.

Solar radiation on the roof is largely responsible for the whole building's energy performance. Kämpf & Robinson (2010) developed a method for optimising building energy performance based on maximising annual received solar radiation by varying the orientation and tilt angle of the roof faces. Compared with the reference shape, the annual radiation of the optimised roof shape is increased by up to 20 %. Lobaccaro, Chatzichristos and Leon (2016) suggested a solar exposure optimization process for a traditional Norwegian house roof shape in Trondheim (Norway). The process involves testing multiple roof panels' sizes and tilt angle values. The results indicate an improvement in the roof's solar potential of around 30%, compared with the initial roof shape. Xu et al (2021) assessed the solar potential and technical potential of installing PV modules over industrial blocks in a representative Chinese town. Seven types of industrial blocks are identified based on their geometric features. The results show that the geometry of the studied industrial blocks determines solar potential and technical factors. Furthermore, the lowest geometries are more effective. Furthermore, Shi and Yang (2013) tried to optimise the roof solar exposure by generating complex multi-faced roof forms based on specific related parameters, such as offset big, offset small, bi-arc, and angle, to control the roof surface shape.

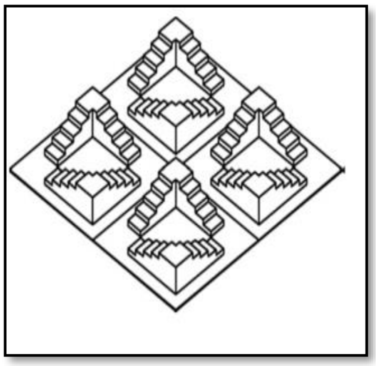
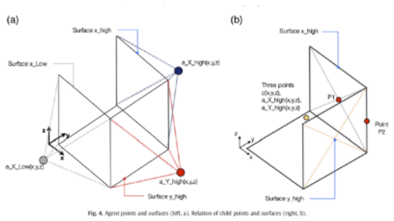
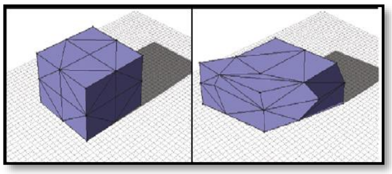
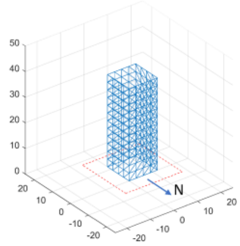
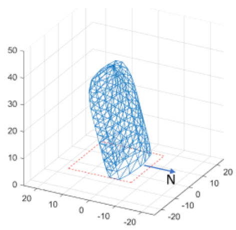
BSM methods for the whole building shape generation process are mostly applied in different locations and for different building types. Many researchers suggest optimization strategies for the building shape based on the transformation of regular shapes into irregular ones. Yi and Malkawi (2009) elaborated a building envelope solar exposure optimization based on a geometric control system, including "agent" and "child" points. The method allows the generation of irregular building shapes starting from a rectangular-based one. The results indicate that the implemented geometric control system helps generate more efficient building shapes by modifying the building plan and the three-dimensional shape. Taleb *et al* (2020) developed an early design stage tool that enhances the building's solar protection efficiency. It works by changing the tilt angle of the initial parallelepiped's meshes to manipulate the shape. The results show that the optimization of the whole building shape ameliorates its solar exposure during the hot period by up to 48%. Fokaides et al (2017) optimized the whole building shape to increase the building's annual and seasonal solar heat gain. The results show that the optimal building shape varies according to the climate type; for instance, in Athens, the optimal shape of the building's southern part is quasi-rectangular, while it is an isosceles trapezoid in London.

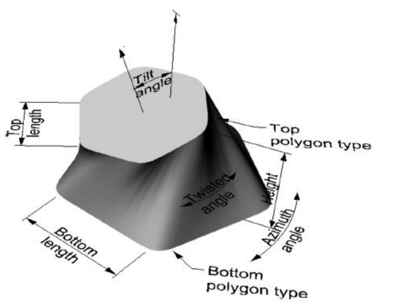
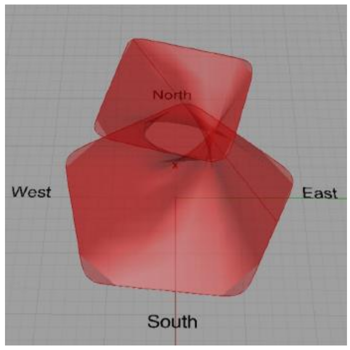
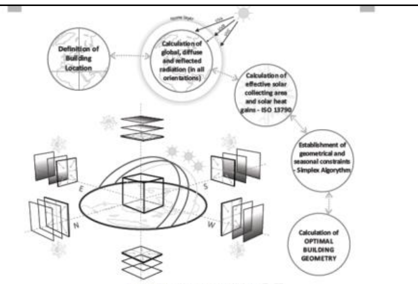
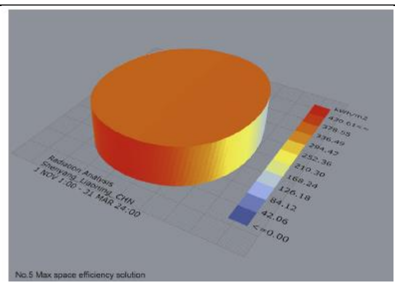
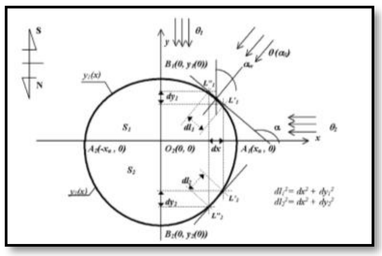
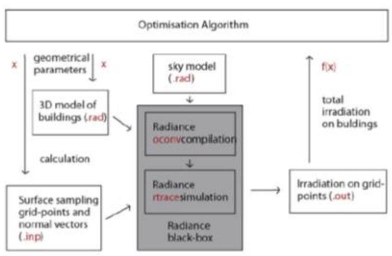
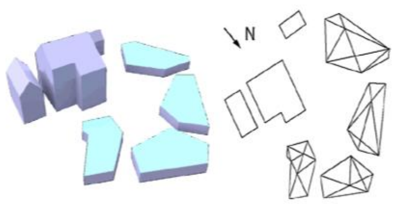
Other studies have dealt with curved building shapes and solar morphing. Adamski, (2007) conducted an optimization study of the southern part of a cylindrical building. The obtained results illustrate that the oval-based building shape is more effective than the circular-based one and significantly better than the square-based one. Zhu et al., (2019) propose a solar exposure optimization method for curved building shapes by introducing energy utilisation parameters and stress distribution. The optimally curved solar surface is obtained by defining the most appropriate structure. Based on total received solar radiation and two additional shape performance indicators: space efficiency and shape coefficient, Zhang et al (2016) conducted solar optimization of free-form building shapes. The method consists of manipulating the cylindrical building shape using four control points. The results show that under North China's cold climate, the optimization enhances the building's solar potential and shape coefficient by 30–53%, and 15–20%, respectively. The space efficiency is decreased by about 5%. Jin and Jeong (2014) proposed an optimization process for free form construction in terms of thermal load characteristics in the early design stage based on the genetic algorithm (GA). It is found that the variation in thermal load characteristics caused by the change in building shape was rapidly predicted and optimised in the early design phase by architects, who use Rhino and Grasshopper programs.

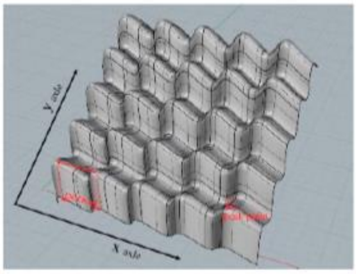
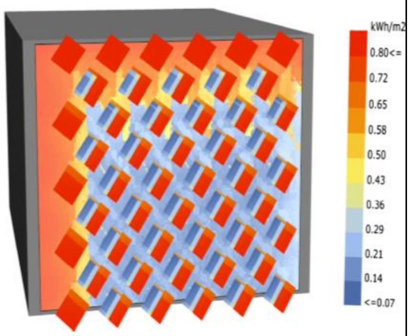
Jayathissa *et al* (2017) developed a dual role facade system composed of modules that ensure façade shading while collecting the available solar energy. Due to the photovoltaic cells installed on the façade modules, the intercepted solar energy is converted into electricity. The modules are of adaptive geometry that is manipulated based on the required energy needs. The assessment of the developed system is performed based on a mathematical model of the photovoltaic electricity harvest, considering the shaded surface of the façade modules. The solar electricity harvest is done using a high-resolution radiance model and a photovoltaic model to estimate the modules' shaded surface. A simulation of all possible dynamic configurations is conducted. The results show that the efficiency of the designed façade system depends upon the climatic conditions of the studied location.

Friess and Rakhshan (2017b) optimized the building envelop features and its shape configuration through an optimization-simulation process to reduce residential building energy consumption in the UAE. Using an enhanced Manta-Ray foraging optimization algorithm and RIUSKA software for performing simulation, a set of parameters that included window area and type, different building part insulations, infiltration level, the building orientation, and thermal mass were manipulated to generate optimal geometries. The results demonstrate that optimization helps decrease energy needs by 30% and 79% in individual dwellings and high-rise office buildings, respectively.

Table III-1 Examples of several BSM strategies (Author, 2022)

Research team	Building envelope element	BSM variables	Optimal building Shape
Okeil (2010)	The whole building form	La forme du profil	
Yi and Malkawi (2009)	The whole building form	Agent points / Child points 	
Taleb *et al* (2020)	The whole building form	Penalty Successive Linear Programming (PSLP)	 (a) Isometric view of the initial conventional rectangular building with the terrain boundaries.  (b) Isometric view of the optimized form of the building with the terrain boundaries.

Jin and Jeong (2014)	The whole building form	Genetic algorithm (GA).  Fig. 1. The initial free-form building model.	
		 Fig 1 Methodology flow chart	
Zhang et al (2016)	The whole building form	the multi-objective genetic algorithm	
A part of the shape			
Adamski (2007)	South part of the building	the variational method complicated logarithmic function	
Kämpf and Robinson (2010)	Roof shape	 Fig. 2. The optimisation algorithm applied to a black-box problem type.	

Zhu et al (2019)	surfaces	 Figure 3: simulation model (x=20m, y=20n	 Figure 2: the tiles made by thin-film photovoltaic:
Jayathissa *et al* (2017)	facade shading	Mathematical modelling	

III.9 Conclusion

The presentation and exploration of the BSM factors and parameters in this chapter aim to help designers figure out the most suitable variable combinations that allow them to achieve energy-related objectives and establish effective BSM strategies. Therefore, BSM parameter combinations are mainly done according to the design elements. Established BSM tools and methods need to be set for a specific design stage and a specific building envelope entity. This clarifies the design objectives and process. After verifying the main BSM factors, the window size and area should be well designed and thought out. In this chapter, a detailed approach to solar design elements is explained. Afterwards, the elements of the design process are gathered to show their performance and the contribution of each parameter to the enhancement of the building envelope's solar potential.

CHAPTER IV. BIO-INSPIRED BUILDING SOLAR MORPHING STRATEGIES AND THE ESTABLISHMENT OF BIO-BRIDGES PATH LINE APPROACH

Chapter VI Bio-inspired building solar morphing strategies and the establishment of bio-bridges path line approach

IV.1 Introduction

Biomimicry is a recently established science that is applied in several design fields. Although the initial bio-approaches were effective in obtaining innovative design solutions, they needed to be more tailored to specific design fields, such as architecture.

The history of how biomimicry has been used in the design field is briefly explained. Then, the bio-approaches are talked about to show how their steps connect to each other and what makes the connections between them flexible. The use of bio-approaches in solar architectural design is then investigated by reviewing several research papers. The goal of this paper is to identify the specific design aspects that should be reconsidered in order to improve the efficacy of the bio-approach design in architectural design.

A review of literature is done in order to find out the elaborated bio-design methods and tools applied into architectural design, their effectiveness and limits. Then, the challenge has been clearly identified to suggest a design line-path that facilitates the bio-knowledge transfer process. This chapter presents the stages sequence of the bio-approaches and their key elements, focusing on bio-knowledge transfer stage.

IV.2 Biomimicry overview:

Nature imitation has been applied in the field of design throughout human history, either consciously or unconsciously, with positive results. Aristotle indicated that nature inspired all human design, from the simplest to the most artistic (Dixit and Stefańska, 2022). Thus, biomimicry science emerged as a result of the evolution of human consciousness of the role nature plays in inspiring effective functional design models.

Taking inspiration from nature has been unconsciously practised since the 1950s, exactly 1957, when Otto Schmitt called it "biomimetic" (Schmitt, 1969) and defined it as "the transfer of ideas and analogues from biology to technology." (Yurtkuran, Kırlı and Taneli, 2013). In 1960, the term "Bionic" was introduced by Jack Ellwood Steele of NASA to designate the application of biomimicry in material science (Hu, Feng and Dai, 2013). The American scientist Janine Benyus established "biomimicry" as a discipline that supports bio-inspired design and defined it as the imitation of nature's intelligent systems. (Pandremenos, Vasiliadis and Chryssolouris, 2012). From a technical viewpoint, biomimicry serves humans with mechanisms that help extract functional models from the natural world (Benyus, 1998).

The application of biomimicry in the architectural design field is considered a process of ideas transferring from nature to architectural design (Dixit and Stefańska, 2022). The process of knowledge transfer from the living world to the dead one is known as the "abstraction process", defined by Julian Vincent as ‘the abstraction of good design from nature’(Aziz and el Sherif, 2016). Biomimicry draws links between technical science, and biological systems to generate innovative design ideas, concepts, and principles (Yuan *et al.*, 2017). Thus, it is simply the search for solutions to human problems in nature (Aanuoluwapo and Ohis, 2017). Therefore, we define biomimicry from a practical and technical point of view, as a "set of strategies, methods, and tools that ensure applying the living world’s know-how to different human practices, especially in the design field".

Literally, "Biomimicry" is a compound word that includes two words: "bios" and "mimesis", which mean in Greek "life" and "imitation," respectively (Benyus, 1998). Accordingly, biomimicry is "life imitation". There are similar terms that express the same concept, such as: Biomimesis’, ‘Biognosis’ and ‘Bionics’. The term "Biomimicry" is used to develop sustainable design solutions, and differs from "Biomimetics" that has been applied to the military technology field (Aziz and el Sherif, 2016). These terms are etymologically different, but they are currently considered synonyms (Dixit and Stefańska, 2022). Biomimicry can be defined as a creative design discipline that contains a set of rules for creative design. The assimilation of the meaning of "biomimicry" is crucial to easily understanding all related aspects. Biomimicry science has basically evolved and spread through scientific research publications and design practice, which are discussed in the following section.

IV.2.1 In research and books

The term ‘Biomimicry’ first appeared in scientific literature in 1962 and grew in usage, particularly among material scientists, in the 1980s (Aziz and el Sherif, 2016). In the 2000s, the extent of bionic research has developed to an unprecedented level (Hu, Feng and Dai, 2013). Between 1995 and 2011, approximately 18000 publications on biomimecry research were published (Lepora, Verschure and Prescott, 2013). Nowadays, numerous journals and conferences focus on biomimicry, and aim at exploring biomimicry science and discovering its principles. These figures are rapidly increasing (Cruz *et al.*, 2021). In fact, biomimicry was presented and promoted throughout history through books. Throughout history, many books have documented the evolution of biomimicry perception and comprehension. The first is the book of the zoologist D'Arcy Thomson, published in 1917 that treated the use of bionic patterns by humans and explained the basic mathematical and physics rules behind living organisms' shapes and their evolution (Dixit and Stefańska, 2022). The second is a major scientific work, entitled **"Biomimicry Innovation Inspired by Nature"**, a book written by the biological-science writer **Janine Benyus**. The chronology of biomimicry science evolution is based on the publication date of this book in 1998. In the architecture field, Charles Jenks published his book "Architecture 2000 Predictions and Methods" in (1971), in which he discussed the bio-inspired morphing principles in architecture and engineering (Tavsan, Tavsan and Sonmez, 2015).

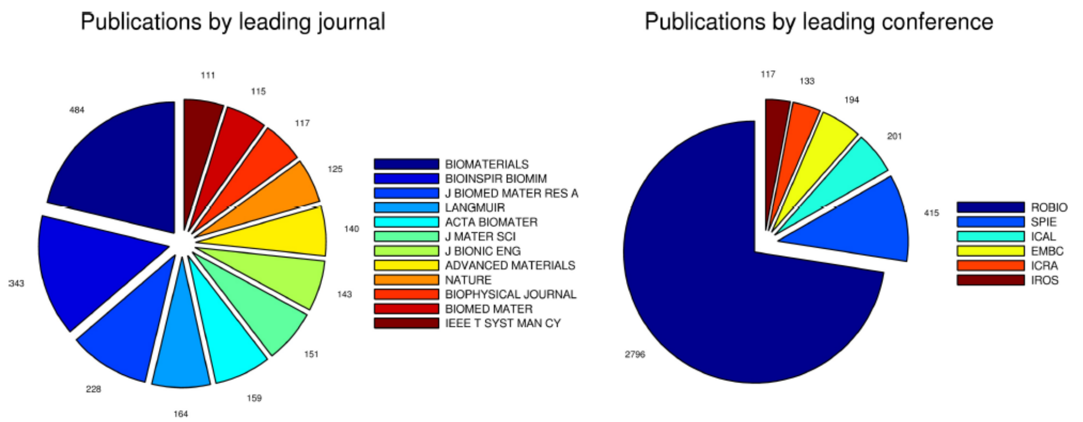


Figure IV-1: Statistics on biomimicry research works publication (Lepora, Verschure and Prescott, 2013).

IV.2.2 In design field

Beyond ornamentation, nature has also served humans with technical and practical functional models that have made their daily tasks easier. The artistic and industrial revolution in Italy relied on nature's organising principles. As an art critic with a master's understanding of how arts and design were practiced, The Italian painter, artist, and architect Georgio Vasari defines "Design" or "Disegno" in Italian, as the basis of all good art. Practicing artists, sculptors, and architects considered nature's imitation of art a fundamental creation rule. This explains the superlative perfection behind Italian Renaissance art; marked by the genius of Leonardo, Raphael, and Michelangelo (Georgio VASARI, 1991). Moreover, Vasari emphasizes in his seminal book "Lives of the Artists" the role the study of living beings and their anatomy plays in the evolution of design techniques. Both of Leonardo da Vinci's flying machines (Yurtkuran, Kırlı and Taneli, 2013) (1452– 1519) (Dixit and Stefańska, 2022) and the first successful plane made in 1903 by the Wright brothers (Dixit and Stefańska, 2022) were inspired by bird flight mechanism (Rao, 2014). Another revolutionary biomimetic innovation is Velcro, inspired by trapped fruit in dog fur (Hu, Feng and Dai, 2013). In 1998, Benyus and Baumeister contributed in many ways to develop and spread biomimicry practice. They set up the Biomimicry Guild to help apply the bio-inspired design approaches. In 2008, they additionally provided the web site AskNature.org, which represents an online database of bio-inspired solutions, then changed its name to Biomimicry 3.8. This website is the medium of biomimetic exchange. They also provided the following resources: the Biomimicry Book (1997), the Biomimicry Guild (1998), the Biomimicry Institute (2006), AskNature (2008), and Biomimicry Professional Pathways (2010) (Badarnah-Kadri_2012). During the past fifty years, numerous natural mechanisms have successfully been applied into technology to produce more effective design solutions, such as rough composites inspired by wood fibre orientations or deployable structures inspired by flowers and leaves (Hu, Feng and Dai, 2013). Therefore, there are still many related areas to develop and explore since biomimicry is a recently established science.

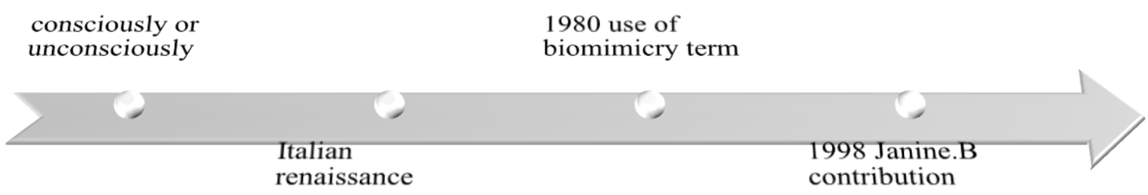


Figure IV-2: Biomimicry evolution (Author, 2022).

(Tavsan, Tavsan and Sonmez, 2015) admitted that biomimicry helps architects understand that a spider is not just a spider but, a producer of material and a designer. Likely, an ant is a builder of structures similar to sand castles. In this section, we attempted to outline the most important elements of a bio-inspired approach to building shape morphing using a critical-analytic approach.

IV.3 Bio-design approaches

There are two approaches to bio-inspired design. The first is **the Design-to-biology** approach, in which the designer begins with identifying the challenge. The second approach, "biology-to-design," consists in identifying a functional natural mechanism that can be used as a design solution or concept. Subsequently, the first step of the Design-to-biology approach is the last one of the **Biology-to-design** approach, and vice versa (Fig. IV-3). Thus, the difference between these two approaches resides in the step sequence (Fig. IV-3). They can both be applied in different design fields. However, the exploration of the existing literature showed that the Design-to-biology approach is mostly applied in architectural design. For this reason, it is deeply analysed in this section.

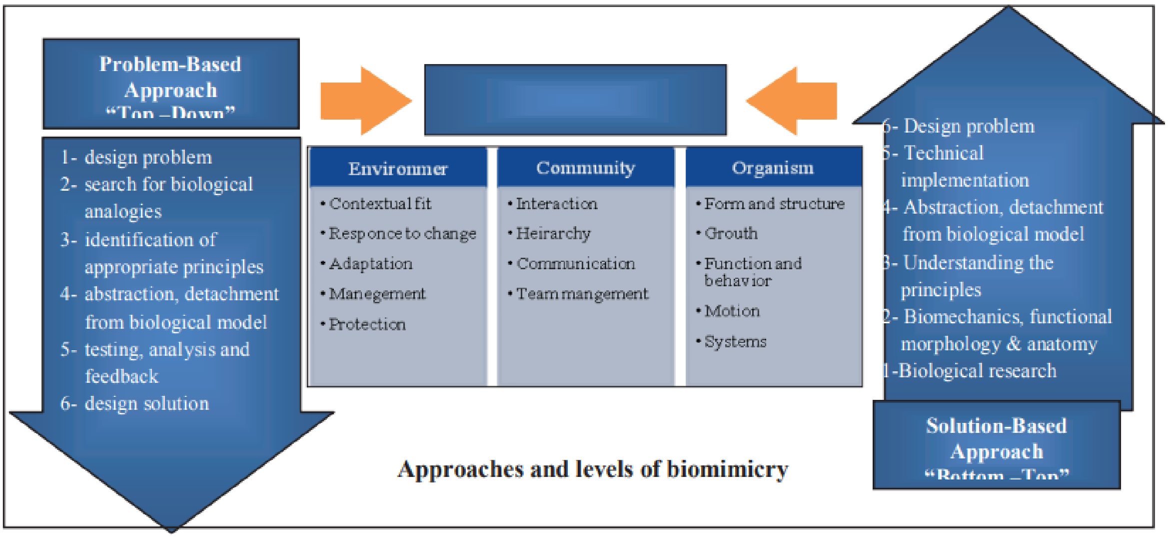


Figure IV-3: Biomimicry approaches (El-Zeiny, 2012)

IV.3.1 Biology-to-Design Approach

It involves using a natural functional mechanism in the design process to solve a similar functional problem. Biology-to-Design Approach represents the inverse of the problem-to-biology approach; the steps are the same but reversely ordered. For this approach, different methods are established by researchers; the difference lies only in the steps' sequence. The sequence of the steps is determined by their interdependence. Biology-to- approach is known by several names, such as the indirect approach, Biomimicry by induction (Gebeshuber and Drack 2008), Biology to Design (Baumeister 2012), bottom-up (grain et al. 2006), solution-based approach (Badarnah-Kadri_2012). This approach is not widely used in architecture. However, many functional models and mechanisms can be observed in nature, analyzed, and then, gathered as a data base that provides bio-inspired design sources. For example, Badarnah-Kadri_(2012) used the Biology-to-Design Approach to investigate several architectural design aspects and potential bio-inspired solutions in architecture.

IV.3.2 Design-to-biology approach

It consists of identifying the problem and then finding a solution through the imitation of natural models. The sequence of steps in the Design-to-biology approach is depicted in (Fig. IV3). Many terms or expressions are used to describe this approach, including problem-based (Vattam et al. 2009), top-down (Speck et al. 2006), biomimicry by analogy (Gebeshuber et al. 2008), and challenge to biology (Baumeister 2012) (Badarnah-Kadri_2012). In this section, the design steps are discussed with respect to the treated elements.

Phase I: Problem system definition and analysis in this phase, the designer must focus on the problem and the functional challenge to be resolved. Problem analysis consists of simplifying complex functions by describing the required design features and the functional mechanisms behind them. It is preferable to use the term "challenge" than "problem". Shu et al (2011) proposed describing physical entities and creating a system by defining their relationships (Badarnah-Kadri_2012). Vincent *et al* (2006) proposed Biotriz and Triz methods in which the problem is transcribed into a set of inconsistencies. Hence, the designer should establish coherence within the composition.

Phase II: Exploration of biological analogies

Heaumes (Lidemann and Grmann) proposed a list of biological terms to assign each technical function a biological term, and then relate it to the organism or organ that performs it. Thus, the design challenge and constraints are transcribed into biological terms and notions. Under extreme conditions, it is beneficial to look for champion creatures of this function. The functional mechanism of the selected inspiration source should be analysed to understand the way it solves the problem. This helps define and refine the desired design features. Moreover, for a single problem, several analogies can be selected to outline their common traits and aspects. It is also advisable to study multifunctional natural systems that are able to solve many problems. This aids in the development and implementation of the solution system. The transcription of the natural mechanism into a design concept then facilitates the design process and delineates the search boundaries. In this case, the champion creatures that developed thermoregulation adaptation mechanisms can be found in desert climate regions that represent extreme conditions.

Methods for finding Analogies

There are two types of biological information resources: direct and indirect. The direct method entails asking biologists for information about living organisms that successfully complete the desired functional challenge. This method is judged to be subjective. The second one is the indirect method, which involves examining available databases to outline the study keywords that should be accurately selected. Thus, looking for keywords in the literature takes the designer away from subjectivity. Vandevenu suggested a scalable approach to collecting more information. Shu proposed a catalogue and summaries of natural phenomena. Other methods are available, such as: model representations, design repositories, functional indexes, organic functional models, and functional design models. The misunderstanding of biological phenomena and terms, the inappropriate choice of biological keywords, and the reliability of the sources are the main challenges in this phase. The use of language tools and the diversification of terms is highly recommended to achieve effective design solutions. Thus, basic and advanced texts can be written to gather the selected keywords and describe the functional mechanism. For example, in the English language, there are several verbs that describe how a given action is done, such as ambling and walking. The latter represents a more detailed alternative and provides an answer on how the function is accomplished (How?).

Therefore, the designer must be accurate in choosing the transcription terms, which include nouns, verbs, and adjectives, to facilitate the transition and brainstorming of new ideas. Biological terms and the corresponding ones in the design field can be gathered afterwards to generate a solution system. The translation of functional terms into biological ones facilitates finding an appropriate source of inspiration. Cooling or air conditioning, for example, becomes thermoregulation.

Phase III: Evaluation of selected analogies

The analogies are chosen based on the evaluation of the resulting power-coupling terms. The frequency of the terms' use defines the most commonly used ones. The biological analogies in the abstract or physical senses are then selected.

Phase IV: Applying bio-analogies in the design process

To write two descriptive texts, the types of analogies should be clearly defined. The first one is about biological phenomena, while the second one is about the functional objective using the design field terms (at the beginning, it is possible to not use the terms and just leave gaps). Finally, similarities are emerging from the two descriptive texts in order to establish logical or functional links between the two sets. Effective implementation of biological analogy in the design process is done through the use of the same biological material. In some cases, terms like "abstraction" or "mechanisms" are dropped because the natural element, such as bamboo flooring, can be simply embedded in real-world practice. Furthermore, several analogies can be applied within the different stages of the same design process.

IV.4 Biomimicry in architecture

Architecture reflects popular values and expressions. The sacred lotus plant served as inspiration for ornaments used to decorate temples in ancient Egypt (Aanuoluwapo and Ohis, 2017). While the ancient Greeks and Romans were inspired by acanthus leaves for their Corinthian order (Hu, Feng and Dai, 2013). this bio-inspired design only concerns formal and aesthetic building aspects by transferring geometrical features from plants, without needing specific transfer design tools and rules. Environmental concerns occupied an important place in architectural reflection, as well as other fields, during the second half of the twentieth century, and particularly in the last ten years (Tavsan, Tavsan and Sonmez, 2015), Environmental concerns occupied an important place in the architectural reflection, as in other fields. Thus, the contribution of biomimicry in architectural design has different aspects, not exclusively aesthetic but also functional and structural. The functional aspect is the most treated and has resulted in a new tendency in architecture called "performative architecture." Furthermore, Palombini suggested an update of the three mandatory aspects of human creation represented in the Vitruvian triad, by giving it a third dimension and adding "Propinquitas", which means "closeness," as a fourth element (Lumini, 2022). The resulting tetrahedron organizes the interactions between man and nature. Each design process determines the closeness between man and nature, which defines their cause-and-effect relationship.

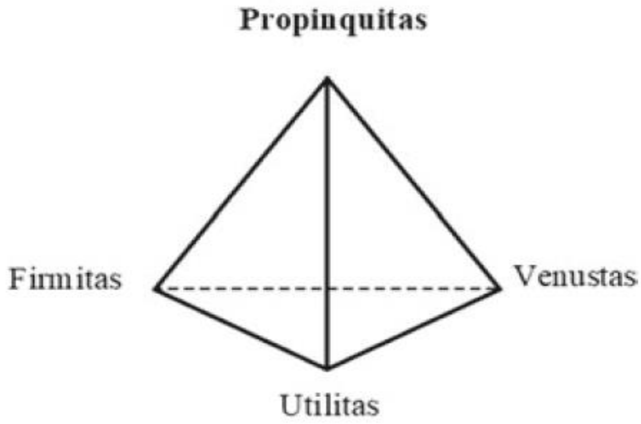


Figure IV-4 : Vitruvian triad update (Lumini, 2022)

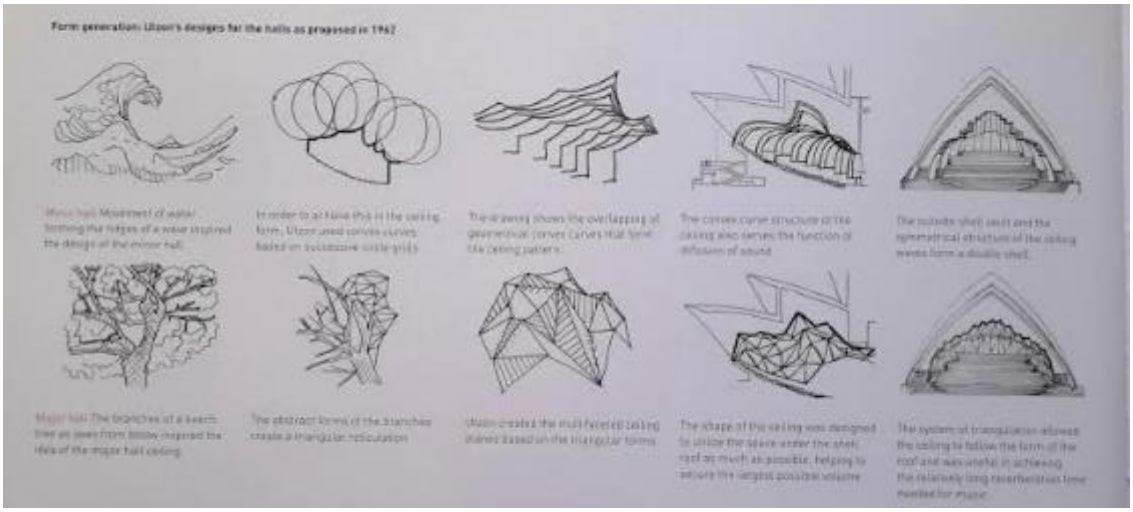


Figure IV-5 : natural source of inspiration in architectural design (Antony Radford, Selen Morkoc and Amit Srivastava, 2014)

Bio-inspired architectural morphing studies are examined in the following section to outline the relationships between architecture and biomimicry, as well as the most influential factors that lead to successful bio-inspired design in architecture. The major parameter that governs solar building potential is the building's whole shape, because it directly affects the building facades' solar exposure. There aren't many papers that deal with bio-inspired whole building shapes. Therefore, we explored the design of building envelope components, focusing on the shape of the solar functional elements.

IV.4.1 Bio-approach challenges in the architectural design field

In fact, biomimicry cannot be applied in architectural design the same way it is applied in technology and industry. Many researchers, including Badarnah and Kadri and Lepora et al. Al-Obaidi *et al* (2017) acknowledged that the most difficult stage of bio-design is the transfer of bio-knowledge from nature to the design field. They attribute this to a lack of clear tools and methods, which leads to the unsuccessful transcription of natural phenomenon mechanisms into architectural design concepts. Moreover, Gruber defines biomimicry as ‘‘delivering identification of new and innovative fields together with a method of transferring ideas from nature's phenomena to architecture (Dixit and Stefańska, 2022). Hence, bio-inspired approaches, methods, and tools need to be better adapted to architectural design specificities. For these reasons, a critical analysis of the bio-approach is carried out in order to clearly identify the factors at fault. Hu, Feng and Dai (2013) admitted that most of the bio-inspiration is superficial. As a result, architects must precisely define (what) and (how) to transcribe.

Biomimicry approaches are broad; their application in specific sub-field design, such as architecture, necessitates outlining specific factors in order to focus on specific details. As a result, we investigated research works to identify the most critical aspects that contribute to the effectiveness of the bio-approach in architecture.

IV.4.2 Bio-inspired solar morphing strategies

Studies that suggest bio-inspired solar morphing methods for building envelopes are discussed to explore the diversity of natural inspiration sources and the effectiveness of the bio-design approach. Khosromanesh and Asefi (2019) used a biomaterial made from ice plant seed capsules to design a second building envelope. The façade is a regular modular network geometry that can carry out functional deformations according to dry or wet conditions due to its hydro-actuated texture to better regulate solar gains. The results show that the bio-inspired mechanism allows the façade modules to undergo deformations according to dry or wet conditions due to their hydro-actuated texture. It therefore helps manage sunlight penetration and reduce building energy consumption. For the same objective, Park and Dave (2014) designed a passive roof system inspired by the reflective superposition eye. It performs based on manipulating the shell's inclination and orientation. The results show that the designed system improves the building's ability to regulate solar energy penetration and protection. Thus, indoor illuminance reaches a much higher level than the minimum required level, reducing energy consumption.Sheikh and Asghar (2019) designed bio-inspired façade modules that change the configuration via a solar-based axial folding mechanism to improve solar protection in highly glazed buildings. The façade is inspired by Oxalis oreganad a leaf which has the ability to adjust its position according to the sun's movement. The established system is tested on a 20-story office building in the hot and humid climate of Lahore, Pakistan. The results indicate that the optimised building energy load decreases by 32%. Additionally, the lighting level is kept within the recommended range of 500–750 lux in 50% of the interior space with minimal reduction in visual comfort.

Other researchers developed bio-inspired solar morphing mechanisms inspired by dynamic solar adaptation mechanisms such as: deployable structures. Based on kinetic patterns, Pesenti *et al* (2015) designed a deployable shading system for adaptive façades, which is manipulated through the variation of geometric parameters using Shape Memory Alloy (SMA) actuators. Kuru *et al* (2019) designed a façade shading system inspired by Echinocactus Grusonii, a golden barrel cactus that can regulate light via the change in surface temperature induced by the areoles' opening-closing mechanism that ensures self-shading via spines. The shading system is inspired by modular origami geometry and performs using SMA springs, which are sensitive to temperature variations that change the glazing shaded area according to solar irradiance levels. Schleicher et al (2011) established a façade shading system based on a hinge-less flapping mechanism inspired by the bird-of-paradise. The system is further enhanced by adapting its geometry to curved façade panels based on Aldrovanda vesiculosa's trapping mechanism. Using dynamic transitory sensitive material, Hosseini *et al* (2021) created an interactive-kinetic facade that allows regulating daylight needs and visual comfort based on sun-timing position and different user positions in the office. The opening-closing sun movement of the plant's stomata inspired the dynamic mechanism.

The results show that the developed system is very effective on the south facade and achieves average spatial daylight autonomy of 60.5% with a useful daylight illuminance of 90.47%, which exceeds the useful daylight illuminance of 2.94%.

Hadbaoui (2018) established a responsive facade to regulate solar exposure inspired by thermonastie, which is the natural phenomenon responsible for the thermally adaptive behaviour that consists of opening and closing movement. The study aims to reduce the indoor temperature. The results show that the temperature was reduced by about 1.7°C and 3.4°C with respect to the initial temperature.

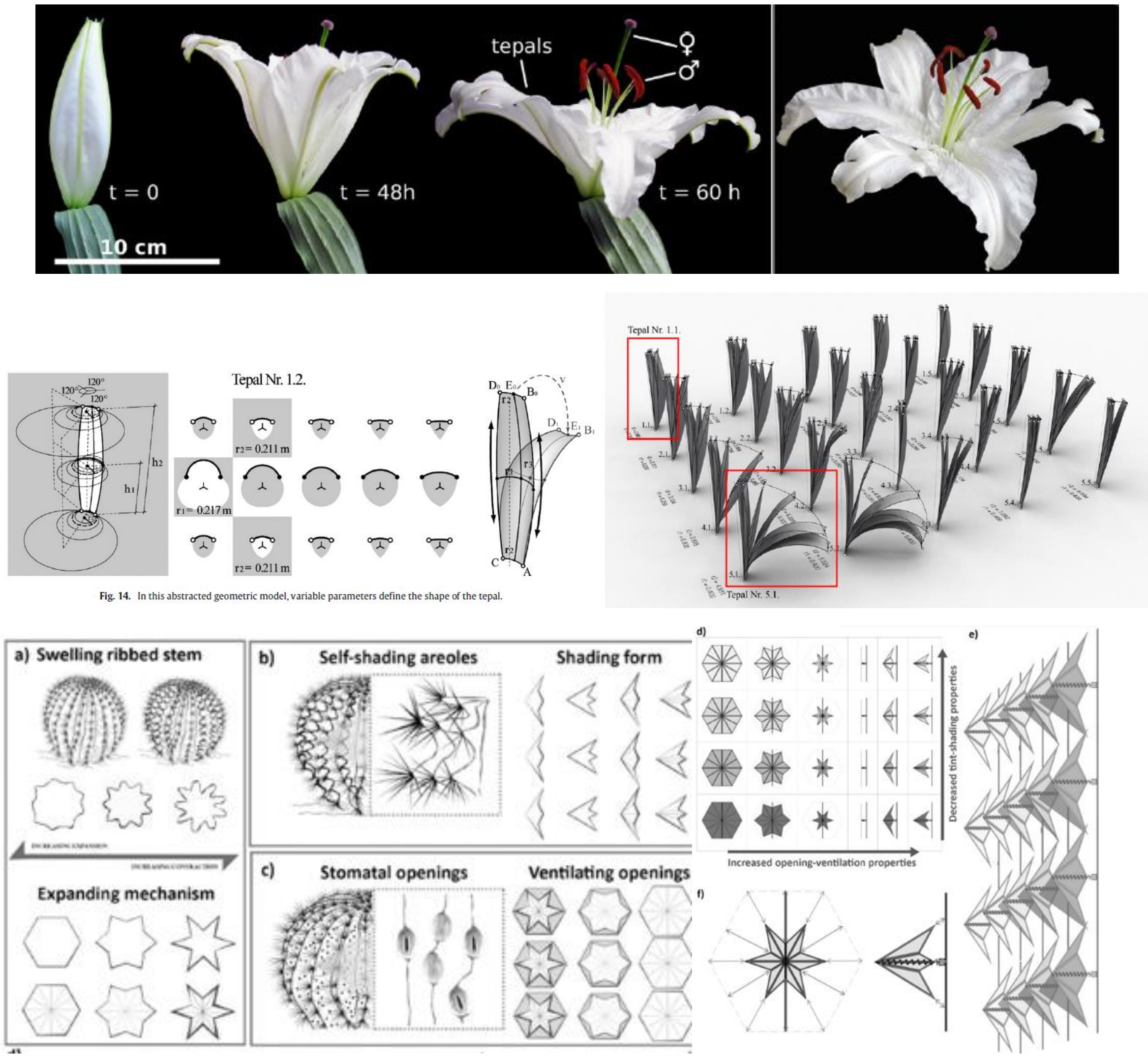


Figure IV-6 : a: inspiration design source, b: geometric abstraction, c: application to architecture systems.1 : *(Kuru et al., 2021)* 2 : *(Schleicher et al., 2015)*

IV.4.3 Intrinsic traits and extrinsic relationships of bio-morphing approach

The use of a bio-approach in the design process results in novel solutions in a wide range of fields. Still, biomimicry, which is a new field, needs to be studied in depth so that its methods and tools can be used in architectural design. Thus, in order to improve the effectiveness of biomimicry science, researchers should conduct a critical analysis of its intrinsic traits and extrinsic relationships. Indeed, the intrinsic traits of biomimicry represent the main characteristics of bio-information as well as the mechanisms that influence the efficiency of the bio-inspired design approach. While its extrinsic relationships are the characteristics of the design field that impact the bio-approach's implementation.

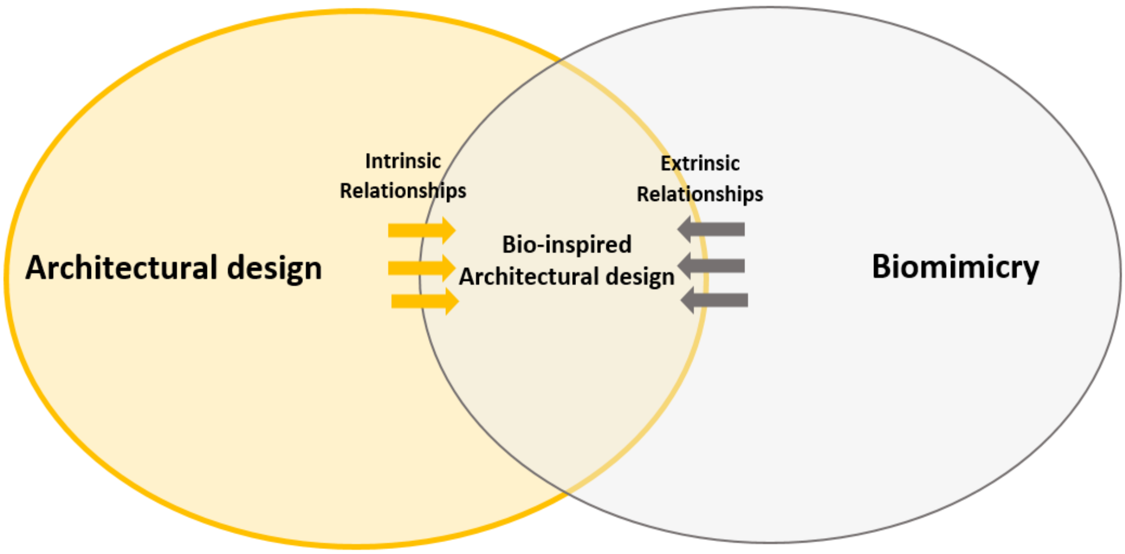


Figure IV-7: intrinsic and extrinsic relationships of bio-inspired architecture (Author, 2022).

Accordingly, biomimicry's intrinsic traits impact the bio-inspired architectural design process. The natural world is characterised by its diversity since it includes numerous communities and sub-fields, such as plants, animals, insects, and others that are separately addressed in several research works. Hence, the functional challenge should be accurately defined, which helps choose the appropriate natural community and, subsequently, the design inspiration source. For instance, many architectural adaptation mechanisms were inspired by plants due to their static state (Cruz *et al.*, 2021), (López *et al.*, 2017) and the elasticity of their members in performing movements, such as in adaptive facade systems (Schleicher *et al.*, 2015). Furthermore, a recent biomimicry sub-field, known as "geo-derived developments" (Speck *et al.*, 2017) has emerged, which encourages designer inspiration from the natural dead world (geology), based on non-bio-concepts. According to Butcher & Corfe, (2021), geo-inspired science was proposed by William Whewell and developed by the English geologist James Hutton, then popularised by Charles Lyell, who considered that future innovative solutions reside in the geological past. This sub-field relies on biomimicry approaches.

Moreover, **the multi-functional aspect** of natural organisms is very challenging to transfer to design fields (Cruz *et al.*, 2021). Consequently, biomimicry's methods and tools are generally developed to resolve a single functional challenge. Functional trade-offs can be set between contradictory objectives of the same nature, but rarely between two different functions. In fact, designing **multi-functional solutions** is complex and would lead to higher design effectiveness levels (López *et al.*, 2017). Furthermore, a major point of contention in the bio-approach is the use of terms to identify and describe functional mechanisms. Different types of terms are grouped together in the same category.

Meanwhile, biomimicry was implemented in the architectural design process to enhance several functional aspects. Only bio-BSM strategies are discussed in this section, i.e., studies dealing with the bio-inspired morphology of the building shape and its components, such as the envelope shape, the envelope's element shape, and its structure, because the envelope is rarely treated as an entire entity. Thus, bio-BSM strategies mostly focus on the development of adaptable facade systems (Asefi, 2010) or bio-inspired structures (Dixit and Stefańska, 2022). As a result of its reliance on mathematical principles and theorems, the transformation of an entire building's design is typically more difficult than the manipulation of adaptable facade components or the building structure. Additionally, the dynamic aspect of adaptable façade's systems and their modular geometry facilitate both the design and construction processes. Schleicher *et al* (2015) considered this feature to be advantageous in comparison to the overall building shape design. In fact, the building form and the design of the façade elements should be complementary phases of a single process to optimize the building envelope's efficiency. When the entire building shape is treated, it is possible to define the main characteristics of the facade's shape, such as orientations and tilt angles, which can then be further regulated using dynamic facade systems. The building's shape is primarily defined by its structural elements' shape, which has been widely inspired by functional natural mechanisms during the last century (Hu, Feng and Dai, 2013).

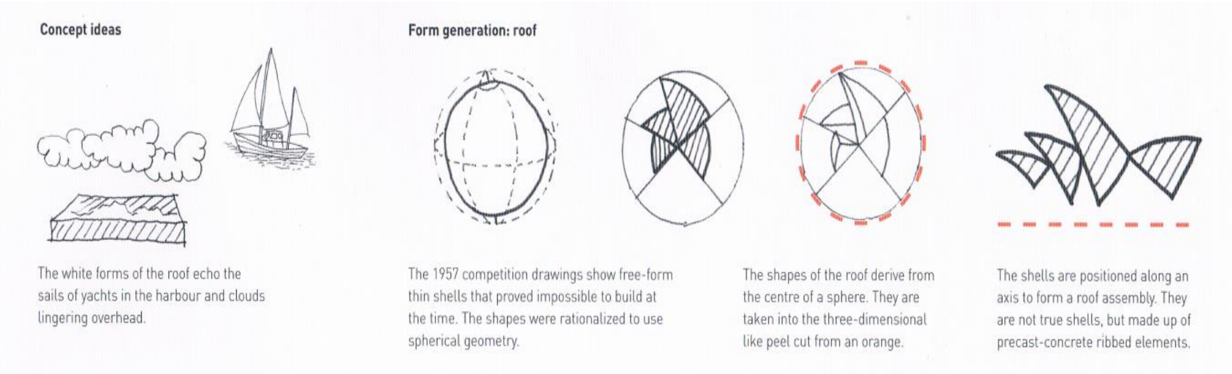


Figure IV-8: The process of form generation (Antony Radford, Selen Morkoc and Amit Srivastava, 2014)

Indeed, many researchers have suggested methods and tools to make bio-information transfer more flexible. Vincent (2001) acknowledged that bio-information transfer can be accomplished by passing through several design stages. The more additional details that are addressed, the more successful the bio-information transfer and the design concept will be. Accordingly, the top-down approach is more effective in the engineering discipline. Based on Figure. IV-9, additional knowledge, such as physics, is needed in the advanced transcription phases.

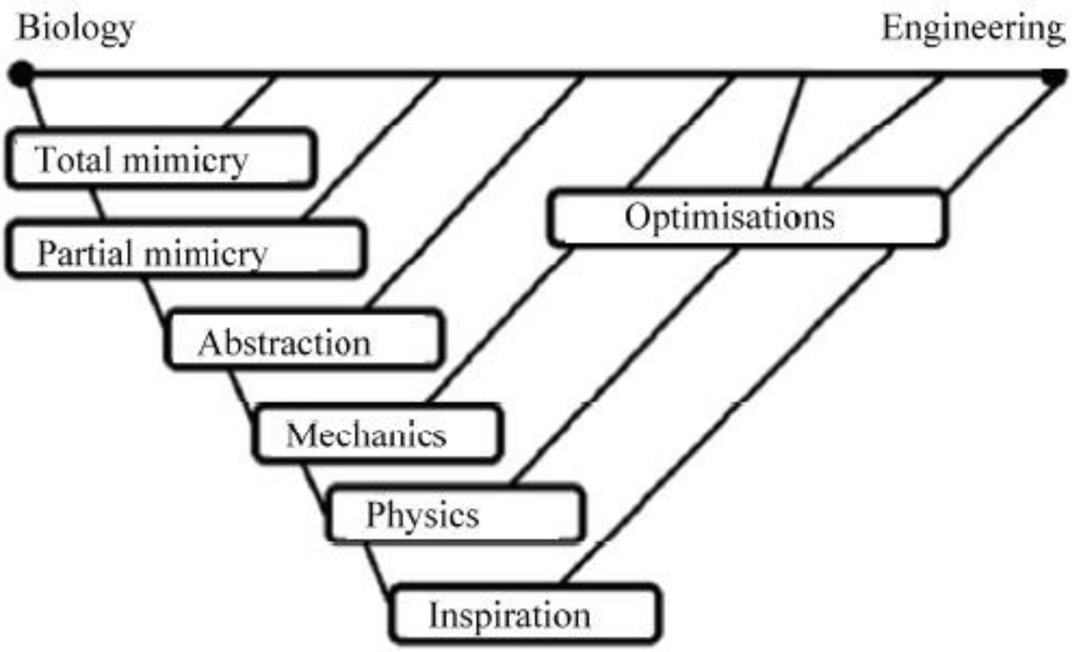


Figure IV-9 Biomimitic map (Vincent, 2001)

(López *et al.,* 2017) analysed the theoretical principles of bio-approach design and suggested a methodology for transferring biological information specifically from the botanic world to architecture. Furthermore, Al Amin, Taleb (2016) adopted a biomimicry thinking process that consists of three parts: scoping, discovering, and creating and evaluating. Scoping includes analysis of the studied building and its climate to identify areas for potential improvements in terms of climate responsiveness and energy efficiency. Furthermore, Hu, Feng and Dai (2013) discovered a link between natural words and bridge design to facilitate inspiration. Thus, building designers are aware of the difficulties of bio-knowledge transfer to design fields and look for more tangible transfer tools and methods. In this chapter, we examine the connections between architecture and biomimicry.

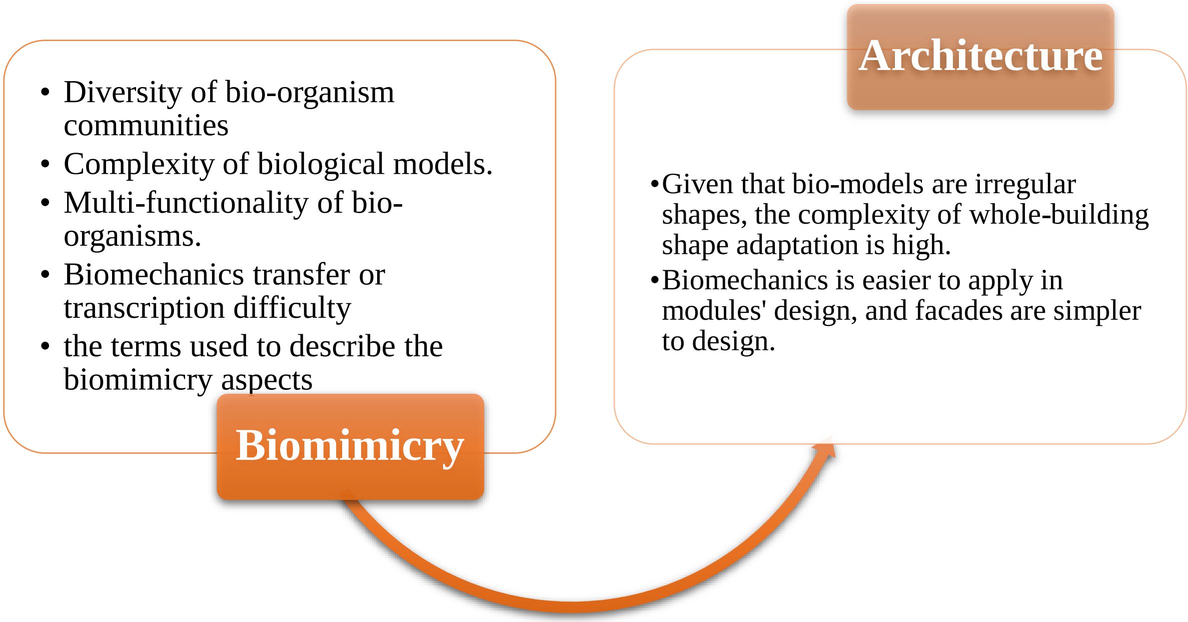


Figure IV-10 : biomimicry-architecture relationships (Author, 2022).

IV.4.4 Bio-Bridge design path-line implementation in bio-inspired approach

Bio-knowledge transfer is the crucial step that must be revised to ensure a successful implementation of bio-inspired approach in architectural design. In the present chapter, we suggest outlining the connection points between the two fields to make **the transition from biology to architectural design more flexible**. These **key concepts**, called **"bridge concepts"** help set a relevant design concept and get closer to the optimal solution. They emphasize the most impactful notions in the bio-knowledge transfer process, minimizing the field of possible solutions and, consequently, saving time and energy.

In this study, the goal of the design process is to find connections between theoretical ideas at different stages. In fact, our method was made with a Bio-Bridges line-path design in mind to make it easier to come up with design ideas. The suggested line-path phases have been organized introducing bridge-concepts that help architects select the appropriate bio-inspiration design source and then derive the design concept from its functional mechanisms.

IV.4.4.1 Biomimicry Levels

The terms used in the bio-approach to designate its different aspects and elements should be accurately chosen. The meaning of the term "levels" in biomimicry is different for different research teams. (Al Amin, Taleb 2016) defined three main levels: organism, behavior, and ecosystem, with additional sub-levels considered in terms of dimensions, including form, material, process, and function (Kuru *et al.*, 2019). A similar definition was suggested by (Al-Obaidi *et al.*, 2017) maintain form and ecosystem and substitute behaviour through process. Moreover, Al-Obaidi *et al* (2017) admitted that the form encloses the shape, its components, and materials. While material reactions are mostly unrelated to their morphological aspect, "Process" as a term does not actually describe the natural functional mechanism. Finally, "Ecosystem" represents the entity that encloses the above levels: form and process. On the other side, Hu, Feng and Dai (2013) found that the bio-design approach is mostly superficially addressed. They describe levels based on inspiration, distinguishing high and low inspiration levels. Nevertheless, the notion of "deep" in biomimicry is strongly related to the analogy. Moreover, Vincent identifies two classifications: total and partial, based on the monofunctional and multifunctional aspects of bio-organisms. Dixit and Stefańska (2022) identified three levels of biomimicry, beginning with the geometric level, which includes a mathematical theorem that aids in the generation of three-dimensional shapes, such as Delaunay triangulation. The second is the behavioural level, which is related to the surrounding conditions and the natural adaptation mechanisms developed by natural organisms. The third level is the ecosystem that treats the multi-functional performance aspect of a building.

These conflicting definitions push us to give the term "level" an appropriate meaning in biomimicry that makes the bio-inspired process clearer. In fact, it is important to distinguish between biomimicry aspects and levels before getting into **the functional technical level** (mechanism). Firstly, we should define biomimicry levels, then aspects within each level, including mechanisms and **inspirational aspects**.

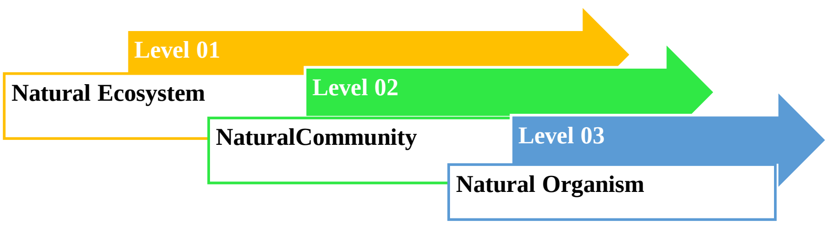


Figure IV-11 Biomimicry levels (Author, 2022).

IV.4.4.2 Analogy-based design

Broadbent (1978) says that four different methods have been applied when forming an architectural style. These have been described as the following approaches: Pragmatical, Typological, Canonical, and Analogical (Usta, 1994) (Tavsan, Tavsan and Sonmez, 2015). Biomimicry is based on analogies limited to the natural world. In fact, the bio-approach is a specific approach to analogy-based design that takes inspiration from nature. Analogy is a cognitive mechanism that helps learn new concepts (Tavsan, Tavsan and Sonmez, 2015). Analogy-based thinking helps assimilate new concepts based on their similarities or contradictions with existing ones. Thus, analogy-based design involves, a mapping between the features of the existing concepts, and those of the new ones (Glynn et al., 1989) (Tavsan, Tavsan and Sonmez, 2015). In biomimicry science, analogies could be established for several functional mechanisms. However, its application in the morphological aspect can be classified into two categories: the **deep** and **superficial** ones. In architecture, many buildings were inspired by only the natural morphological shape, regardless of the functional aspect. This kind of inspiration can be found through history, such as in Greek or Egyptian civilizations, and is classified as superficial. Deep analogy involves the functional aspects of any analogical aspect, such as behaviour and others. Therefore, nature has constantly been an inspiration for architectural shape and architectural theory. Biomimicry cultivates architect creativity, and we can say that analogy is a design bridge method between architecture and biology.

Knowledge transfer is a mandatory step and the key principle of an analogy-based design process (Gomes *et al.,* 2006). The theory is called model-based analogy (or MBA) It relies on setting functional relationships between the different design elements, which can be: structural behavioural or functional (SBF) models (Goel and Bhatta, 2004). Furthermore, in analogy-based design, abstraction is considered a tool to embed effective analogies in the design process. Ishikawa, et Terano (1996) investigated the utility of analogy by abstraction (ABA) in establishing innovative design. In fact, analogy by abstraction (ABA) is a thinking algorithm to find design solutions. It is based on specific actions that lead to innovative and effective design solutions. These steps are: SEARCH, ABSTRACT, REFINE, APPLY and VERIFY.

IV.4.4.3 Mathematical tool

The goal of a design process is to come up with a physical object that can be made easily using rules and theorems from physics or math. Plato believed that there was a perfect solution for everything. It is through mathematics that forms and patterns can be understood. It helps define the Platonic ideal (Allison, 2008). Identifying the appropriate math rules and then embedding them into the design process is the key to a successful bio-knowledge transfer. Moreover, the mathematical transcription of theoretical concepts is a mandatory step to ensure the link between the theoretical design concept and its transcription into a design algorithm using computational design software.

The main difference between architecture and abstract art is that architecture can be built. Architectural design and industrial design are philosophical and abstract ideas that are difficult to concretize into a building. This requires the natural laws of mathematics and physics. So, the right choice of the mathematical tool is decisive and determines the appropriateness of the established method. Furthermore, the main objective of elaborating design tools in bioclimatic architecture, and especially in the field of solar architecture, is to make solar design easy by allowing designers to use simple mathematical or digital tools. As a result, using math rules aids in the development of simple design tools that can be applied in a systematic manner. In other words, according to the study objectives, designers must find the appropriate mathematical law that links between the architectural design thinking philosophy and the digital modelling and form generating process. Using exact sciences enables the development of practical design tools and methods. Additionally, rules and digital design tools are both based on mathematical rules.

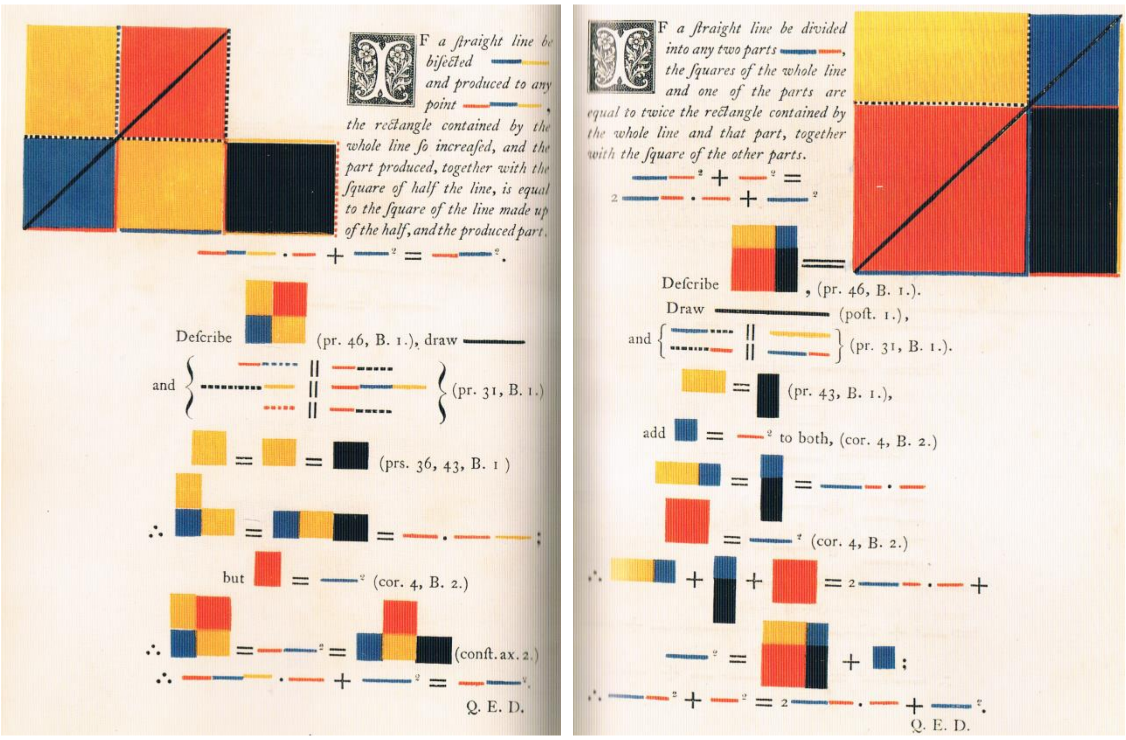


Figure IV-12: mathematical laws explained through the use of geometric figures to show the relationship between maths and geometric forms (Werner Oechslin, 1847).

A three-dimensional object can be physically expressed or described using mathematics. However, mathematical tools are diverse. Thus, the designer must find the most appropriate mathematical rules or theorems that describe the type of geometries he desires to generate. Exploration of geometric shape classification in mathematics, or collaboration with mathematicians, is required to facilitate design generation and development. Moreover, mathematical basic rules can be implemented as a starting point to derive more adapted equations and rules (Zboinska, 2015). Accordingly, the same mathematical rule can be used to generate many designs using mathematical models, which means that mathematics enhances the designer's creativity and helps embed the design rules into computational software. For example, Heinrich Scherk, a renowned mathematician in periodic minimum surfaces, contributed to the creation of a lattice in 1834 by iterating repeatedly over a surface to produce a regularly repeating lattice of these forms (Sutcliffe A., 200) (Zboinska, 2015).

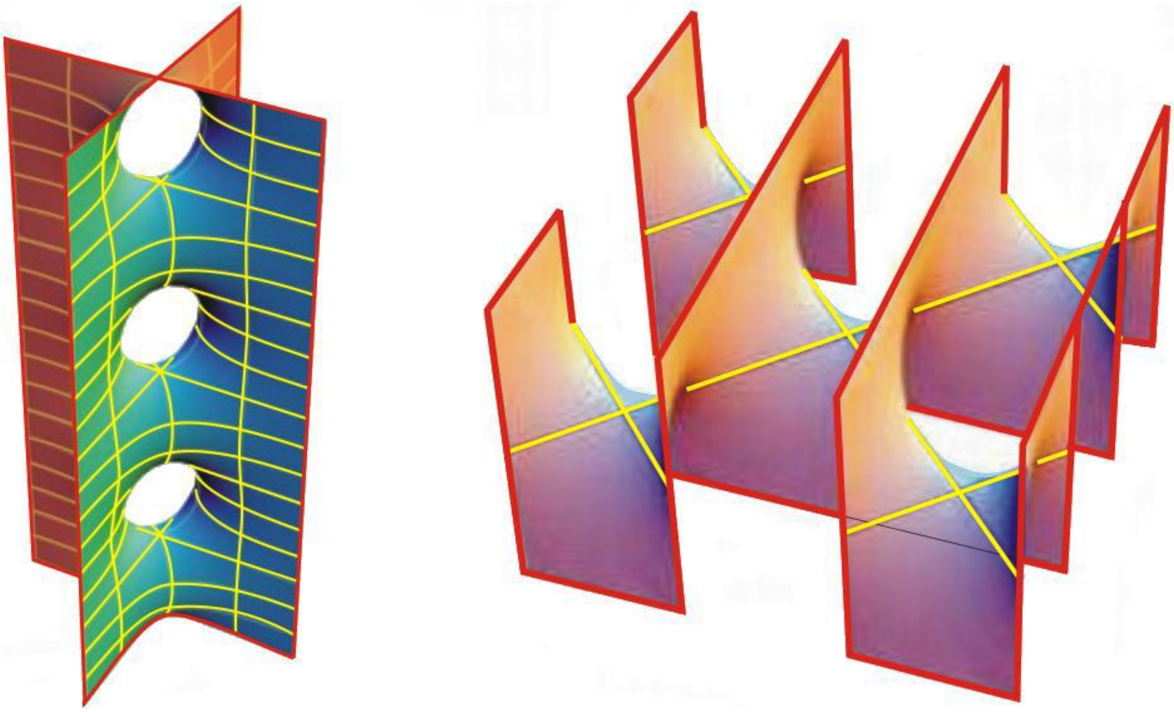


Figure IV-13: Singly-periodic Scherk surface with angle Ø= π/2
2 (left), and its conjugate surface, the doubly-periodic Scherk surface (right). Images courtesy of M. Weber. *(Meeks & Pérez, 2012)*

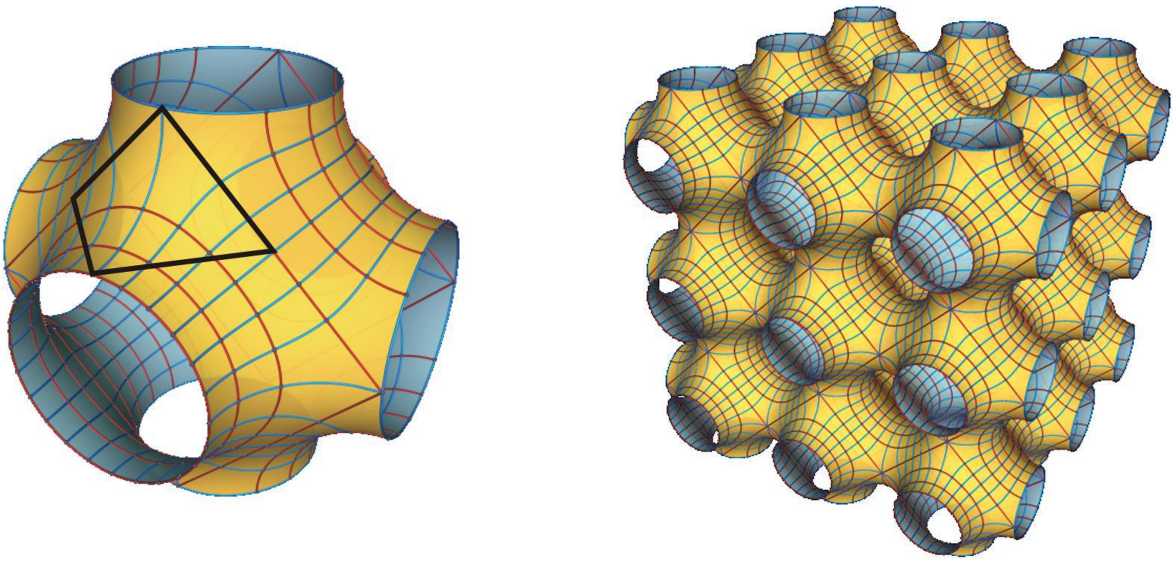


Figure IV-14 : Left: A fundamental domain of the Schwarz P-surface, with a graphical quadrilateral. Right: A larger piece of the corresponding space tiling. Images courtesy of M. Weber. *(Meeks & Pérez, 2012)*

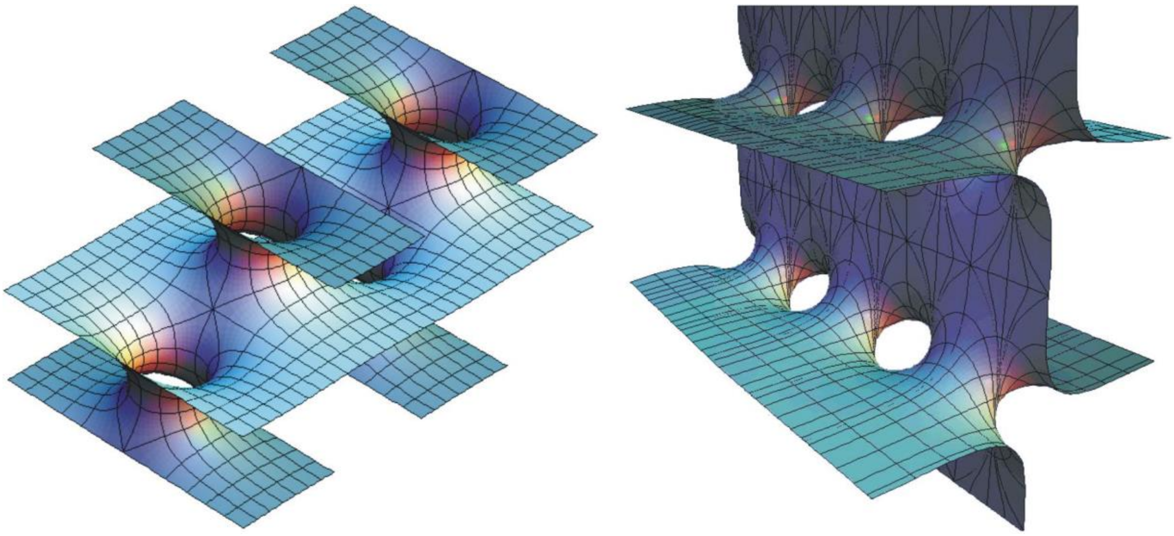


Figure IV-15: Two examples of doubly-periodic KMR surfaces. Images taken from the 3D-XplorMath Surface Gallery.Design approach *(Meeks & Pérez, 2012)*

IV.4.4.4 Design approach

There are numerous design approaches that impact the results of the bio-inspired design process. They have mostly emerged from the embedding of computational design tools. As demonstrated in the first chapter, several design approaches with varying logic-thinking exist. The latter has an impact on the design's outcome and features. As a result, the use of appropriate approaches and their combination with biomimicry must be done precisely. Hence, as in other architectural design tendencies, bio-inspired architecture was influenced by innovative design tools and approaches. Computation helps develop and evaluate new ideas inspired by nature, which is difficult to do otherwise. (See chapter.02)

The adaptation of the bio-approach to architectural design requirements resides in the restructuring of its steps and the relationships between its elements. Accordingly, the above-mentioned bridge concepts are embedded into the bio-approach as connecters between its main steps and elements.

As shown in Fig. IV-16), the bridge concepts are mainly integrated in the solution system derivation step. They help to accurately find the appropriate natural source of inspiration. Levels allow for a gradual examination of the possible natural communities and the definition of the limits of the research fields: ecosystem, organism, or mechanism. In fact, the challenge in bio-approach is basically functional. Consequently, an analogy-based definition allows for clearly outlining the nature of the needed functional mechanism. These permits identify the science that will help designers derive a relevant design concept, such as mathematics or physics. The transcription of functional mechanisms into a mathematical model is the key to the generation of relevant design concepts. It can be sufficient to end the process by establishing design rules derived from a functional mechanism using math. However, the incorporation of mathematical models into computational design tools allows for the evaluation of the design product and further exploration of the possible design solution field.

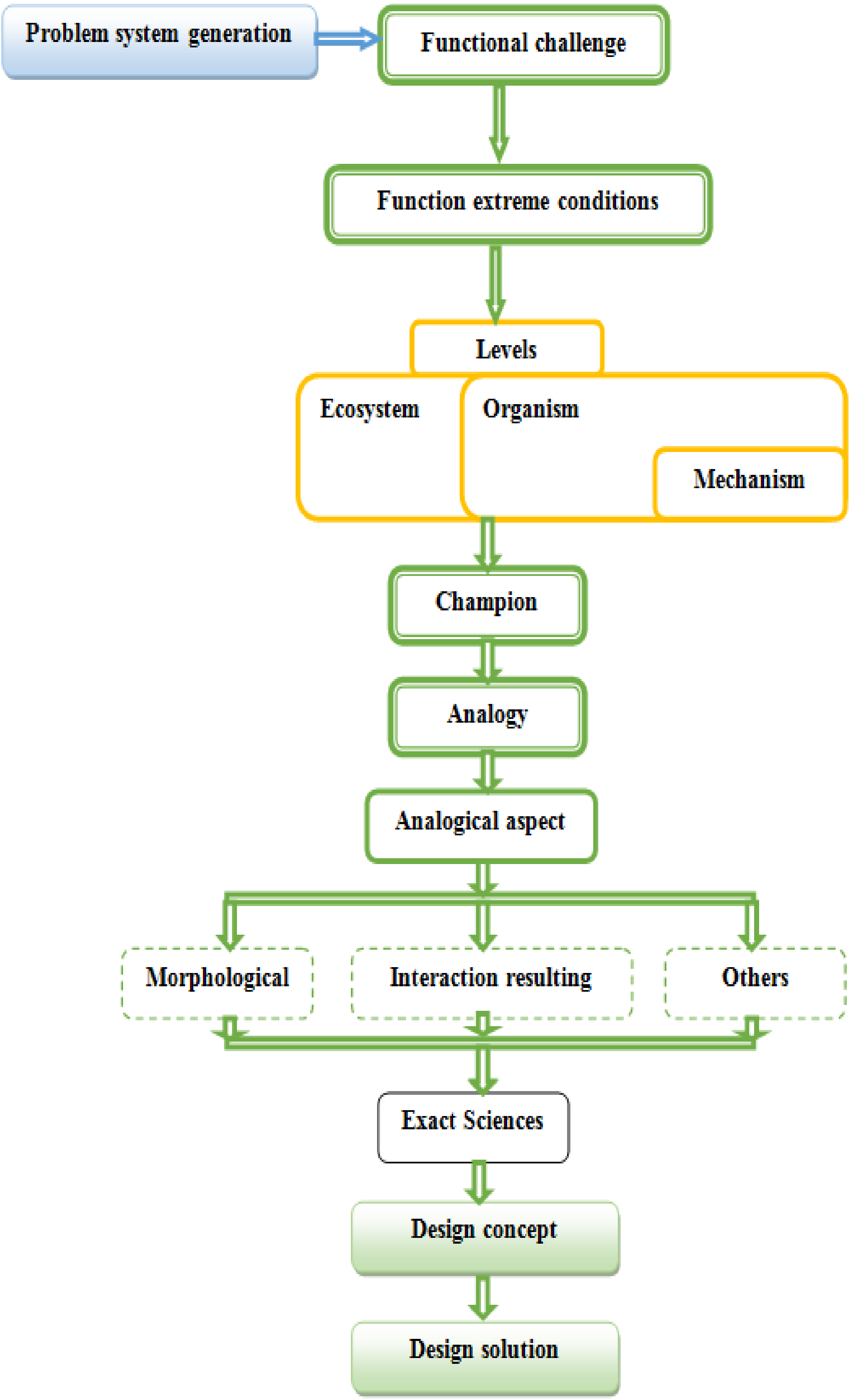


Figure IV-16: Bio-Bridge line path (Author, 2022)

IV.5 Conclusion:

Nature was and remains the best teacher of know-how to human beings. Biomimicry was established in order to facilitate transferring nature's know-how to our real lives. Unfortunately, this transfer faces numerous challenges, especially in certain fields, such as architecture. Consequently, many researchers addressed this topic, trying to resolve this problem, by suggesting new design methods and tools.

This chapter's primary contribution is identifying the reasons for the failure of bio-knowledge transfer to architecture. As a result, we attempted to outline the bio-aspects influencing architectural design as well as the architectural design specificities influencing the bio-approach. These concepts were called intrinsic and extrinsic relationships, respectively. It is commonly thought that embedding biomimicry in architectural design gives complex forms that are not easy to construct and require advanced technologies and resources. The aim behind applying biomimicry in architectural design is to free the designer from existing paradigms and expand the domain of possible solutions.

Therefore, the redefinition of certain concepts, such as levels and functional or analogical aspects, was mandatory to restructure the process that leads to a successful solution system and relevant bio-knowledge transfer.

CHAPTER V. APPLICATION OF BIO-BRIDGES PATH LINE DESIGN AND THE ESTABLISHMENT OF GEO-SOLAR SEGMENTATION ALGORITHM

Chapter V Application of bio-bridges path line design and the establishment of geo-solar segmentation algorithm

V.1 Introduction:

As seen in the first part of the thesis, the basic theoretical concepts of innovative architectural design approaches are discussed to define the study framework. However, they are addressed separately in three different chapters. Therefore, the present chapter aims to connect the different theoretical concepts in one section to explain the step-by-step sequence of the adoption of a bio-inspired solar approach in the architectural design process. Hence, the relationship between the design elements is outlined by explaining how knowledge of different areas can be connected to help set an innovative design path.

In fact, the above-established design line-path bio-bridges in Chapter 4 are implemented by highlighting the main design elements, stages, and tools in order to validate their effectiveness. The different disciplines implemented design outline approaches in the present study to set the solar design algorithm for building morphing.

The methodology section describes the sequence of solar morphing and the tools used to generate an optimal segmented building envelope (SBE). Initially, when applying the top-down design approach, a naturally occurring phenomenon is identified and a bio-design concept is derived from it to respond to solar constraints.

The partial conclusions of the present chapter are explained using mind maps (schemes). The proposed bio-bridges design path-line is a tool that connects the theoretical basic concept implemented in the design process with the transition to a practical level by deriving **a generative design concept**.

V.2 Highlighting basic interdisciplinary connections in Bio-Bridges line-path

In fact, the ideas about innovative design in the first three chapters come from many different fields. While their common point is their contribution to enhancing the designer's creativity and, as a result, assisting in the production of innovative design solutions. The analysis of bio-inspired BSM strategies revealed that interdisciplinary collaboration is essential for successful innovative architectural design. The relationships between the above-explained design approaches (see chapter 2) must be detailed in order to derive an effective design concept. As a result, several approaches are combined to achieve functional complementarity. Accordingly, two main interdisciplinary interconnections that govern the establishment of our BSM method are abundantly explained.

V.2.1 Interdisciplinary connections between biomimicry and technology

The implementation of biomimicry in the design field results in the generation of design products with complex geometry and functional mechanisms. The development of solar bio-inspired BSM strategies in architectural design has been limited to dynamic facade systems. However, the whole building form was rarely treated. For these reasons, advanced technological tools have been embedded in the bio-inspired design process to help generate unusual geometries. Furthermore, using high-tech devices and systems, solar bio-inspired façade systems and related adaptation strategies have been successfully realized. Schmitt (1969) attributed biomimicry to successive technological evolutions. In fact, in ancient Greek philosophy, the term "téchne" designates the meaning of the coupling of two other terms: "art" and "technique", which both include the know-how and rules of several activities and crafts (Palombini). Thus, we admit that technology is the art of know-how, which means that biomimicry and technology interact with each other to reinforce innovation and creativity in the design field. Subsequently, technological progress frequently relies on bio-inspired procedures and appliances. For instance: Benyus emphasises the leading role biomimicry plays in technological development, through the imitation of natural material properties and the implementation of natural growth and behaviour algorithms in the design field (Dixit and Stefańska, 2022).

Furthermore, the evolution of architectural form expression (see Chapter 1) In architectural design, this is attributed to the emergence of digital design tools that rely on the use of generative algorithms. The latter are derived from natural sciences, such as genetics and its principles (crossover, iteration) (see Chapter 2). In fact, the parametric design approach helps embed natural system evolution algorithms through genetic algorithm-based design. Thus, the natural creatures' evolution and growth order are applied in design production. Beyond its contribution to the design field, biomimicry is considered an economic development tool in some countries. For instance: the contribution of biomimicry to the US economy was estimated in 2008 at about USD 1.5 trillion, and it provides about 1.6 million new jobs(Dixit and Stefańska, 2022). Unfortunately, the use of biomimicry and especially bio-inspired technologies is very limited in some countries, like Algeria.

Meanwhile, despite the effectiveness of biomimetic tools and strategies, there are researchers and designers that disagree with the fact that nature is perfect (Töre Yargın, Moroşanu Firth and Crilly, 2018).

Nature also includes all of the life sciences and is the setting for many chemical, physical, mechanical, and other interactions. The natural interaction series occurs in perfect harmony and complementarity. Accordingly, numerous disciplines support the bio-inspired design approach. Thus, interdisciplinary interconnection enriches the bio-inspired design process and permits it to achieve its targets. Hence, interdisciplinary interconnection results in the emergence of new ideas, philosophy, design principles, new styles, and consequently, new technologies (Yuan *et al.,* 2017). During the 21st century, the evolution of biology was behind the progress made in several fields. Subsequently, if philosophy is the mother of sciences, biology becomes the motor of evolution that ensures sustainability and eco-friendly development. In fact, the architectural forms generated using a bio-inspired design approach are generally characterised by their complexity and free form. Consequently, the treatment of details, such as sculpture, is neglected in favour of an innovative general building form. Thus, architecture with repetitive elements has emerged (Dixit and Stefańska, 2022). Thus, mathematical models are required to analyse complicated natural shapes and systems. Transcribing a design using math's rules is a kind of abstraction, which must be a crucial stage in the biomimicry design process. Hence, mastering the bio-design process requires specific knowledge of the mathematics that governs the studied phenomenon. For this reason, architects have to understand geometry and math rules in order to develop bio-inspired design tools and make the bio-design process as clear as possible. Therefore, a bio-inspired design process is the result of the interconnection between life sciences, technology, and a parametric approach.

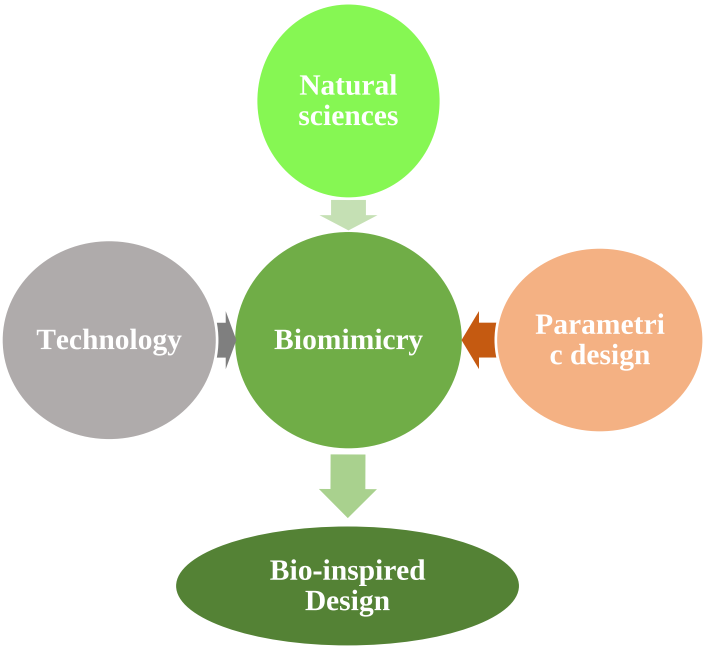


Figure V-1 Interdisciplinary in biomimicry (Author, 2022)

V.2.2 Interdisciplinary interconnection between solar geometry, mathematics, and parametric approach

The study of solar phenomena relies on an understanding of the basics that treat both the geometric and energetic aspects. In fact, the solar phenomena are the results of earth movement around the sun. However, in architectural solar design, the earth is considered static and the sun is in constant movement around to facilitate the geometric representation of the sun's movement. This movement is called the sun’s apparent motion, which is described using a mathematical theorem, specifically trigonometric rules. Therefore, mathematical geometry is the basis of solar geometry and, subsequently, architectural solar design (Fig. V-2)

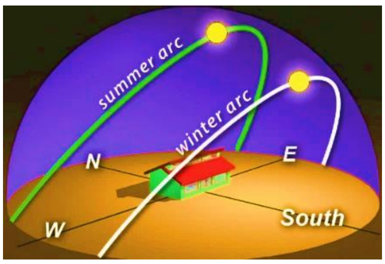


Figure V-2: Sun’s apparent motion

https://www.permaculturenews.org/2015/10/23/charting-the-suns-motion-in-relation-to-your-home-and-permaculture-site/

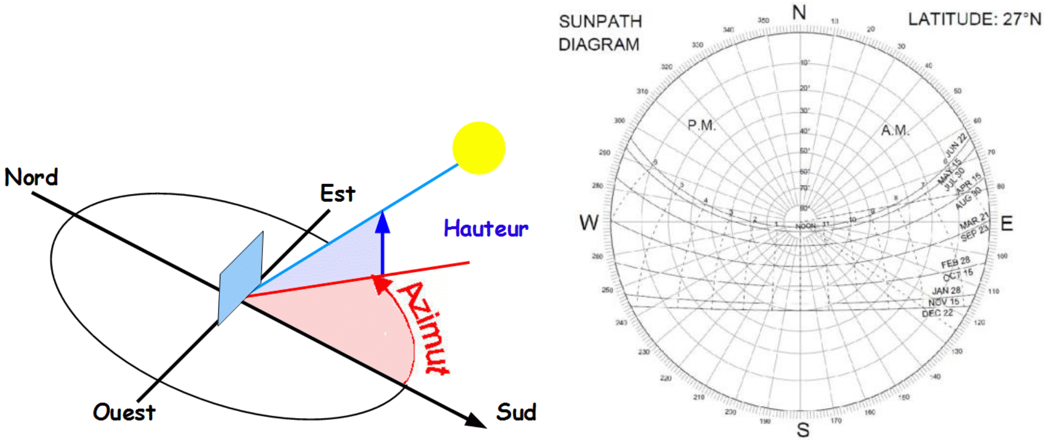


Figure V-3: solar coordinates and diagram

http://michel.lalos.free.fr/cadrans_solaires/doc_cadrans/theorie_cs/notions_astronomie.html

As seen in Chapter 2, most of the developed BSM strategies are assessed using software that performs based on a parametric design approach, which basically relies on a mathematical parametric model. Additionally, the design of facades’ solar systems is done based on changing their configuration through the manipulation of a set of geometric parameters. The parametric design approach is not only effective in bio-inspired design but also in architectural solar design. Therefore, responsive building skins rely on many technologies. For instance, some research studies dealt with mechanical systems, which require the exploration of mechanics to understand the basis of the systems' construction (Hudson, no date). Therefore, interdisciplinary connections between solar design, mathematics, and parametric approaches are mandatory to reach the design process targets. Otherwise, the innovative design approach in architecture is very challenging; since architects must at least have an idea on the several embedded disciplines in the design process (Fig. V- 4) (Fattahi Tabasi and Banihashemi, 2022).

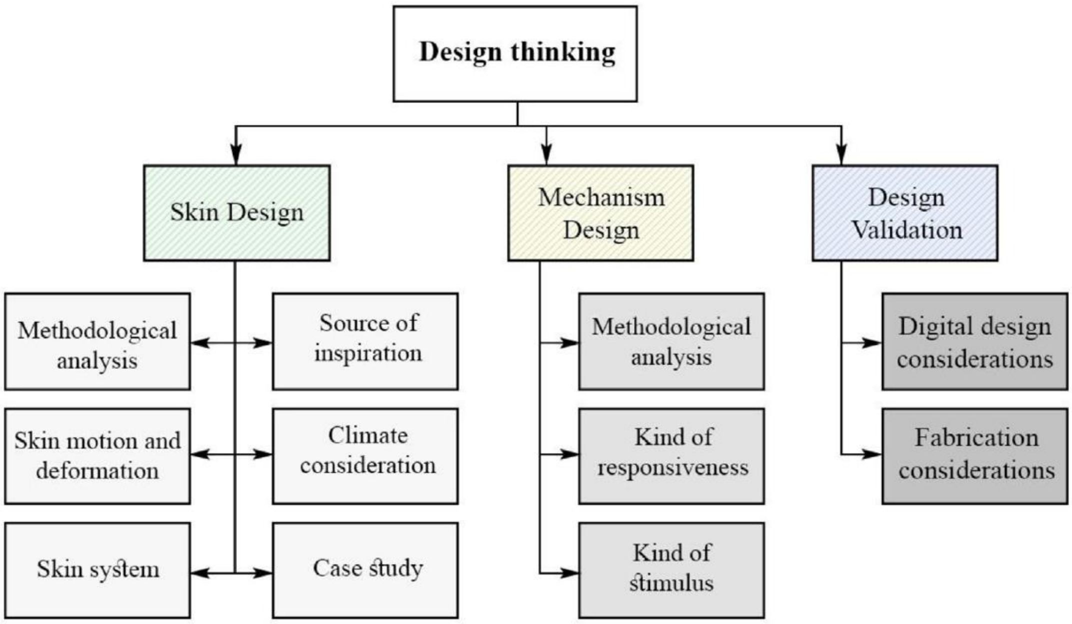


Figure V-4 : design thinking and interdisciplinarity interconnexion (Fattahi Tabasi and Banihashemi, 2022)

V.3 The aim and the objectives of the study

Despite the existing literature (see Chapter 4) on bio-inspired BSM strategies, it remains insufficient. Most of the BSM studies suggest bio-inspired façade dynamic systems; the bio-inspired static building envelopes are rarely addressed. The application of BSM strategies is limited to envelope optimization. However, in the current study, the suggested method is applied to generate a building envelope as well as optimise its performance, i.e., regulating the total solar radiation received by the building envelope. Accordingly, the present study aims to develop a BSM method that enhances static building envelope solar exposure. This method is versatile, allowing shape exploration for several climatic regions. It can be applied in the early design stage to avoid modifications to the building's shape post-construction. Thus, it allows for the saving of time, energy, and resources for future upgrades. Moreover, López *et al* (2017) admitted that a static building envelope does not allow a building to take advantage of available solar energy. Accordingly, our study was conducted to verify the above-mentioned statement. Furthermore, opting for an adapted static solar design significantly decreases technology charges, allows for energy savings, and makes the design more sustainable.

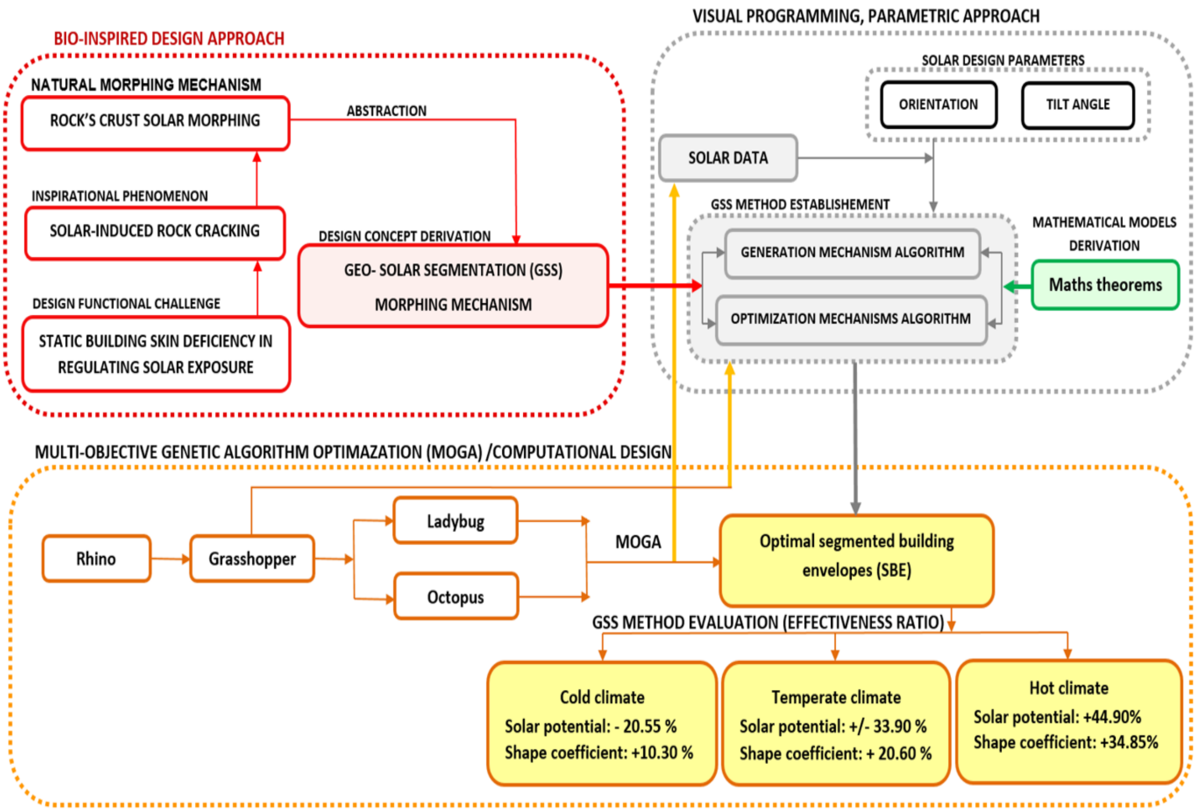


Figure V-5. Conceptual framework of the study (Author, 2022).

V.4 Application of the bio-Bridges path line approach:

Attentive exploration of the natural world increases the designer's awareness of the existing adaptation strategies developed by natural organisms. Bio-Bridges path-line approach makes the design process more rational by setting coherent connections between design elements (variables and constants). In fact, many natural systems and organisms represent potential inspiration sources for solar architectural design. Nevertheless, the natural world is vast, and it is difficult to find an appropriate inspiration source to resolve a functional design challenge. For these reasons, we adopt the bio-Bridges path-line approach (see Chapter 4) to verify its effectiveness in facilitating the transfer of bio-knowledge to solar architectural design and deriving a design concept. The sequence of the design stages is explained below.

The top-down Bio-bridge path-line consists in starting from the design challenge analysis in order to find an appropriate source of inspiration. The top-down approach design process involves four stages, in which the bridge concepts are integrated and emphasized:

- Phase 01: Challenge definition
- **Examining the eventual source of inspiration based on "biomimicry levels".**
- **Identifying the analogy aspect.**
- Phase 02: Extraction of the functional characteristics of the bio-inspiration design source.
- **Embedding mathematical modelling to transcribe the natural shaping mechanism, and derive the design concept.**
- Phase 03: Bio-functionalities transcription and design concept generation
- Phase 04: Design generation and modelling process
- Phase 05: Further optimization of the resulting solar design.

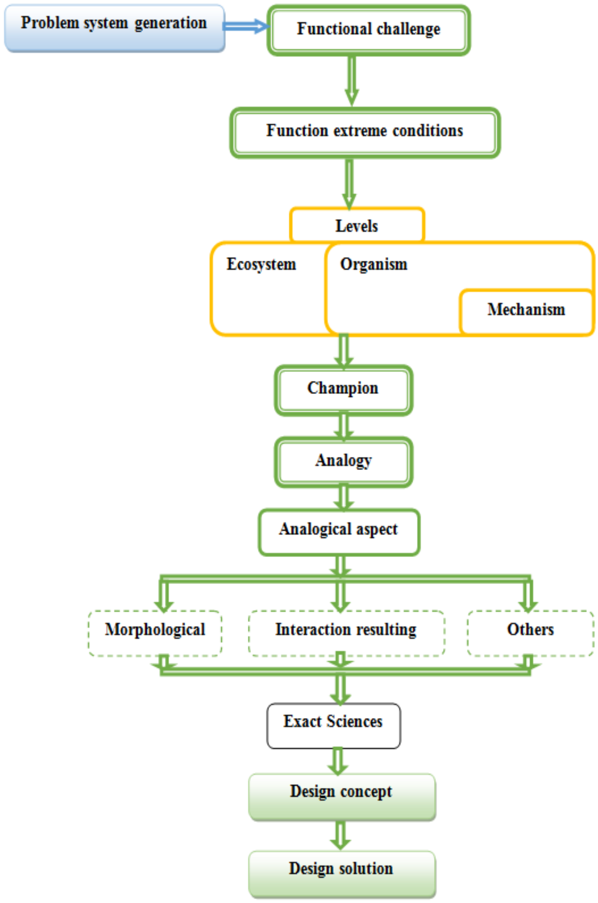


Figure V-6: Bio-Bridge Line-path (Author, 2022)

The bio-bridge concepts help the designers brainstorm through the details they provide, drawing their attention towards more inspirational ideas, facilitating the selection of an appropriate bio-inspiration source, and consequently deriving a design concept. levels, analogy, mathematical modelling, and the parametric approach will facilitate the search for an appropriate source of inspiration. The design process stages' succession, the studied details addressed in the several design stages, and the terms used in describing the different design process aspects and elements.

V.4.1 Stage 01: Definition of the problem system and the functional challenge

The functional features are defined according to two main aspects of the design, explained below.

Static building envelope

The formulation of the problem system and the addressed functional challenges aid in defining both the source of inspiration and the functional features of the design. In our case, the functional challenge of solar architectural design is clearly identified in the preceding chapters and consists in improving the static building envelope's ability to regulate its solar exposure. Accordingly, the main functional features are defined, which are:

- We should look for a static, natural organism that interacts with solar energy.
- The interaction of the natural system envelope with solar energy results in a morphing (shaping) mechanism.
- The resulting envelope shape of the natural system should last for a long time.

Functional aspects of architectural solar design

In deed the analysis of the building solar functional aspect is mandatory to understand the required functional features and the design source of inspiration characteristics. Accordingly, the architectural solar design principles are listed in the table below (Table. V-1) based on:

- Solar design functions
- Functional aspects of solar design
- Functional features of solar design

- Functional factors of solar design
- Functional parameters in Solar design.

Functional adaptation must be based on how the design works. For this reason, we started the adaptation process by making a list of the functions of solar design. The image below shows the solar functions of a building. They are identified based on the different layers (see Chapter 3) and solar design objectives, which are defined according to the climate conditions. Based on the envelope entities defined in Chapter 3, our study is interested in the first entity that involves the geometric envelope parameters being manipulated to regulate solar exposure.

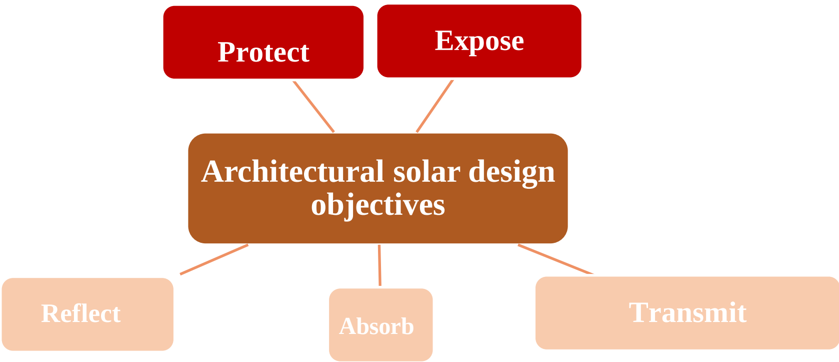


Figure V-7: solar design objective in architecture (Author, 2022).

In fact, understanding the required functional features and the characteristics of the design source of inspiration requires a functional analysis of the building's solar functions. Accordingly, the architectural solar design principles are listed in the table below (Table. V-1) based on:

Table V-1 Solar functions in architectural design (Author, 2022)

<table>
<tr><td>Solar design</td><td>Solar design functions</td><td>Solar design functional aspect</td><td>Solar design functional factors</td><td>Solar design functional parameters</td><td>Desired features of the bio-inspiration design source</td><td rowspan="6">bio-inspiration design source</td></tr>
<tr><td rowspan="5">design functional challenge</td><td>Expose</td><td rowspan="2">Morphological (external)</td><td rowspan="2">Building skin shape</td><td rowspan="2">Orientation/ incident angle</td><td rowspan="2">Position of each part ok the skin to the others</td></tr>
<tr><td>Hide/ protect</td></tr>
<tr><td>Absorb</td><td>Behavioural (external /internal)</td><td>Building envelope composition</td><td>Materials Coefficients</td><td></td></tr>
<tr><td>Reflect</td><td>Behavioural (external)</td><td>Building envelope composition</td><td>Materials Coefficients</td><td></td></tr>
<tr><td>Transmit</td><td>Behavioural (external /internal)</td><td>Building envelope composition</td><td>Materials Coefficients</td><td></td></tr>
</table>

The search for design inspiration features is then conducted at various biological levels. Fortunately, in our case, a source of inspiration at the ecosystem level was identified given its obvious interaction with solar energy.

V.4.2 Stage 02: The selection of a source of inspiration

The search for a solar morphing mechanism in nature was ambiguous. Given the fact that many bio-inspired BSM strategies are developed based on natural mechanisms inspired by plants, In fact, the first desired functional feature is adequate with the plant static state outlined by other researchers, but the third one is not. Additionally, plants are known for their adaptation mechanism of "heliotropism," which consists of tracking the solar energy. Tracking means that it is a dynamic phenomenon that relies on the motion of some parts of the plant, which means that it is not an appropriate source of inspiration given that we aim at establishing a static, solar-adapted building envelope. For this reason, we applied the first Bio-Bridge "levels," which helped us focus on a limited sub-natural world.

V.4.2.1 Applying "Levels" bio-bridge and the discovery of a new biomimicry sub-field

The implementation of "levels" as a bio-bridge helps identify the natural systems scales that are in continual interaction with solar energy. Besides its interaction with living organisms, solar radiation is a major factor in shaping the earth's crust and the various relief features, through weathering phenomena. This led us to "geo-inspired science" (Butcher and Corfe, 2021), or, in other words, 'Geo-derived developments"(Speck *et al.*, 2017), which is a biomimicry sub-field that supports designer inspiration from the natural dead world (geology), based on its non-bio-concepts. According to (Butcher and Corfe, 2021), geo-inspired science was proposed by William Whewell and developed by the English geologist James Hutton, then popularised by Charles Lyell who considered that future innovative solutions reside in the geological past. This sub-field relies on biomimicry approaches.

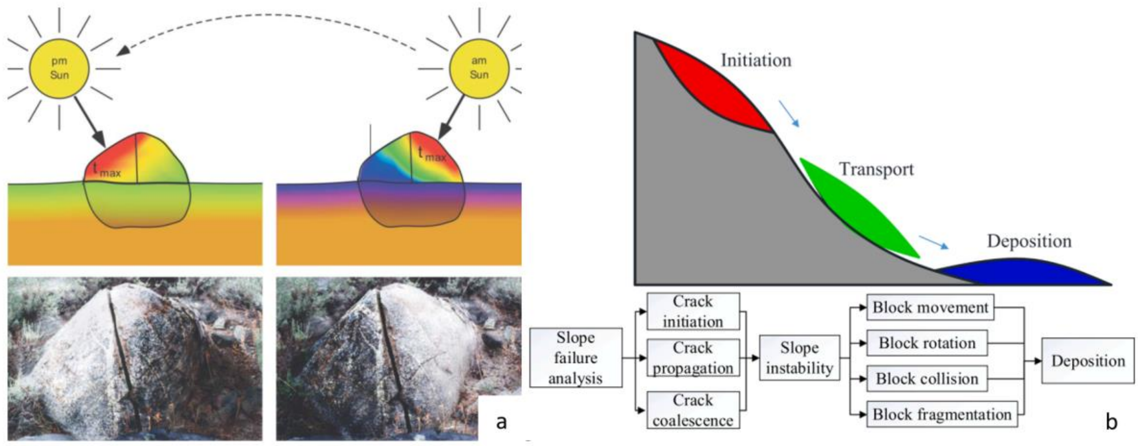


Figure V-8. (a) Temperature fluctuation*(McFadden* et al.*, 2005)*, (b) Rock cracking process*(Sun* et al.*, 2022)*.

V.4.3 Bio-inspiration design source analysis

Earth's rotation around the sun impacts the distribution and variation of the available solar energy across various regions of the world. Because the earth is shaped like a globe, its different parts (world regions) are exposed and hidden by the sun at different times. Therefore, the terrestrial reliefs represent a set of contiguous faces that are repeatedly exposed to and/or hidden from solar rays. The investigation of the earth crust shaping process reveals that the earth relief shapes vary, but they all result from two main natural phenomena that are temperature-dependent on and beneath the earth crust surface (the closer layer beneath). These two phenomena act in a complementary way: the first one is "rocks metamorphism," which is responsible for shaping the terrestrial relief, while the second one is "solar-induced rock cracking," which acts as an external sculptor and shapes the crust faces. The relief faces are continuously in touch with weather factors. Therefore, solar energy is the main phenomenon that influences temperature values by creating a temperature fluctuation between the external rock's surface and its internal mass. Moreover, solar energy influences the relief profiles' shape.

The main objective of our research is to develop a design that could best manage solar energy and derive a solar design concept. Accordingly, we explain in this section the way solar energy maintains rock stability and the reasons that lead some parts of the relief to fall down in order to expose new faces to external environmental conditions.

V.4.3.1 Solar-induced rock-cracking phenomenon

In fact, the daily and seasonal variation of solar radiation results in temperature fluctuations and produces thermo-mechanical stress that changes the rock's crust relief shape (Marmoni *et al.,* 2020). Therefore, the initial rock's mass is cracked under the solar energy effect to generate a new surface with a new profile shape (Sun *et al.,* 2022). Although, rock's crust solar-induced cracking is a dynamic process, we considered the resulting rock's shape as static assuming it is kept so, for a long time. This makes the rock-morphing solar mechanism a potential inspiration source for static building envelope design. Additionally, both the rock crust and building envelope are exposed to solar energy and enclose an internal thermal environment, which is in continual heat exchange with the external one. As a result, the current study's design concept is based on the solar-induced rock-cracking phenomenon and consists in cracking the reference building volume based on solar data to generate new profile shapes.

V.4.3.2 Metamorphism

Metamorphism can be defined as "the mineralogical, chemical, and structural adjustment of solid rocks to physical and chemical **conditions** that have generally been imposed at depth below the surface zones of weathering and cementation and that differ from the conditions under which the rocks in question originated" (Bates and Jackson, 1980)(Barker, 1990)

interactions of metamorphism factors

In fact, metamorphism is caused by changes in pressure and temperature that keep and change the stability ranges of rocks (Marmoni *et al.,* 2020). Furthermore, daily and seasonal temperature variations cause a series of dilation and contraction events that affect microfractures and main joints over time (Marmoni *et al.,* 2020). This is called **the thermodynamic effect** (Winter, College and States, 2020) that causes the mineralogical transition and changes the rock stability ranges. Therefore, metamorphism's role is to equilibrate the external and internal rock conditions. Consequently, temperature, pressure, and time are the most important factors that influence the metamorphism process. Thus, metamorphism is a mineral transition caused by a chemical reaction that results from the thermodynamic effect (Winter, College and States, 2020). On the other hand, we must distinguish between: the metamorphism phenomenon, which occurs deep down and affects the inner composition, which in turn changes the external crust's shape and texture. While, solar induced rock cracking changes the rock profiles' shape from the external side.

V.4.3.3 Definition of the morphing mechanism specificities

The derivation of an effective design concept relies on a detailed analysis of the natural inspiration source and an understanding of the functional relationships. Accordingly, the structure and appearance of the resulting rock's surface shape are discussed in this section.

V.4.3.4 Metamorphic rocks shape patterns:

The morphological aspect of metamorphosed rocks is the most important aspect to be analysed and transcribed into generative design rules that define shape characteristics. In fact, the fragmented rock faces show a particular layered texture that exhibits the organisation of the mineral rock composition. These layers are arranged according to two structuring schemes that are directly related to the mineral composition that makes up the rock and to the crystallisation process orientation. The examination of metamorphosed rock types revealed a wide range of styles and geometric models. Accordingly, two main and global types of rock layering schemes are distinguished:

- **Foliated and Lineated Rocks**

The principal shape organisation that characterises this type is **"parallelism,"** which defines the position of the different mineral layers relative to each other. Firstly, foliation and lineation refer to planar and linear organization, respectively. They both are based on the same geometric arrangement principle, which is parallelism. There are also rocks with multiple foliations and/or lineations (Winter, College and States, 2020). Furthermore, based on the crystallographic alignment of the rock, a distinction is made between two main mineral foliated and linear arrangement patterns:

Dimensional preferred orientation (DPO): According to the rock structure and its minerals' grain sizes, the rock layers are arranged following one orientation pattern. In some foliated rock types, such as: cleavage and schistosity, the orientation is generally planar but linear in other cases. Gneisses type is typically layered (also called banded); it generally exhibits alternate mineral layers.

Lattice preferred orientation (LPO): in this mineral arrangement type, we can find more than one main crystallographic axe orientation in the form of a lattice.

Examples: when micas are aligned so that the plates are coplanar, for example, their c-axes are also parallel, so LPO usually accompanies DPO. Some minerals, however, rarely exhibit good crystal shapes in metamorphic rocks, yet may still have a lattice-preferred orientation of crystallographic elements. Quartz and olivine are two notable examples of minerals that typically appear granular, thus lacking a dimensional orientation, yet may have a lattice-preferred orientation. Either a poorly developed schistosity or segregation into layers by metamorphic processes Gneissose rocks are generally coarse-grained (Winter, College and States, 2020).

Figure V-9 Miniral lineation in rocks.

https://www.quora.com/What-is-folliation-and-lineation

- **Non-foliated and non-lineated rocks**

This rock type doesn't really show any preferred crystallographic orientations. In fact, its inner mineral composition generates a non-linear texture (Winter, College and States, 2020).

Metamorphism grades

In fact, the successive events exert many metamorphism processes on the same rock. For this reason, the metamorphism effect can only be observed after a certain period of time. Subsequently, there exist rocks with many metamorphism grades: metamorphosed and poly-metamorphosed rocks, and low-grade or high-grade metamorphosed rocks. Consequently, external rock crust geometry is frequently and continually adjusted to both external and internal conditions.

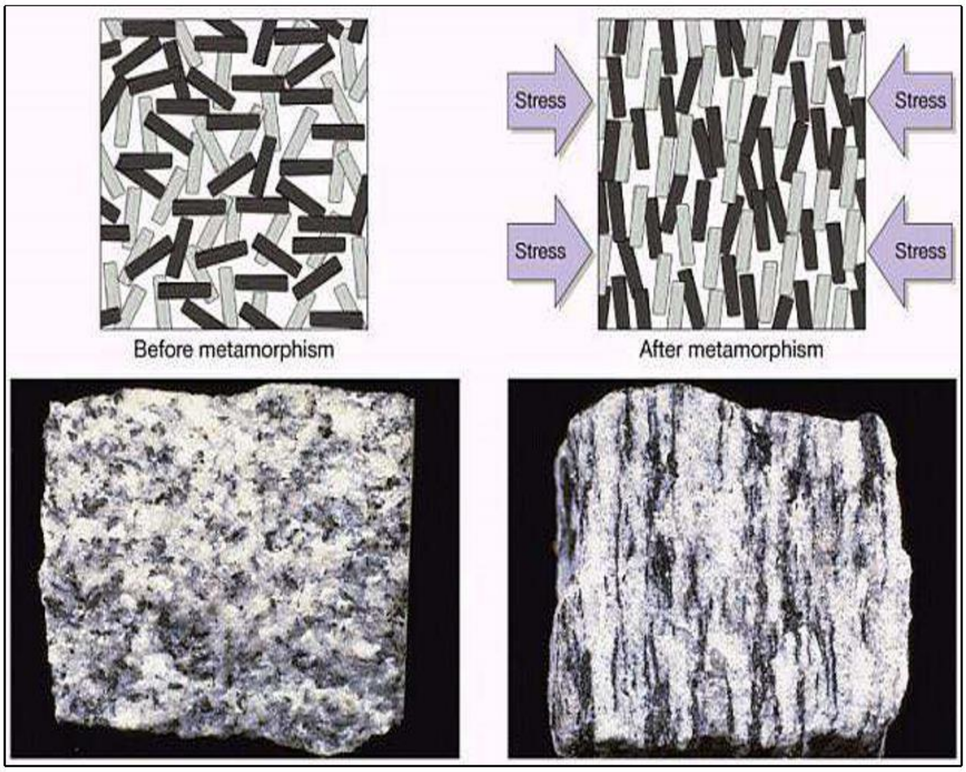


Figure V-10: metamorphism effect on the mineral structure of rocks.

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V.4.4 Stage 03: Transition from nature to architectural design field

The design concept derivation is the abstraction of a natural functional mechanism and its transcription into design rules based on the design field context. A designed object that performs the desired function is then produced. Obviously, formulating a design concept is mostly related to the analytical study of both the inspiration source and the objective design function. In this phase, we have explored the proposed methods and tools but focused more on the solar design specificities; bridge concepts, as a suggested tool, are also supposed to simplify the derivation of the design concept.

These elements are largely determined by the source of design inspiration. Actually, using existing biomimicry design methods to transform bio-features into architectural design concepts has not always been successful. The difficulty of developing design concept ideas and incorporating them into the design functional aspect remains unresolved.

Kuru (2020) called the mechanism of transferring bio-features to the design field "the translation process," but we further prefer "transcription," because design information transfer is like a transcription process, we should avoid word-to-word translation and instead look for the term or the expression that expresses the same meaning in the design field, and sometimes we must use other kinds of languages like computer programming. As a result, establishing design concepts aids designers in developing design guidelines but does not always lead to the practical level.

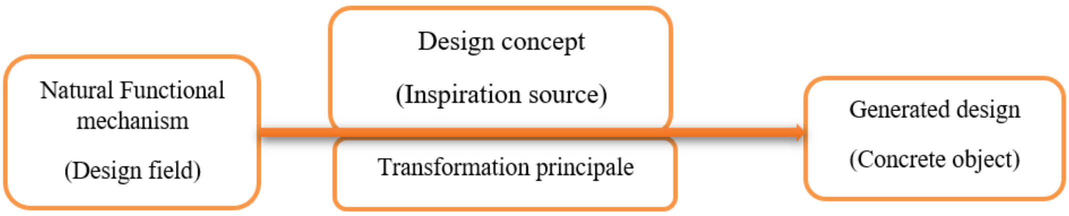

Figure V-11: The basic role of the design principle in a bio-inspired design process (Author, 2022).

V.4.4.1 Transcription of the natural phenomenon Metamorphism to design rules

It was necessary to analyse the "rock metamorphism" phenomenon as a generative shape process in order to establish a solar design concept. Consequently, a diligent analysis has been done in order to emphasize shape generation steps, mechanisms, and factors. First, we wrote a text about the functional aspect of solar design, and then another about the logical succession of metamorphism stages. The rock formation phenomenon (metamorphism) has been simplified and explained; in order to outline the inspirational elements using language as a driven design concept tool. We describe both the functional and source inspiration phenomenon systems in the two texts below.

First text:

The building envelope represents the boundary between indoor and outdoor conditions. The objective of the architectural solar design is to provide optimal comfort conditions. The relationship between internal comfort requirements and external conditions, especially climatic factors is clearly expressed. The geometric relationship between these two conditions is translated into shape design rules and guidelines.

Second text:

The metamorphism process is a natural phenomenon that shapes the external rock surface (crust) in order to adjust its structure and mineral composition to ensure rock stability. According to the rock mineral composition and the crystallographic axes, the new mineral composition exhibits foliated or non-foliated layers. Obviously, the metamorphism process relies on parallelism as a shape generator and layer organizer, following crystallographic axes.[1] Furthermore, (Winter 2020) suggests including terms such as: lineated, layered, banded, folded and "spot" when studying rocks' structural aspects. We have emphasized the main geometric and structural aspects to get inspiration from.

After selecting the key words of each text, we have tried to connect each of the bio-keywords to the appropriate one in the design field text (Tab.V-2). We noticed that the bio-inspiration text contains more keywords than the design field text. In fact, the remaining keywords are the most important ones because they will bring innovation and new ideas into the design process. They are the design concept keywords.

Table V-2 Key concept of the bio-knowledge transcription process (Author, 2022)

Text	**Design object**	**Current conditions**	**Design constraint**	**Desired conditions**	**The relationship between those internal comfort exigencies and the external ones**				
First text:	building solar skin	internal conditions	external conditions	the rock stability state	adjust its structure and mineral composition	crystallographic axes parallelism	a design	Lineated layered banded folded	spot
Second text:	the external rocks skin	mineral composition	external conditions	optimum comfort conditions	No appropriate keywords				

Then, functional and inspirational systems have been derived from Table V-4 in order to, generate the design concept system. In contrast to the proposed methods, we have drawn a functional system rather than a problem one.

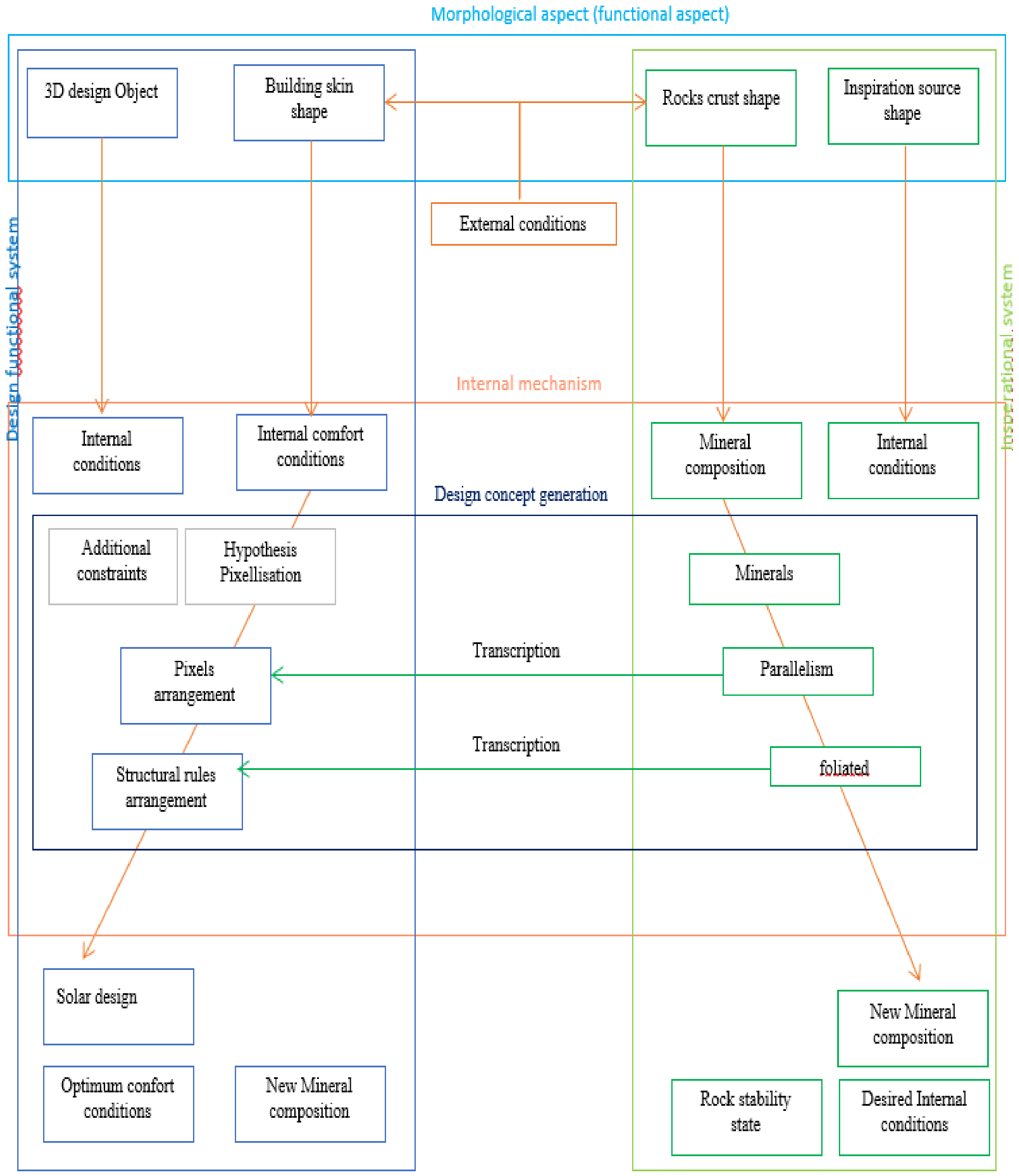

Figure V-12**:** Transcription process of bio-knowledge (Author, 2022).

Inspiration elements

Solution elements

Challenging elements

Functional elements

V.5 Establishment of the geo-solar segmentation generation mechanism

In fact, the solar-induced rock-cracking phenomenon can geometrically be perceived as the generation of a new rock's crust surface according to solar-segmented profiles. This surface exhibits lineated structure and texture with parallel layers organisation and lattice shape (Winter, College and States, 2020).According to the previous structural characteristics 'Geo-solar segmentation' morphing concept is set (Fig. V-13). It generates a segmented building envelope based on the 'Solar Useful Time' SUT represents the daytime during which solar normal direct radiations affect dry bulb temperatures. Moreover, it is the interval of the best solar orientations. 'Geo-solar segmentation' (GSS) method touches the building part included between the azimuth coordinates of the SUT, called the 'Building front face' BFF. The next section explains the implementation of the GSS generation mechanism at plan and elevation levels and the corresponding mathematical models.

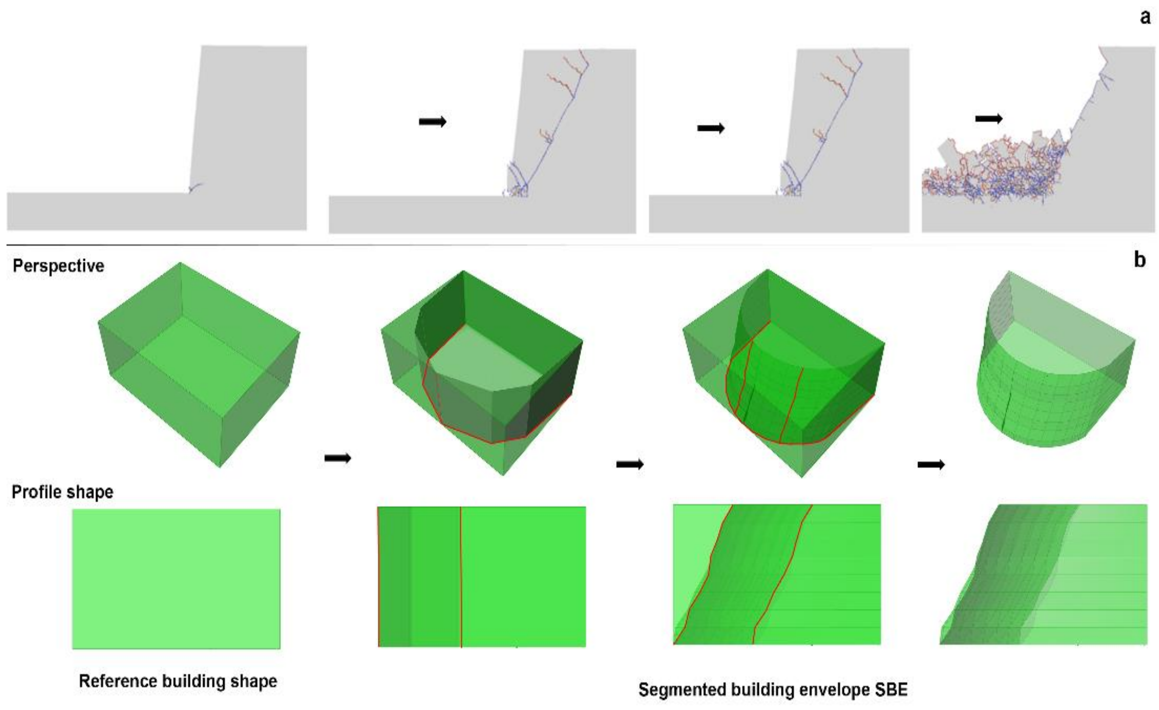

Figure V-13. (a) Rock thermal cracking process (Sun et al., 2022), (b) geo-inspired design concept (Author, 2022).

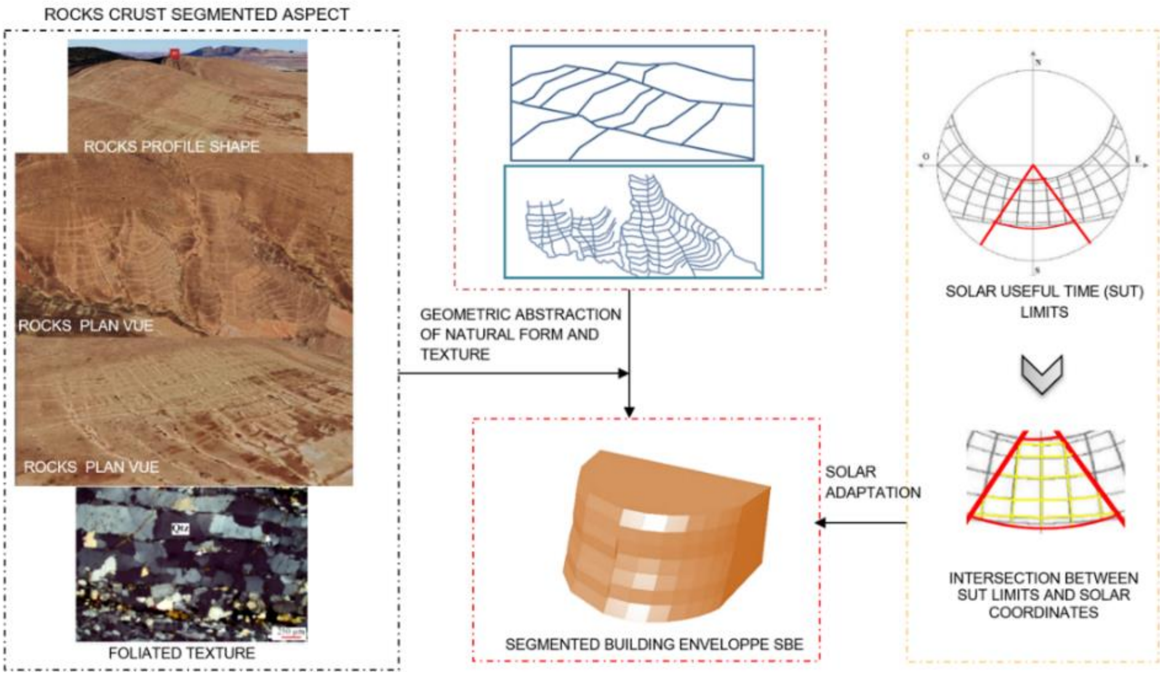

Figure V-14 : Rock structure and texture geometric abstraction and solar adaptation of the design concept (Google Earth, 2021), (Matrose et al., 2019) (Author, 2022)

V.5.1 Azimuthal segmentation at the plan level

The reference building has a rectangular footprint, with a length of L and width of W. A line is then drawn parallel to the initial rectangle length and at a depth of 1/3W from the backside. To generate the segmented envelope, an arc of radius R=2/3W is drawn from the mid-point of this line. This ensures that the new building area is maintained within the initial footprint. The corresponding sun-path diagram is then centred along the arc centre (Fig. V-15 a). The same point is afterwards, joined with the SUT limits azimuthal coordinates (Fig. V-15 a). Eventually, the intersection points of the arc with the SUT azimuthal limits are joined to the building back-face BBF to draw the north east N/EBF and the north west N/WBF building faces (Fig. V-15).

Given that, until noon, the sun traces an upward path in the sky followed by a downward path until sunset, the BFF is divided into morning and afternoon parts based on the respective solar data (Fig.V-15. b). SBE shapes were generated based on direct normal radiations, since they greatly affect the building solar potential (Caruso and Kämpf, 2015).In order to generate the BFF surfaces, each of the morning and the afternoon SUT intervals is divided into sub-intervals of minimal duration of half an hour (Fig.V-15. c). Then, between the intersection points of each sub-interval limits and the arc, the surface length, which is the normal segment to the bisector of the sub-interval angle $\varnothing n$is drawn, applying the tangent trigonometric law (Werner Oechslin, 1847) Eq. 2. The bisector represents the direct normal radiation at sub-interval mid-time (Fig.V-15. d). Azimuthal sub-interval angle($\varnothing_n$) equals:

$$\varnothing n = \varnothing n_{end} - \varnothing n_{beginning} \quad \text{Eq. 1}$$

According to the above-mentioned trigonometric law (Fig. V-15. d), we deduce that:

$$Sin½\ \varnothing_n = ½\ SRF_L / R \quad \text{Eq. 2}$$

$$½\ SRF_L = Sin½\varnothing_n * R \quad \text{Eq. 3}$$

Where:

n: a specific sub-interval

SRF_L: the length of each of theBFF surfaces and the corresponding azimuthal segment.

$\varnothing n_{end}$: azimuth coordinate of the end of the Sub-interval (n)

$\varnothing n_{beginning}$:azimuth coordinate of thebeginning of the Sub-interval (n)

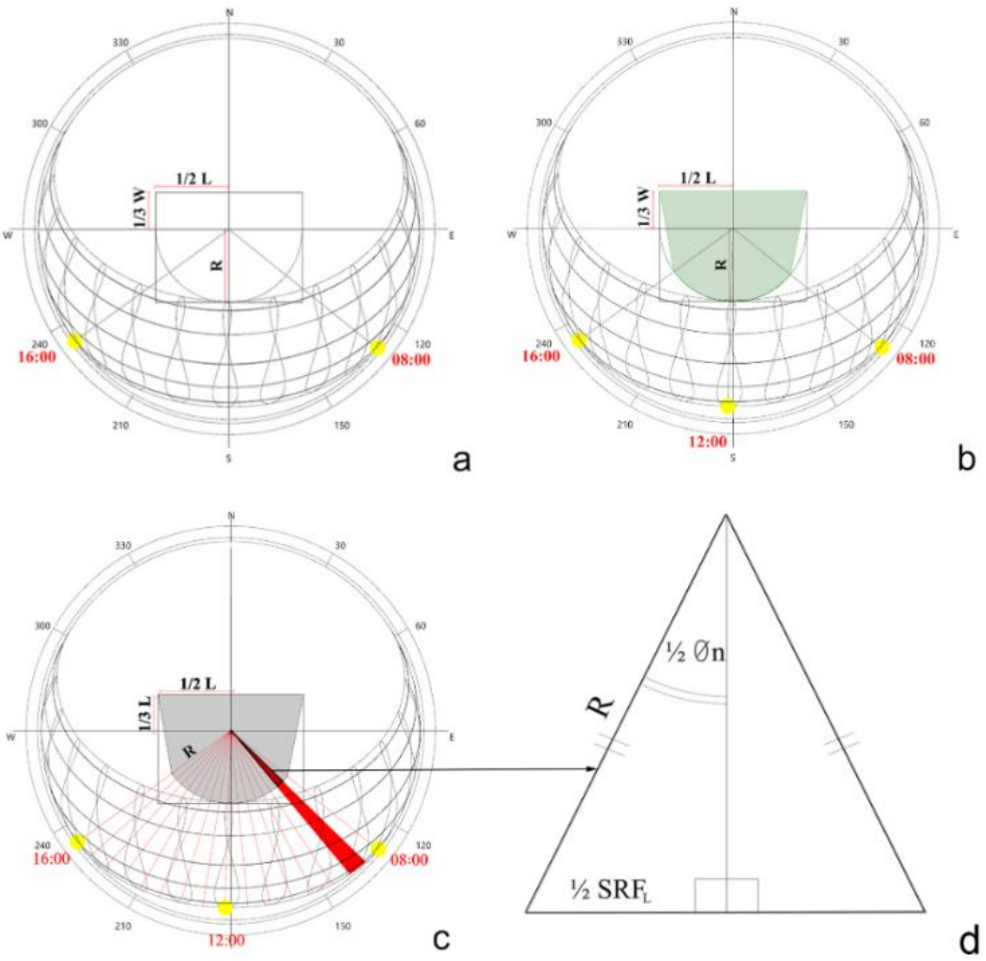

Figure V-15 : Azimuthal segmentation steps sequence; (a) the intersection of the SUT limits and the arc, (b) joining the building front and back faces, (c) drawing the sub-intervals, (d) geometric rule of azimuthal segmentation (Author, 2022).

V.5.2 Elevation segmentation at the profile level

Both of the BFF profiles are generated based on the plan segmented line (Fig.V-16). The building height is first divided equally according to the vertical segments number to create a lattice with the horizontal lines, drawn based on horizontal D_H and vertical D_V distances (Fig. V-16). Each BFF surface is normal to direct radiation at the corresponding sub-interval mid-time (Fig.V-16). According to the triangle angles sum theorem (Eq. 4) we have in the ABC triangle (Fig. V- 16):

$$A + B + C = 180° \text{ so, } C = 180° - (A + B) \qquad \text{Eq. 4}$$

$$= 180° - (A + 90°) \qquad \text{Eq. 5}$$

$$= 180° - 90° - A \qquad \text{Eq. 6}$$

$C = T = 90° - A$ Eq. 7

According to the theorem of two parallel lines (w) and (y) cut by a transversal line (K), A and H angles are equal since they are congruent (Eq. 8) (Werner Oechslin, 1847). We have then:

$A = H_{mid}$ Eq. 8

From Eq.7 and Eq.8, we deduce that:

$T = 90° - H_{mid}$ Eq. 9

According to triangle trigonometry formulas applied to the A'B'C triangle,we have:

$\sin T = \sin C = D_V / SRF_W$ Eq. 10

$SRF_W = D_V / \sin T$ Eq. 11

And: $\cos C = \cos T = D_H / SRF_W$ Eq. 12

So: $D_H = SRF_W * \cos T$ Eq. 13

From (Eq.11) and (Eq.13) we deduce that:

$D_H = (D_V / \sin T) * \cos T$ Eq. 14

$D_H = D_V (\cos T / \sin T)$ Eq. 15

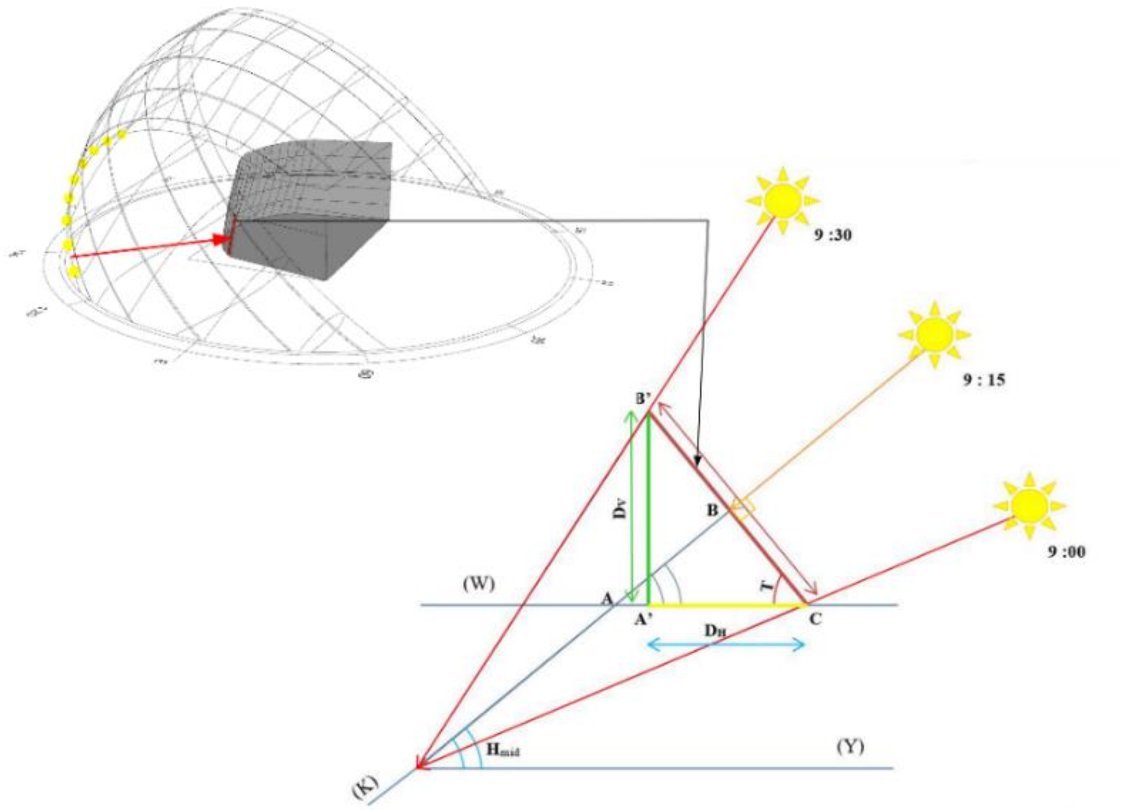

Figure V-16 Geometric rules of elevation segmentation (Author, 2022).

Therefore, GSS Mathematical models are derived from trigonometric laws. They describe the geometric relationship between the surfaces of the BFF and normal solar radiation.

V.5.3 Determining geo-solar segmentation parameters

solar optimisation parameters categorisation, the GSS method parameters and variables are classified into three groups as shown in Table V-3. Static parameters are kept the same, while dynamic ones vary during the optimisation process to obtain diverse parameters combinations. Indeed, each BFF part has its own Azimuthal (SN_A) and elevation (SN_E)segment numbers that range between 2 and 8. Besides segment numbers, dynamic parameters include new established geometric characteristics of SBE, such as solar state S_S, obtained from the weather data (epw) file, 2004-2018(https://climate.onebuilding.org/), combined orientation angles COA, combined tilt angles CTA (Tab.V-3). These parameters facilitate the discussion of the simulation results. The third group consists of independent variables of the GSS generation data, such as: vertical and horizontal distances

(Fig.V-16). Therefore, the novelty in the present study resides in elaborating a geo-inspired solar morphing method and new corresponding parameters.

Table V-3 Geo-solar segmentation method parameters (Author, 2022).

Parameters groups	**Parameternotation**	**Description**
Static parameters	Building Back-face BBF	The initial foot print northern edge
	Building height B_H	The building's total stories height, with 3 m story height
Dynamic parameters	Building front face BFF	The building envelope part included between SUT limits.
	Azimuthal segment number SN_A	There are two: morning **SN_A** and afternoon **SN_A**, with: 2< **SN_A**<8.
	Elevation segment number SN_E	There are two: morning **SN_E** and afternoon **SN_E**, with: 2< **SN_E**<8.
	Combined tilt angles CTA	The BFF surfaces tilt angles, resulting from a given solar state. CTA(α_1°, α_2°…) their number depends on **SN_E**.
	Combined orientation angles COA	TheBFF surfaces orientation angles, resulting from a given solar state. COA (β_1°, β_2°…) their number depends on **SN_A**.
	Segmented building envelope SBE	Specific segmented building envelope generated using solar GSS for a given solar state. It is characterised by specific CTA (α_1°, α_2°…) and CTO (β1°, β_2°…).
	East-north building face E/NBF	Their configuration and dimensions depend on the BFF configuration.
	west-north building face W/SBF	
Independent variables	Solar state S_S	A specific day solar data in a given location. It comprises all of: studied location, latitude, and the solar data
	Horizontal distance D_H	The projected distance between each two successive azimuthal segments Fig. V-16
	Vertical distance D_V	The vertical distance between each two successive elevation segments Fig. V-16

V.5.4 Geo-solar segmentation optimisation mechanisms

Taking into consideration the direct normal radiation effect on SBE potential is not sufficient. Consequently, the iterative cracking process that undertakes the rock's crust over time; inspired us to set optimisation mechanisms. The resultant rock's crust is a multi-faceted surface characterised by heterogenic tilt angles (Román-Sánchez *et al.*, 2019) and orientations. Additionally, many solar morphing optimisation methods (Hosseini *et al.*, 2019), (Yadav and Chandel, 2013)rely on the variation of building faces' tilt angle and orientation. Accordingly, four optimisation mechanisms are established, then, implemented in the GSS method.

The first and the second mechanisms are based on the variation of combined tilt angles CTA and combined orientation angles COA respectively, while keeping the building orientation fixed (Fig. V-17). The minimal COA angle is fixed at 30° to avoid having a plan shape with acute angles (Fig. V-17 b). The third mechanism CTA/COA is based on a simultaneous variation of CTA and COA. Eventually, the irregular rock's profiles shape inspired a fourth optimisation mechanism 'the segments position permutation' SPP. It is implemented in the GSS using the factorial of the elevation segment number SN_E. The SPP mechanism allows evaluate the effectiveness of numerous SBE profiles configurations ($SN_E!$), as shown in Fig.V-17. c

$$SN_E! = SN_E *(SN_E -1)*(SN_E -2)*(SN_E -3)*\ldots*1 \qquad \text{Eq. 16}$$

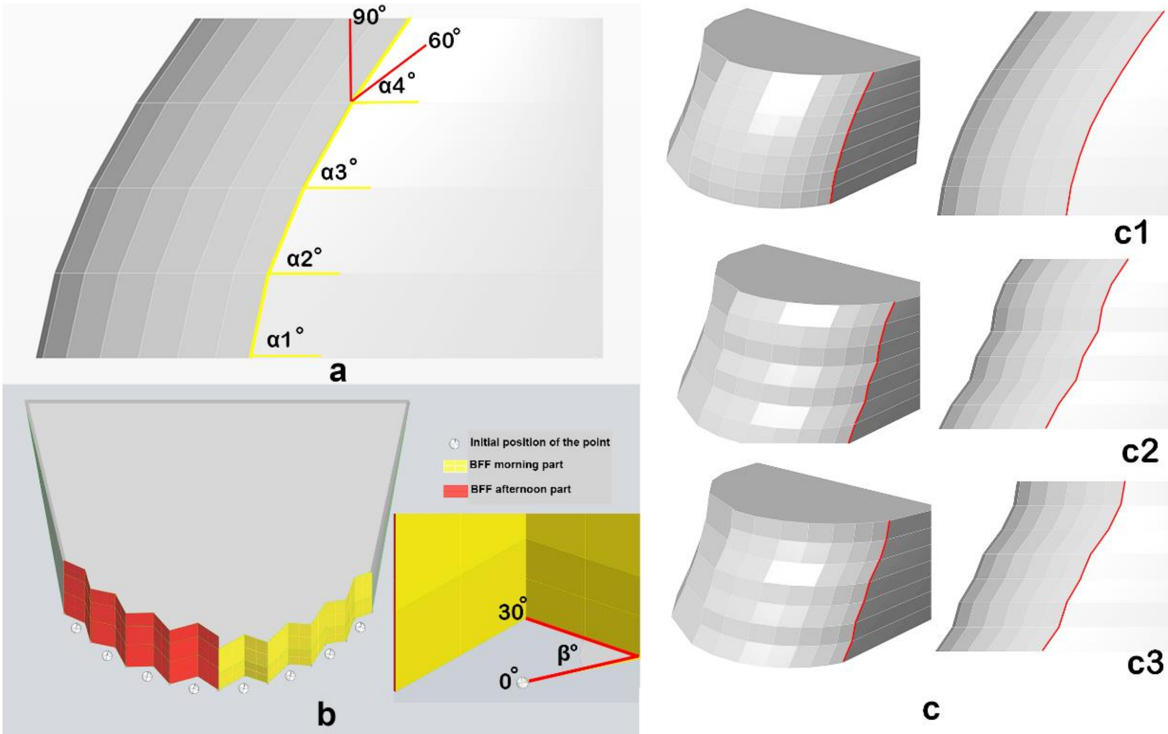

Figure V-17: Geometric manipulation principles of GSS optimisation mechanisms; (a) CTA, (b) COA, (c) SPP (Author, 2022).

V.6 Conclusion:

In this chapter, the effectiveness of the bio-design bridge concepts was verified. applying them to the top-down bio-approach design. In fact, the first bridge concept, "levels," helped us limit our search and be easily oriented to an effective and appropriate source of inspiration. Afterwards, the analogical aspect definition aided in focusing on the most important features and elements in the natural system to be transcribed into the design field. The third bridge concept supported the practical transcription of the natural system features into a generative design concept for building solar morphing. The adoption of a parametric design approach helped focus on the main design parameters and effectively manipulate the building envelope geometry.

CHAPTER VI. APPLICATION OF GEO-SOLAR SEGMENTATION METHOD

RESULTS AND DISCUSSION

VI.1 Introduction

This chapter gives an overview of visual programming and how the optimization method can be used in architectural design. In fact, optimization is a mathematical theory that helps make trade-offs between several objectives to get the optimal choice. The optimization is a method that facilitates choosing the optimal building geometry. The transcription of the bio-inspired solar design concept is based on solar parameters. Grasshopper, a visual programming environment within Rhino software, is chosen. The details of the parametric design approach and the building geometry parametric control are presented and explained.

In this chapter, the transition of theoretical concepts or architectural design intentions to the generation of architectural design objects is ensured by the embedment of design concepts developed in the preceding chapter into the architectural design process. Visual programming was chosen as the tool for generating designs and controlling them so that the change could go smoothly. To perform the optimization-simulation process, visual programming environments typically rely on specific plugins. As a result, we present a theoretical framework for visual programming and optimization-simulation processes. The steps of the design process's parametrization are then explained in detail.

VI.2 Visual programming

In fact, VPL is one of the design approaches emerging from shape grammar theory (see chapter II). Stiny (2006) admitted that shape grammars can be supported by "visual calculating" process (Wortmann and Stouffs, 2018). Similarly, Tnpia (1999) recognized that shape grammar theory is the basis of visual programming in computer science, which allows a quick exploration of design alternatives based on their geometric transformations.

The concept of dimensions constantly emerges when discussing visual programming. Compared to conventional textual programming, visual programming includes numerous dimensions that are treated in the process of programming, such as: time and three-dimensional space (BURNETT, 2002). In visual programming, the several dimensions are related to each other in a specific order that defines the design algorithm and helps translate the philosophical and abstract ideas into a design object. This makes visual programming easier to use than conventional programming because it stimulates many areas of the human brain (Myers, 1986).

Visual programming entails identifying the appropriate components and then connecting them to perform a given geometric transformation on the geometry. VPL is a non-textual programming language that involves icons, connecting lines indicating relationships, motion, colour, texture, shading, or any other non-textual device to develop algorithms (Cox, 2008). A visual algorithm is characterised by its specific: model, objectives, and whether they are declarative or imperative, or whether programmes are constructed directly or by demonstration (Cox, 2008). Thus, visual expression or syntax can be diagrammatic, iconic, or form-based. On the other hand, the elements of visual programming are mainly two: the components that include a geometric entity like a rectangular-based 3-D form, a mathematical operation, a unit converter, or any other part of the algorithm. The second element is connections, which are represented by edges that connect components to each other. These connections are for one-directional data transfer (Dino, 2012).

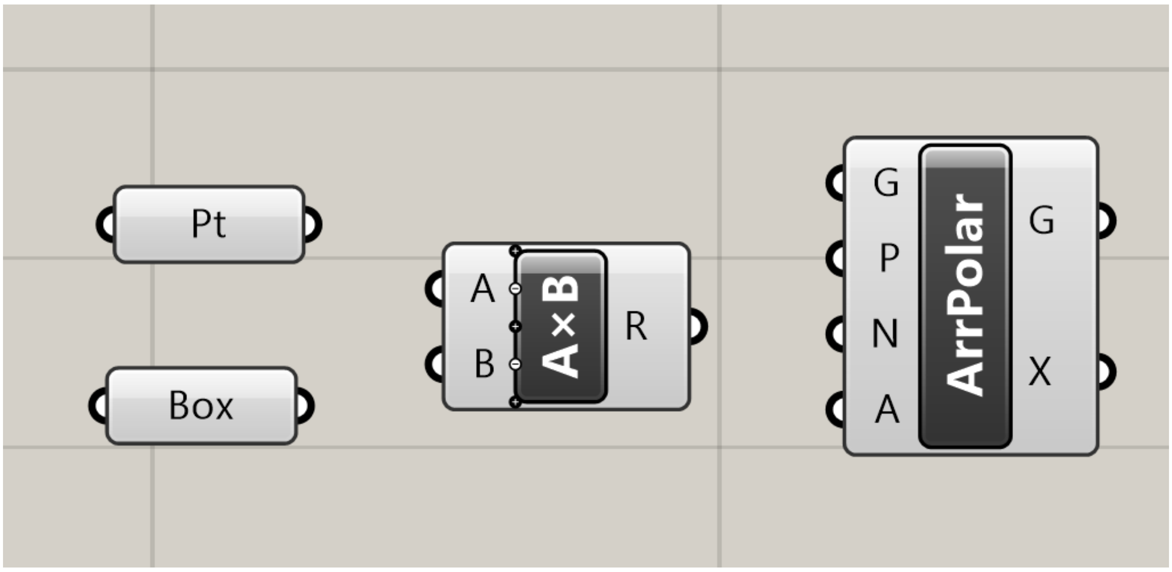

Figure VI-1: Some of the components type in Grasshopper (Author, 2022).

The programming approach to design is a digital design approach that has been addressed by theorists, such as Kalay (2004) and Oxman (2006, 2008) (Salman, 2014). Nowadays, computational design tools play a crucial role in generating the architectural model and evaluating its energy efficiency. The use of visual programming software, particularly in architectural design, enables the generation of creative forms that are tailored to their surroundings' context. Subsequently, the best architecture firms in the world, such as Zaha Hadid Architects, use visual programming extensively in the form-finding process. Furthermore, the new design paradigm that originates from the use of coding in building form generation illustrates a new design approach, perception, and use of both architectural form and space.

Generally, designers draw sketches to communicate their ideas and describe the imagined 3-D form. However, the use of computational design tools in architecture has changed the way architects think, design, and manufacture buildings. Thus, the designer encodes the algorithm, based on a specific design line path using a textual or visual editor (Dino, 2012). Therefore, visual programming improves the understanding of the design essence, skills, and performance in architectural design and research (Salman, Ravi and Hooker, 2008).

VI.2.1 Complexity level of visual programming

Visual programming allows manipulating a given geometric model to generate optimal variants (functional optimality). These manipulations vary from a simple operation, such as resizing a window, to a deformation of the general shape of the building. The complexity of the algorithm depends on the complexity of the morphogenesis operation applied to the reference form and the adopted design approach (inverse or direct).

Shu (1985) classified the programming languages based on their characteristics. The first characteristic is "level," which describes the number of details treated in the developed program. In comparison to low-level programming, high-level programming treats many details of the desired result. The second characteristic that defines the level of programming process is "procedural languages," which are based on the information the designer has to provide to the computer to achieve the desired design. The designer performs a high-level procedural programme when he describes the design process step by step using programming tools. Thus, he gives an order to the computer to perform specific operations instead of relying on automatic ones.

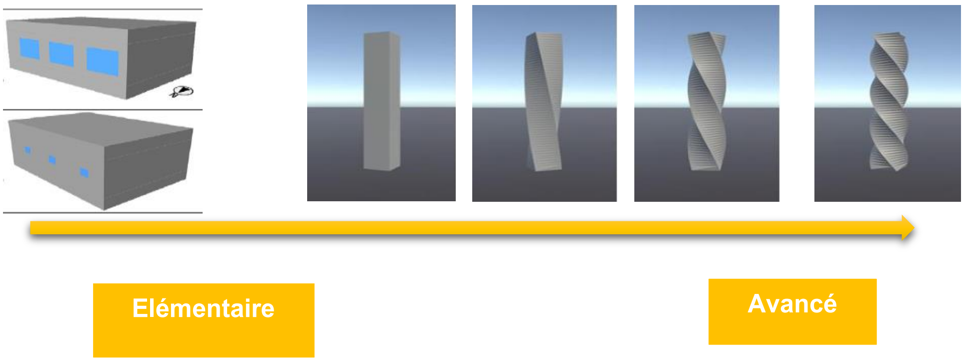

Figure VI 2: Visual programming level (Cordeiro *et al.*, 2018).

Advantages visual programming languages

As mentioned above, the VPL tools facilitate the programming task. Moreover, Kiper, Howard and Ames (1997) admitted that abstract and contiguous ideas can be better explained using visual representation and graphics. Contrary to textual language, VPL helps clarify the relationship between the entities and the ambiguities (Kiper, Howard, and Ames, 1997). VPL is considered a "by example" programming process in which the outputs depend on the user inputs introduced at the right time and within the right phase of the process (Kiper, Howard and Ames, 1997). The user executes the required function, indicating the steps to be taken, and then the algorithm performs the same process by simply introducing inputs.

It is important to highlight the difference between visual languages and graphical interaction systems (programming, for example). In graphical interaction systems, the user's interaction with the system is important, and in visual languages, the arrangement of symbols on the screen is important (Kiper, Howard and Ames, 1997). Visual languages consist of graphical symbols assembled into "visual sentences with a specified grammar and semantics". To determine the underlying grammatical structure, visual sentences must subsequently be spatially analysed. The syntactic and semantic analyses of a visual language are comparable to traditional approaches to language. In Figure VI-2, Singh and Chignell propose a classification of visual languages based on the graphical abstraction utilised to create the programme: flow diagrams, icons, and forms and tables.

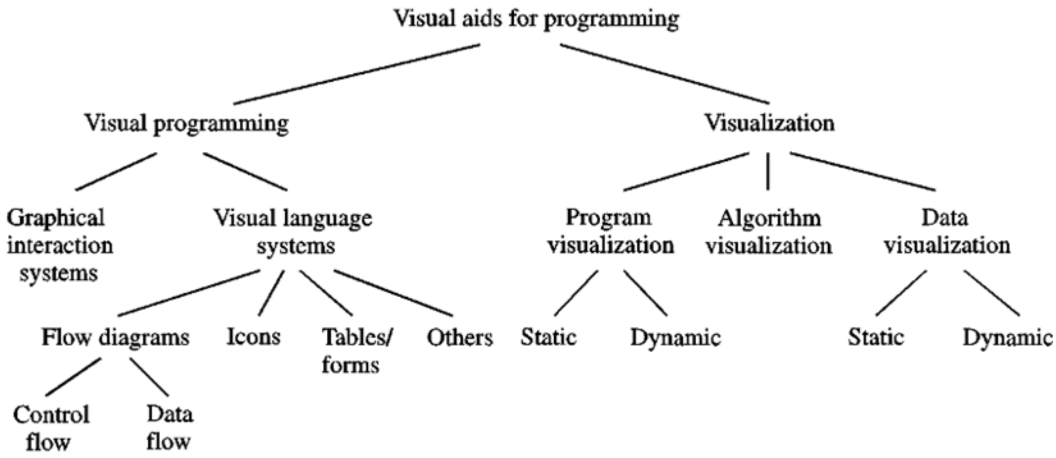

Figure VI-2 Taxonomy of visual programming aids. *Singh and Chignell*

VI.3 Optimization-simulation process:

Optimization is a step in the design process that allows for the exploration of a wide range of possible solutions. This is the step that follows the visual programming process to assess the usefulness of the developed algorithm. In fact, optimization is generally combined with the simulation process in order to instantaneously evaluate the generated design variants. Thus, the computational tool allows synchronising the optimization and simulation process, which merge them into a single operation. The optimization is considered an effective tool for comparing the different possible solutions that obviously have different impacts on the building's indoor and outdoor environments. Accordingly, the set of optimal solutions is represented in an n-dimensional space, with n the number of the study objectives (Ciardiello *et al.*, 2020). The optimal solution generated using optimization is generally kept until the last design phase or slightly changed to meet other design constraints (Liu et al., 2020). Objectives related to building energy efficiency play a crucial role in defining the optimal form (Granadeiro *et al.*, 2013), (Feng *et al.*, 2021).

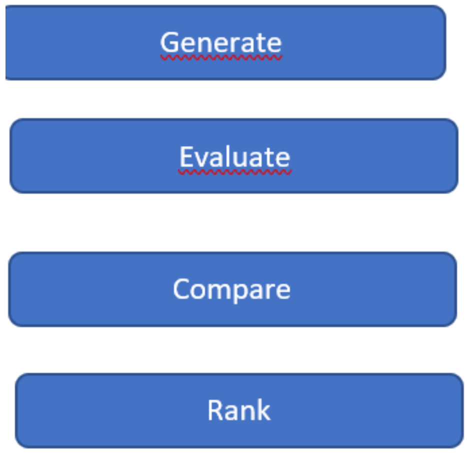

Figure VI-3: steps' sequence of Optimization process (Author, 2022)

In fact, there are many tools on the internet in the form of computer programmes that calculate the amount of irradiation falling on several regions of the world (Abramczyk, 2022). However, the use of optimization in solar design allows embedding other parameters than solar radiation to set the possible trade-off between the objectives.

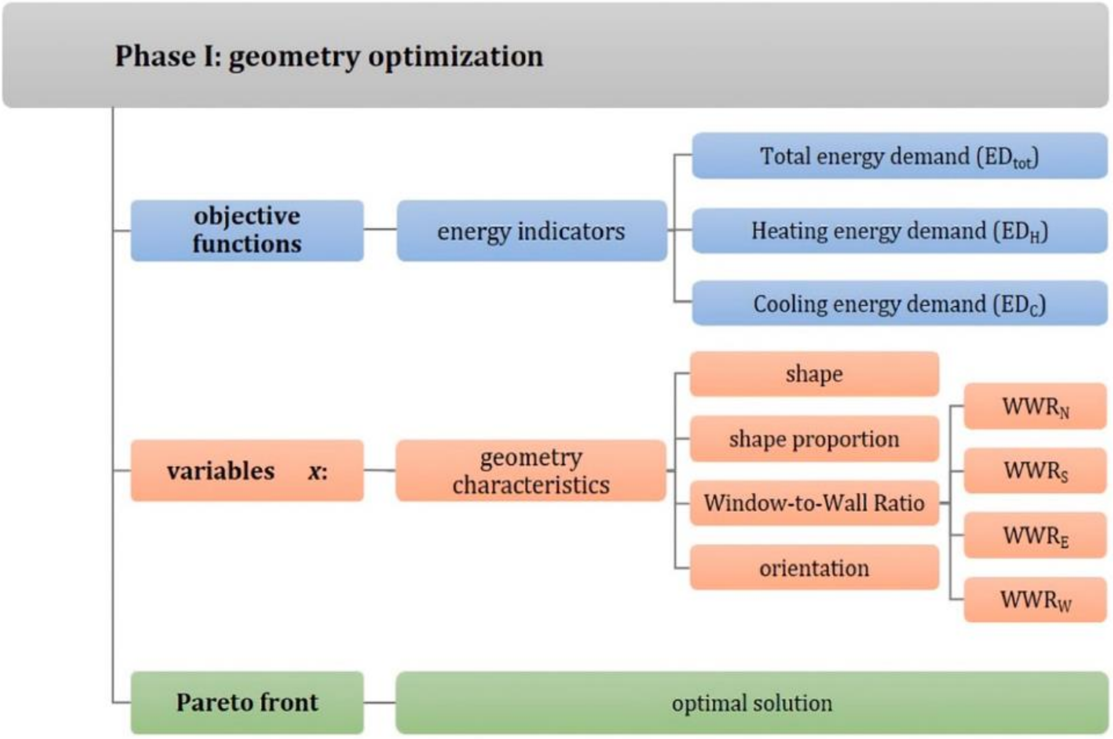

Figure VI-4: Optimization process objectives and parameters (Ciardiello *et al.*, 2020).

Application of Geo solar segmentation method results and discussion

In this section, research papers are examined to show how different software can be used together in the optimization-simulation process. Zhao and Du (2020) combined a smart optimization algorithm (NSGA-II) and Design Builder energy simulation software to perform an optimization-simulation process. In fact, Builder energy simulation software is useful for designers who lack programming skills. On the other hand, geometric envelope parameters, such as orientation and window configuration, and material properties were examined to reduce energy consumption for heating and cooling, and discomfort hours. Friess and Rakhshan (2017b) optimized the building envelope features and its shape configuration through an optimization-simulation process to reduce residential building energy consumption in the UAE. Using an enhanced Manta-Ray foraging optimization algorithm and RIUSKA software for performing simulation, A set of parameters that include window area and type, the insulation of different building parts, infiltration level, building orientation, and thermal mass were manipulated to generate optimal geometries.

The computational tools for developing algorithms and coding are in constant evolution. Nowadays, advanced procedures are used in the design process in general and particularly to perform the optimization process. Abramczyk (2022) used artificial neural networks, internet satellite data, and online tools available on the website of the European Commission to develop an algorithm that allows estimating the direct incident solar irradiation based on the geometric variation of the whole building shape.

There are numerous functional approximation models that ameliorate the relevance of the optimization process, such as surrogate models. The latter are the simplified forms of more complex models that facilitate getting from the input to the output when the relationship between the two is ambiguous (Wang et al., 2014) (Han and Zhang, 2012). They are also embedded in the optimization process (Karolius and Williams, 2016). Chen and Yang (2018) applied a surrogate model based on multi-objective optimization of a high-rise residential building to explore the effect of weather conditions on the sensitivity analysis and optimization. There are relationships between outdoor thermal, ventilation, and solar radiation conditions under the five climatic zone objectives. The relative weight analysis is first compared with the Fourier amplitude transformation analysis (FAST) in prioritizing the weighting of design inputs for different climatic zones. The relative weight analysis is then proved to be a feasible alternative sensitivity analysis method when its corresponding multiple linear regression (MLR) model can achieve good prediction performance.

Furthermore, a tuning programme in R is developed to improve the prediction performance of surrogate models with the Support Vector Machine (SVM) algorithm in the above climatic zones. Modifying the Sigma and C parameters significantly improves model fitting performance with SVM.

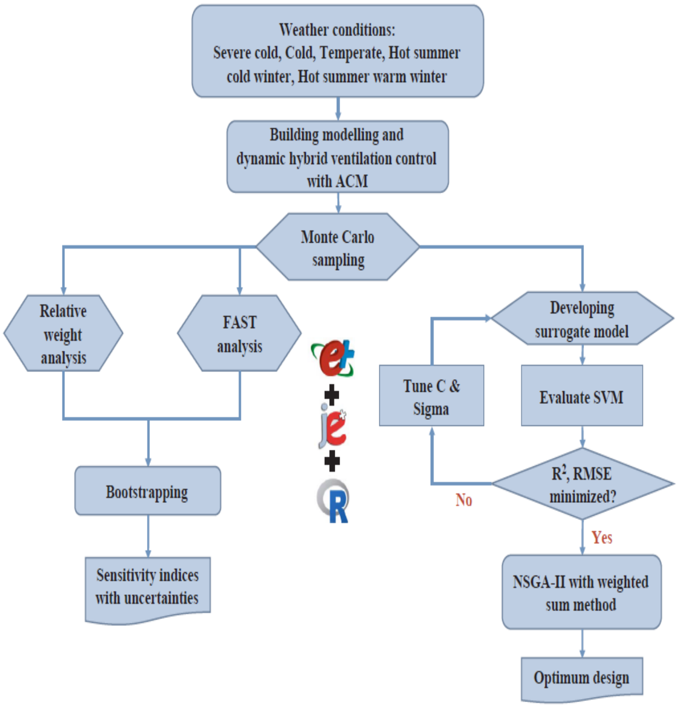

Figure VI-5 Research frame work (Chen and Yang, 2018)

Other specific models are embedded in the optimization process in order to make it faster and get us closer to the optimal solution. Although evolutionary algorithms coupled with building simulation codes are often applied in academic research, this approach has limited use for actual applications of building design due to the high number of expensive simulations runs. The use of a surrogate model can overcome this issue (Prada, Gasparella and Baggio, 2018). Prada, Gasparella and Baggio (2018) conducted a comparative study of polynomial, Kriging (GRFM), radial-basis function networks (RBFN), multivariate adaptive regression splines (MARS), and support vector machines (SVM) functional approximations. The results indicated that the MARS method is the most relevant compared to the other examined methods. It outperforms the other surrogate models both in terms of efficiency and effectiveness, and also by assessing the quality of the Pareto front (Prada, Gasparella and Baggio, 2018). outperforms the other surrogate models both in terms of efficiency and effectiveness and also by assessing the quality of the Pareto front (Prada, Gasparella and Baggio, 2018).

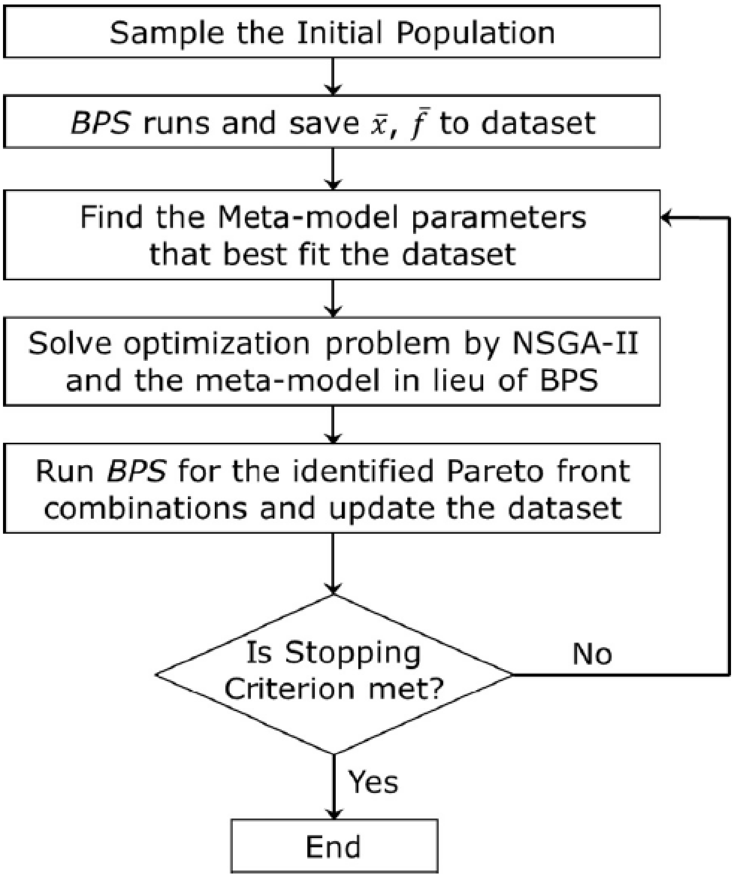

Figure VI-6 Flowchart of the developed optimization algorithm (Prada, Gasparella and Baggio, 2018).

VI.4 Computational design use in the development of GSS algorithms

Computational design process in the present study includes both of visual programming and an optimization-simulation process. Thus, the steps sequence of the visual programming process and the development of GSS method algorithm are presented. Moreover, the process of generating an architectural form and the assessment of its performance is also explained.

Precisely, the geo-inspired design concept is transcribed into a design algorithm, using visual programming tools on Grasshopper, based on mathematical models to generate optimal segmented building envelopes SBE. Afterwards, a multi-objective genetic algorithm optimisation is conducted to explore the possible trade-offs between SBE solar potential, and the corresponding compactness and space efficiency. The plug-in Octopus ('https://www.food4rhino.com/en/app/octopus', no date) used in this study is a multi-objective evolutionary solver, developed based on a genetic algorithm. The next section compares the performance of the various generated design alternatives. Eventually, the conclusion summarises the learning from the study and the applicability of the GSS method in other locations.

VI.4.1 Visual programming and parametric modelling approach

In the present study, the implementation of the parametric approach required the use of computational design tools. Therefore, Grasshopper, rhino visual programming environment is used to establish the GSS generation mechanism, which is a parametric design algorithm developed by making connections between components according to the previously presented mathematical models. Optimisation mechanisms are afterwards implemented by embedding the corresponding dynamic parameters and the necessary Grasshopper components that govern them. The process of developing a visual algorithm relies basically on the above established mathematical models (see chapter 5). we aim to provide more details on the steps sequence of the application of visual programming into architectural design process. Moreover, we outline the advantages of using visual programming tools in generating optimal architectural form that generally balances various, even contradictory objectives. Before starting the algorithm development, the weather file of the studied location is introduced in the grasshopper environment.

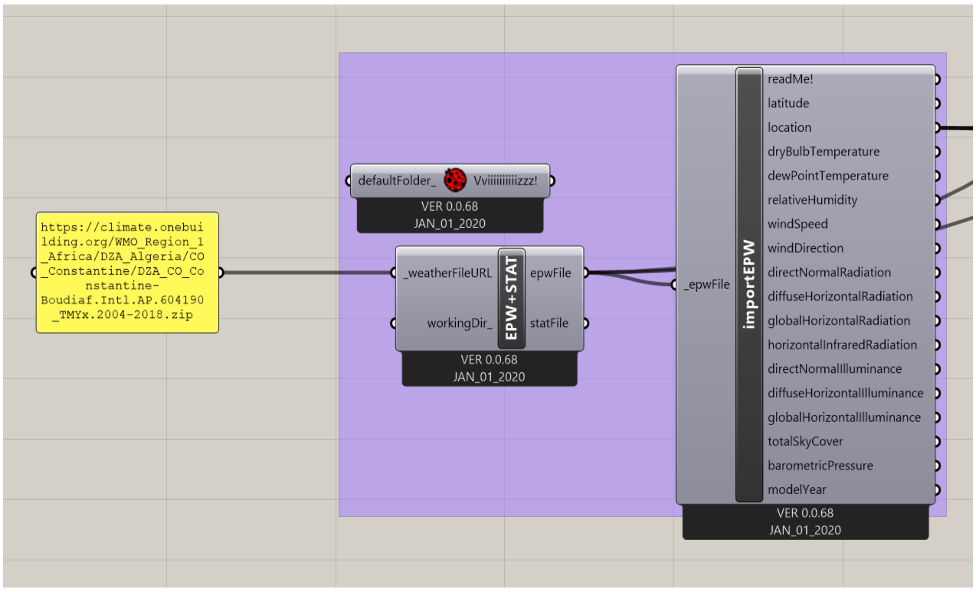

Figure VI-7: insertion of the climate file into Grasshopper environment (Author, 2022).

Indeed, the weather file contains all necessary climatic data that help performing analysis and simulation. the weather data (epw) files 2004 - 2018 are uploaded from the web site Onebuilding. com (https://climate.onebuilding.org/). On this web site the weather data are organized based on the several regions of the world. each of them includes a number of countries, and the weather data files of many locations are available. As shown in the figure (Fig. VI-8) many climatic data that can be generated using the plugin ladybug are:

- The geographical location information: city location and latitude
- Temperatures: Many temperature data points are available, such as dry bulb temperatures, dew point temperatures.
- Solar radiation data: solar radiation falling on the different building surfaces is evaluated, providing direct normal radiation, diffuse horizontal radiation, and global horizontal radiation.
- wind data, including wind speed and direction.
- Relative humidity.

As a result, solar data are generated based on a predetermined date and time.The time data represent the limits of the simulation period, like the beginning and end of the month, day, and hour of the critical period. Both time and weather data are then connected to the radiation analysis component that generates the simulation results, including the total received solar radiation (Fig. VI-8). to the radiation analysis component that generates the simulation results, including the total received solar radiation (Fig. VI-8).

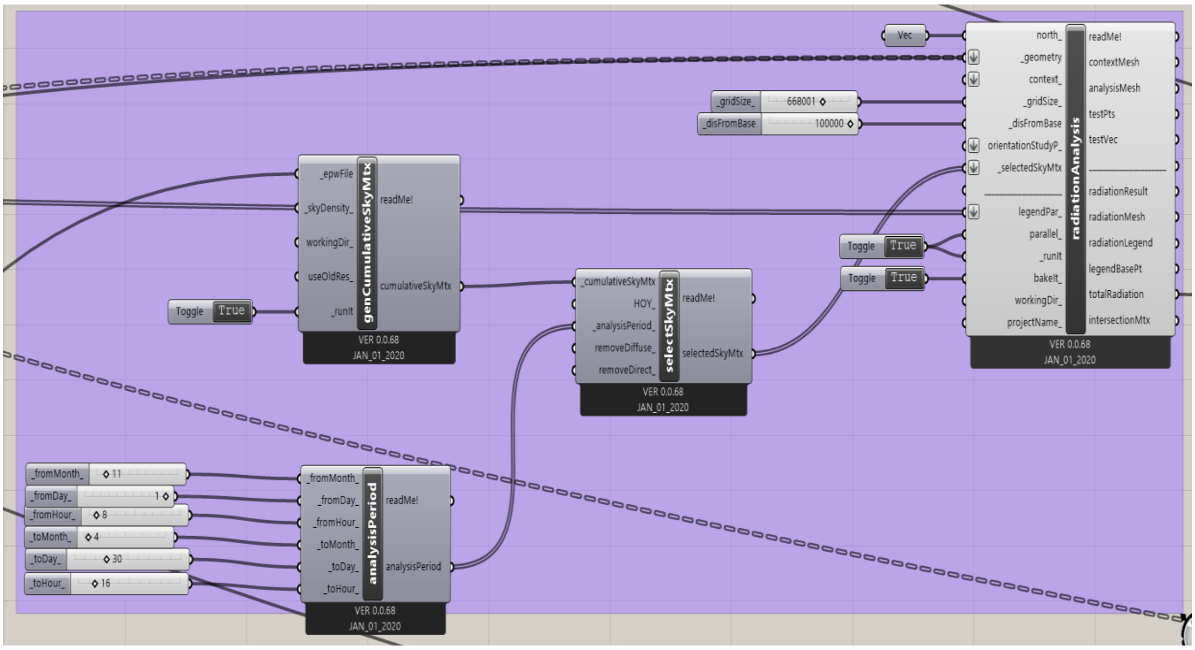

Figure VI-8: Solar radiation analysis generation in grasshopper (Author, 2022).

Then, the mathematical models of both horizontal and elevation segmentations are transcribed into a visual algorithm (Fig.VI-9).

Besides solar data, the building's geometric parameters are also introduced in order to define its three-dimensional shape. As a result, the geometric parameters mentioned above (see Chapter 5) are introduced as inputs into the design algorithm. (Fig.VI-9).

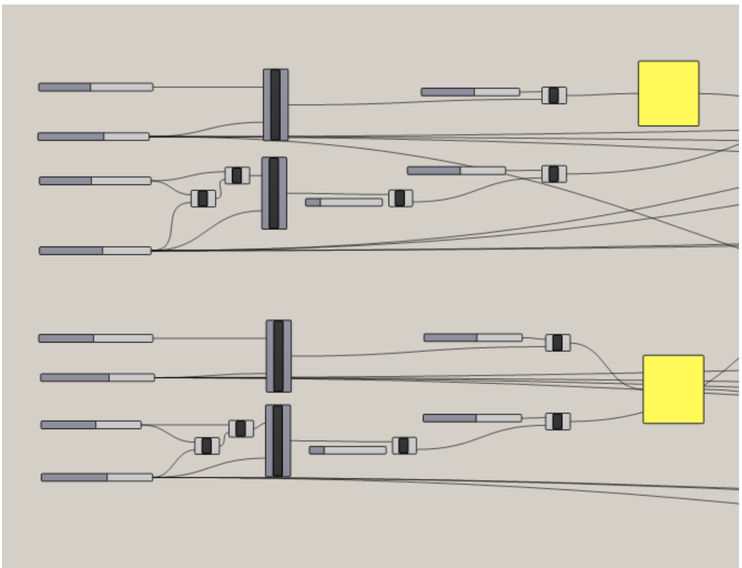

Figure VI-9 A part of segmentation algorithm (Author, 2022).

VI.4.1.1 Geometry parametric control of Segmented building envelop

The GSS algorithm performs based on solar coordinates that are generated as functions of the solar state inputs. The geometric manipulation of the SBE shapes is ensured through the change of the first kind of parameters, which are the building dimensions and measures. They involve the initial foot print limits, the building depth BD, and the solar radius (Fig. VI-11) at plan level, as well as the building height BH, as shown in (Fig. VI-10). The values of the building measurements can be easily varied by the simple act of introducing the dimensions that fit the ground.

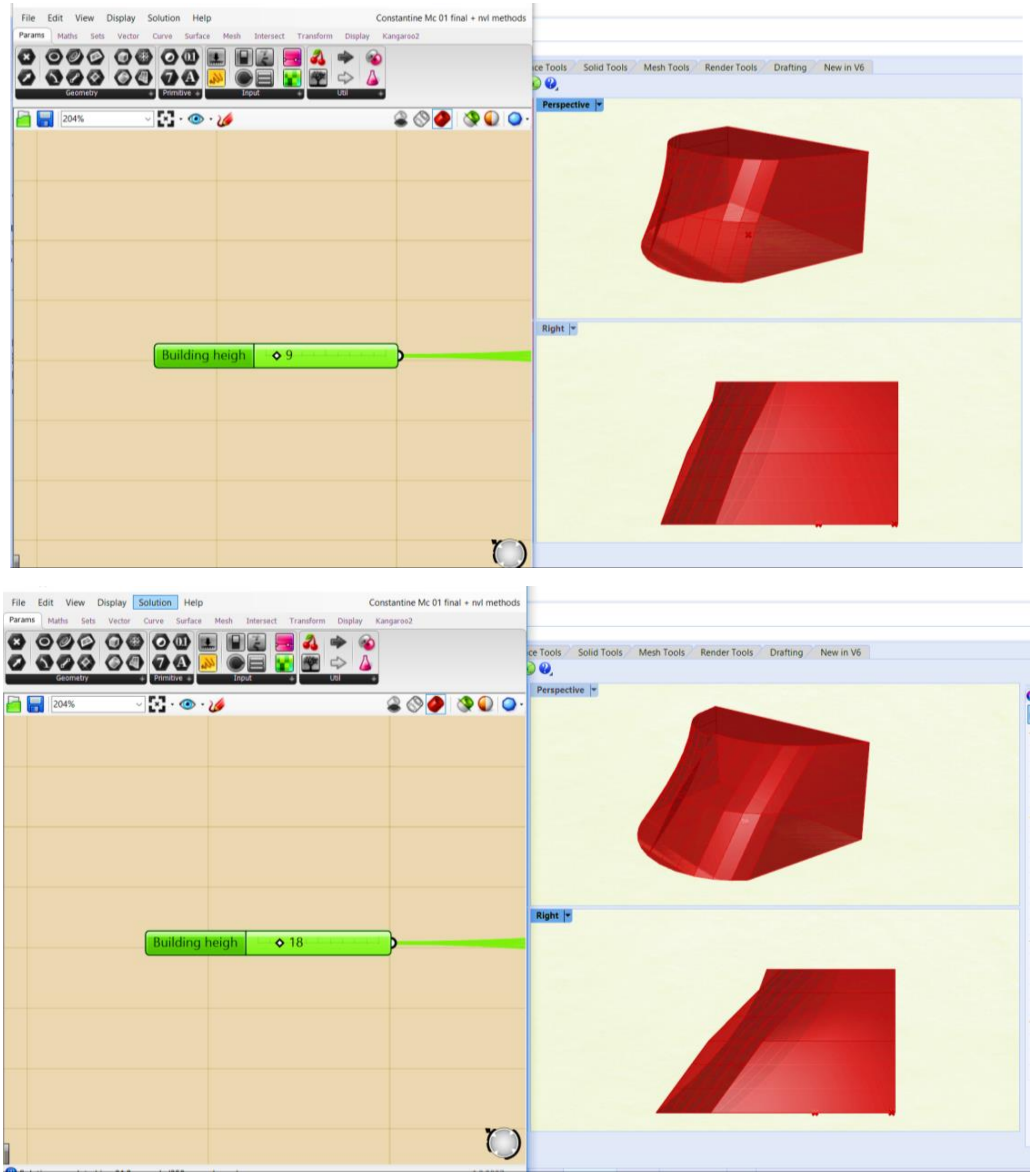

Figure VI-10: Parametrization of the building height (Author, 2022).

Application of Geo solar segmentation method results and discussion

In fact, the dimensions of the building footprint depend on the ground dimensions and the building type, which determine both the plan dimensions and the building height. Thus, the GSS method can be applied to the design of all types of buildings. Moreover, the development of such algorithms helps generalize the implementation of bioclimatic architecture through the simple act of introducing the required inputs. Additionally, the designer is able to introduce azimuthal and elevation segment numbers based on the desired segmentation level and the building aspect.

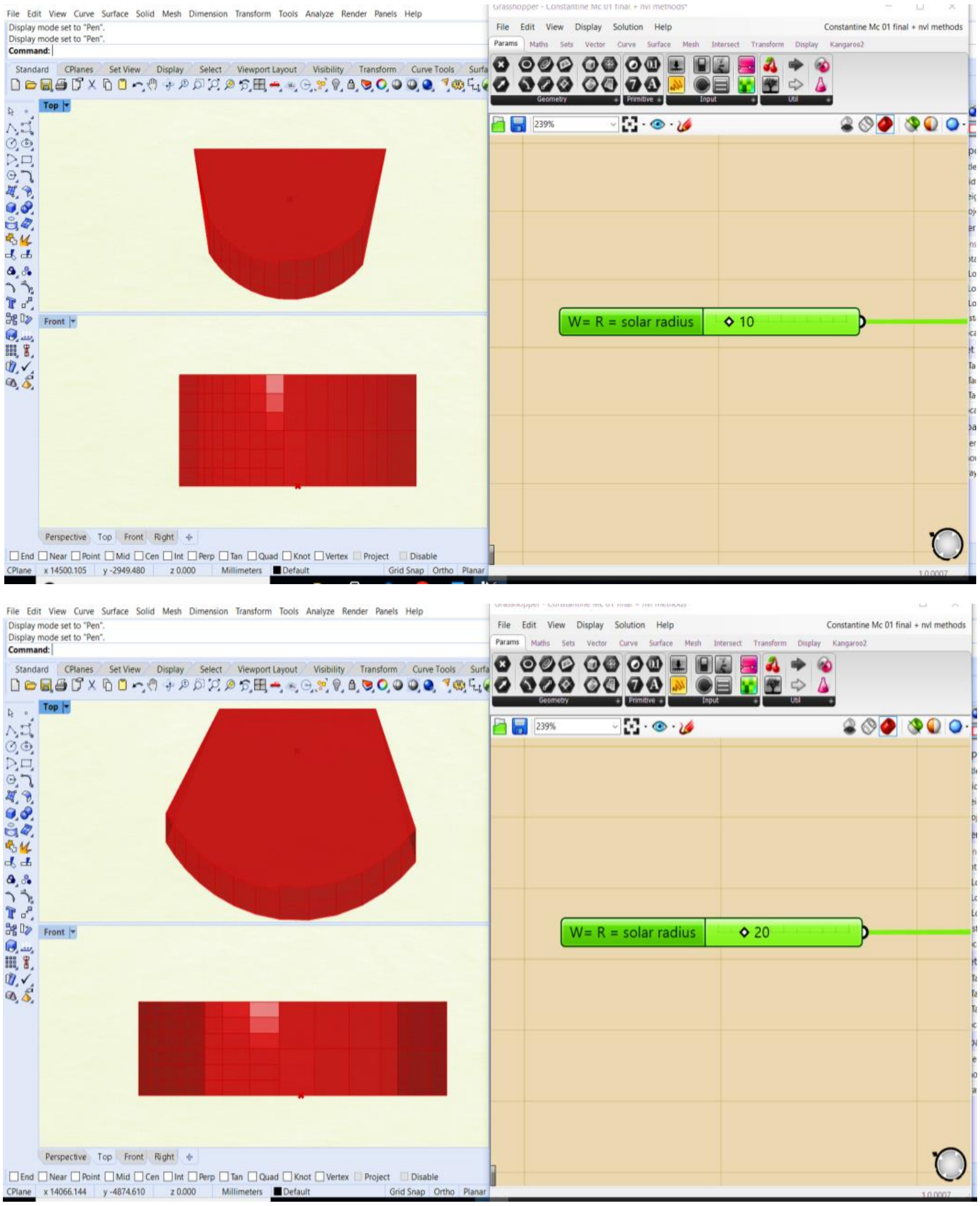

Figure VI-11: Parametrization of the building depth (Author, 2022).

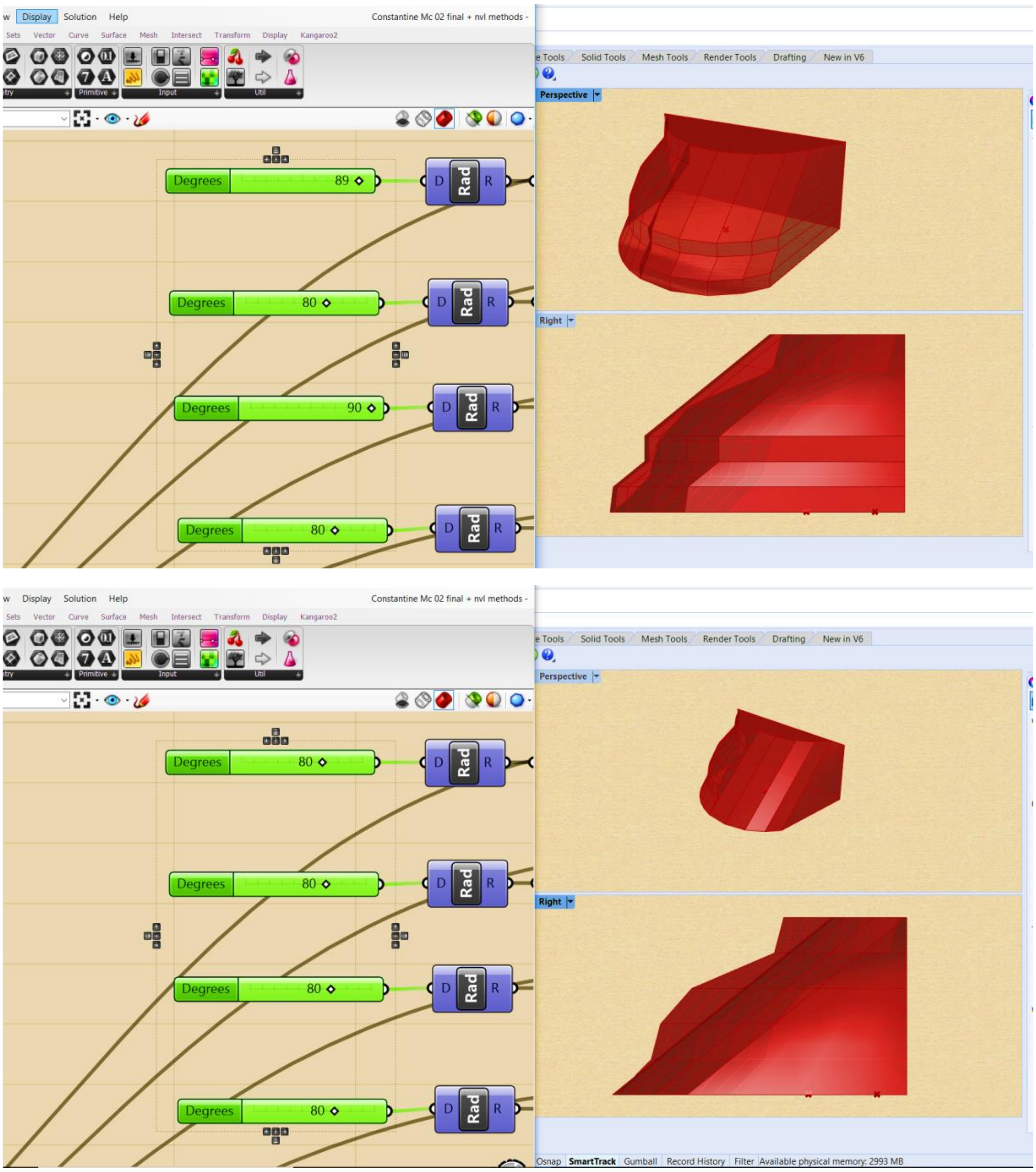

Figure VI-12: parametrization of the SBE tilt angles (Author, 2022)

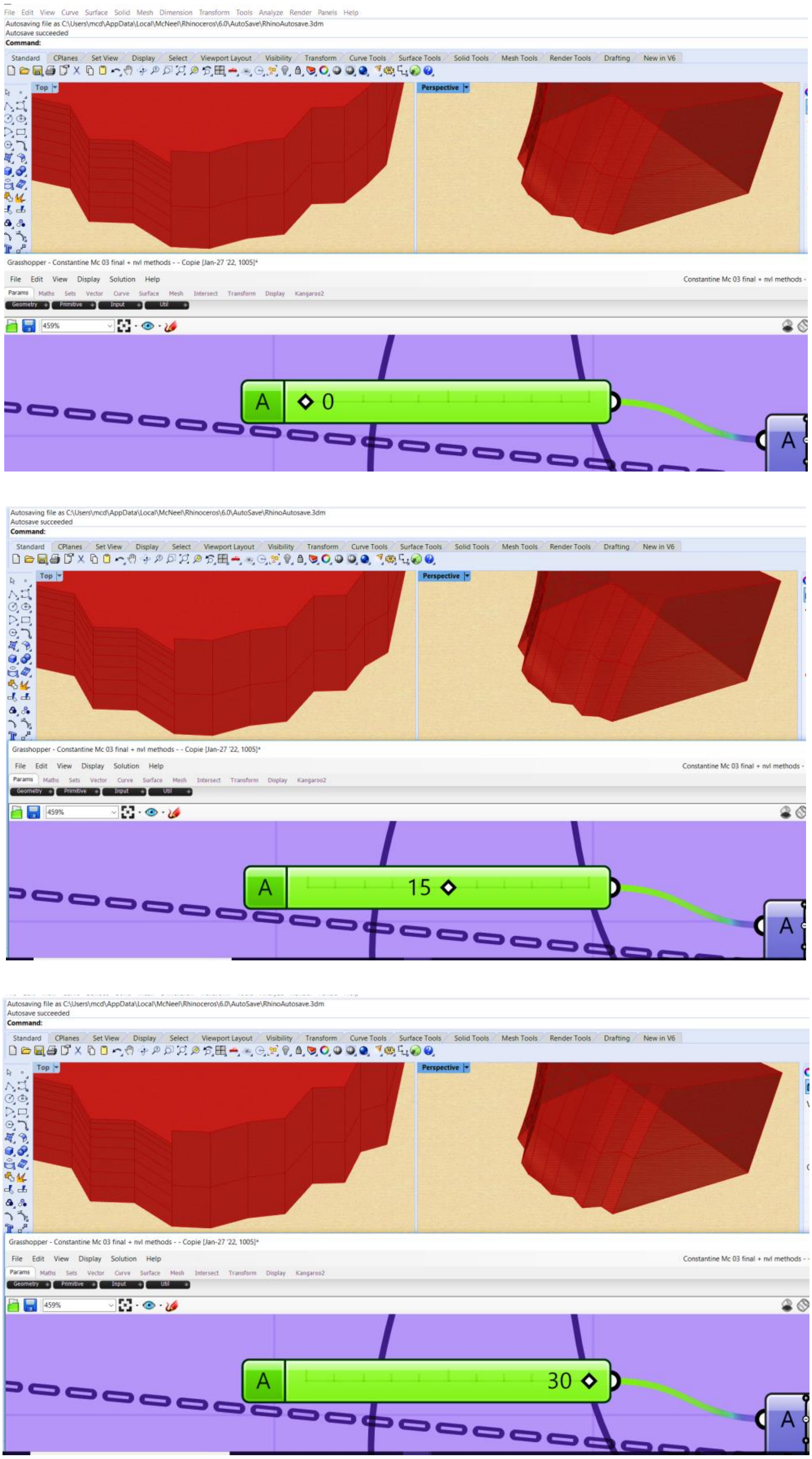

Figure VI-13: Parametrization of the SBE orientation (Author, 2022).

VI.4.2 Studied locations

GSS mechanisms are tested under different climate conditions, according to which the solar morphing objective is set. Indeed, solar collection and protection optimisation are sought in cold and hot climate regions respectively. Under temperate climate, a trade-off between solar exposure and protection should be set. Considering the above-mentioned design objectives and conferring to temperature factor, three climate zones are defined based on Koppen world climate classification: cold, temperate and hot (Carver, Mikkelsen and Woodward, 2002)(Table. A. 1). Two Algerian towns: Constantine (36 N°) and Ghardaia (32 N°) that represent temperate and hot locations respectively are selected, and Montreal (45 N°) taken as cold location. This selection is restrained by: the availability of climate data on (https://climate.onebuilding.org/) web site and short-day duration in cold regions. The latter is taken into account when defining the SUT for critical months, since the values of solar coordinates, which are the main GSS algorithm inputs, are null in night-time. Hence, the effectiveness of GSS method is assessed for critical months during which direct normal solar radiations are available and the temperatures are out of comfort range.

Optimal SBE shapes are generated based on the same dimensions of the reference building shape, which has a rectangular plan with a size of 15 m × 20 m. It is a three-story building with 3 m story height.

VI.4.3 Solar potential evaluation indicators

Solar potential evaluation indicators are categorised by (Nault *et al.*, 2015) into three groups: geometry-based metrics, external solar and geometry-based metrics, full climate and geometry-based metrics. Additionally, building solar morphing is based on the manipulation of two parameters types: continuous and discrete parameters. Continuous parameters include all building shape geometric parameters. Whilst, discrete ones consist of values that define the building envelope characteristics, such as: material thickness (Lobaccaro, Chatzichristos and Leon, 2016). In fact, GSS method relies on the variation of continuous parameters design and the geometry-based metrics evaluation. Therefore, the present study aims to keep an acceptable space efficiency and enhance the building compactness. Therefore, the following indicators are calculated during the optimisation process to evaluate the SBE shapes.

VI.4.3.1 Usable shape evaluation

Building space efficiency question is generally discussed in slopped and free form buildings envelope that both reduce the building usable space. SBE shapes are generated using plate sloped surfaces that give irregular aspects to the building profiles shape. Beyond its functional aspect, the space efficiency ratio is considered an energy performance indicator, even if it is rarely used (Zhang et al., 2016). Since the building volume is heated and conditioned during winter and summer periods respectively, a building shape with low space efficiency ratio results in excessive energy consumption (Zhang et al., 2016). High space efficiency ratio indicates more usable space inside the building, and better energy performance. Usable space can be evaluated by calculating the usable floor area (Max & Mhshermanlblgov, 2004). In the present study, it is calculated by applying the same rule Eq. 17 used by (Zhang et al., 2016). Accordingly, the space efficiency ratio of a building is the ratio between the usable space volume V_u and the whole building volume V_0. Where n is the building's total stories, and i is the number of stories.

$$E = \sum^{n} (V_u)_i / V_0 \qquad \text{Eq. 1}$$

Usable shape in the present study is related to CTA values ; their variation engenders the variation of the building usable space. Low CTA values make the space near the BFF non-accessible due to the low height (H< 2m). Thus, BFF combined tilt angles COA values range between 90° and 60°.

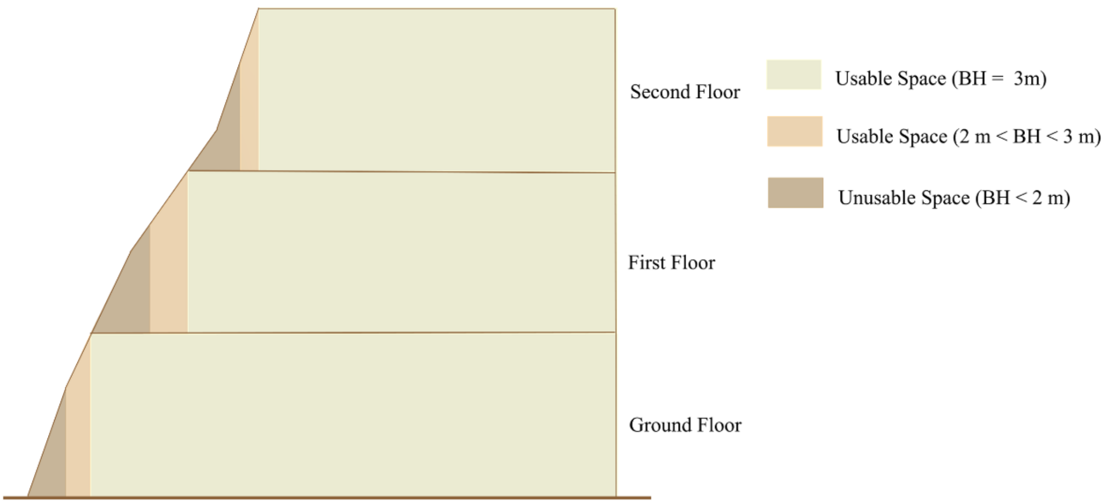

Figure VI-14Segmented building envelope's usable space (Author, 2022).

VI.4.3.2 Building shape compactness

Building shape compactness has been used by many researchers as an energy performance indicator (Caruso and Kämpf, 2015). BSM strategies aim constantly to increase the building compactness by minimising its external envelope area while increasing the internal building volume (Zhang et al., 2016). In fact, reducing shape coefficient decreases heat transfer between indoor and outdoor environment (Filippín *et al.*, 2005), Which affects the indoor climate and energy consumption (Bekkouche *et al.*, 2013). Moreover, building shape compactness offers an economic advantage by reducing the building envelope area and consequently materials need. It is described using shape coefficient S, representing the ratio between the building envelope area F_0 and its volume V_0.

$$S = F_0/V_0 \qquad \text{Eq. 2}$$

VI.5 Multi-objective genetic algorithm optimisation MOGA

In the recent years, multi-objective genetic algorithm optimisation MOGA has been commonly used in the evaluation of BSM methods, and to define optimal design solutions. It consists in defining a set of optimal solutions, based on design parameters and performance indicators (objectives). Furthermore, genetic algorithm iteration principles allow exploring large solutions' domain and lead to effective design. The combination of MOGA and parametric design approach (Yi and Malkawi, 2009),(Jin and Jeong, 2014), (Fokaides et al., (2017) has shown its usefulness in building solar morphing. For these reasons, MOGA is performed to generate optimal SBE shapes.

VI.5.1 Genetic algorithm settings

As shown in the study framework, octopus is a multi-objectives evolutionary solver, developed based on the genetic algorithm SPEA-2 and HypE (https://www.food4rhino.com/en/app/octopus). It is a rhino plugin for Grasshopper, used to perform simulation, and MOGA optimisation. The Pareto 80/20 optimisation is extensively used in MOGA optimisation. It allows generating two solutions types: the dominated solutions that are more effective in one or more of the study objectives, and the non-dominated ones that represent the Pareto frontier set. The latter gathers the best trade-offs between the study objectives. The MOGA optimisation is an open-ended process; the designer can stop it once the needed goals are met. For each mechanism, about 20 to 26 generations were explored, starting by initial population of 200. Respecting a crossover rate of 0.8 and mutation probability ratio of 0.2, the breeding process is performed by keeping the best solutions of each generation and crossing them with the individuals of the next generation to explore possible trades-off (Chore and Magar, 2017). After generating the Pareto frontier set, the non-dominated solutions (i) were ranked from 0 to 100 using (Eq.3) in order to select the optimal ones, based on maximal (max) and minimal (min) performance indicators values. The high objective function Y value characterises the best solution.

$$Y= (I_i - I_{min})\, C1 + (E_i - E_{min})\, C2 + (-1)\,(S_i - S_{min})\, C3 \qquad \text{Eq. 3}$$

$$C1=100/ (I_{max} - I_{min}) \qquad \text{Eq. 4}$$

$$C2= 100/ (E_{max} - E_{min}) \qquad \text{Eq. 5}$$

$$C3=100/ (S_{max} - S_{min}) \qquad \text{Eq. 6}$$

VI.6 Results and Discussion

The assessment of the GSS mechanisms is carried out by comparing the total received solar radiation by optimal SBE against the reference building shape. To account for the change in the geometry and energy performance of optimal SBE, the shape coefficient and space efficiency are calculated. Based on objective function value (Y) (Eq. 19), five optimal solutions are presented for each location to show different design performances trades-off (appendix. B). Additionally, optimal SBE shapes are selected with respect to the reference building volume limits (Table. VI-1).

To analyse the obtained optimal SBE shapes, their geometric features are outlined. Each of optimal SBE belongs to a given generation (G). It is characterised by the solar state date according to which it is generated, and optimal segments numbers: SN_A and SN_E of both BFF morning (M) and afternoon (A) parts. The optimal SBE obtained from optimisation mechanisms are characterised by specific features such as CTA values, COA values and SPP combinations. The first generated SBE performances are compared with the optimal SBE issued from optimisation mechanisms, then with the reference performance values.

Table VI-1 Reference building performance values for the studied locations (Author, 2022).

<table>
<tr><td rowspan="2">Location</td><td colspan="4">Reference building shape performances</td></tr>
<tr><td colspan="2">Solar radiation (kW h)</td><td>Space efficiency (%)</td><td>Shape coefficient</td></tr>
<tr><td>Montreal</td><td colspan="2">323090</td><td rowspan="4">100</td><td rowspan="4">0.34</td></tr>
<tr><td rowspan="2">Constantine</td><td>Cold period</td><td>367620</td></tr>
<tr><td>Hot period</td><td>281230</td></tr>
<tr><td>Ghardaia</td><td colspan="2">712040</td></tr>
</table>

VI.6.1 Under cold climate conditions

For the cold climate of Montreal, optimal SBE shapes (Fig. VI-15) are assessed for the heating period, extending from October to April; for this period, the SUT was kept constant from 8h to 16h. Table VI-2 shows the optimal SBE performances obtained applying GSS mechanisms. It can be seen that, the first generated SBE receives total solar radiation of 219100 kW h, which is amplified by nearly 254780 kW h, varying CTA. This represents an improvement of 16.30%. Any further optimisation using the other mechanisms leads to a slight improvement in total received radiation comparing with the first generated SBE performance Table. B. 1. Nevertheless, the SBE solar potential remains less than the reference value, estimated at 323090 kW h. It is observed that, the implementation of COA and SPP mechanisms provides the best results in terms of space efficiency 98%, which is maintained up to 96%, over optimisation process. The shape coefficient is decreased to 0.30 using the CTA mechanism, which represents an enhancement of 10.30% Table. B. 1.

The optimal solar state's month changes according to the implemented mechanism; it is December in both generation and COA mechanisms and August for CTA/COA mechanism. It varies between the three first months of the year: January, February and March in the CTA mechanism. Therefore, the solar state's month varies as a function of the manipulated geometric parameters. Optimal SBE obtained from the generation and COA mechanisms are characterised by high segmentation levels (SN=08) contrary to those reached in applying the

CTA/COA mechanism, which are of lower segmentation level (03<SN<07) (Fig.VI-15). It is noticed that the CTA values of the lower segments of the BFF Morning part are mostly close to the normal, about 88°. Whilst, the highest ones are close by 60°. Therefore, the segments generated according to early morning solar data are nearly vertical to face the low sunrays. Table. B. 1. shows that the combination of the first profile shape of the BFF morning part with 112, 113, and 114 profile shapes of the BFF afternoon part offered optimal SBE under Montreal climate (Tab. VI-2).

Therefore, the results indicate that, under cold climate the GSS method's effectiveness is limited in terms of solar potential, with less effectiveness of 20.55% than the reference building (Tab. B. 1). However, it can be used to enhance the building shape coefficient. The CTA optimisation mechanism is the most effective, which means that the tilt angle is a crucial design parameter in the GSS method.

Table VI-2 Optimal first ranked SBE for Montreal (cold climate) (Author, 2022).

GSS mechanisms	G	Performance values			Optimal SBE Geometric features					
		Solar radiation (kWh)	Space efficiency (%)	Shape coefficient	SNA SNE (M)	SNA SNE (A)	Date	CTA M/A (°)	COA M/A (°)	P M/A
Generation	18	219100	98.4958	0.3701	8-8	8-6	30/12	/	/	/
CTA	20	254780	97.7612	0.3251	7-4	6-2	16/3	88,78,60,62/ 87,89	/	/
COA	21	221280	98.6139	0.3738	5-2	8-8	22/12	/	1,0 / 1,4,25,29	/
CTA+COA	20	193190	96.1651	0.3050	4-2	7-3	07/08	89,88/83,72, 70	23,24,12, 23 /2,27,23,7	
SPP	26	219910	98.6561	0.3645	8/2	8/7	25/12	/	/	1/4798

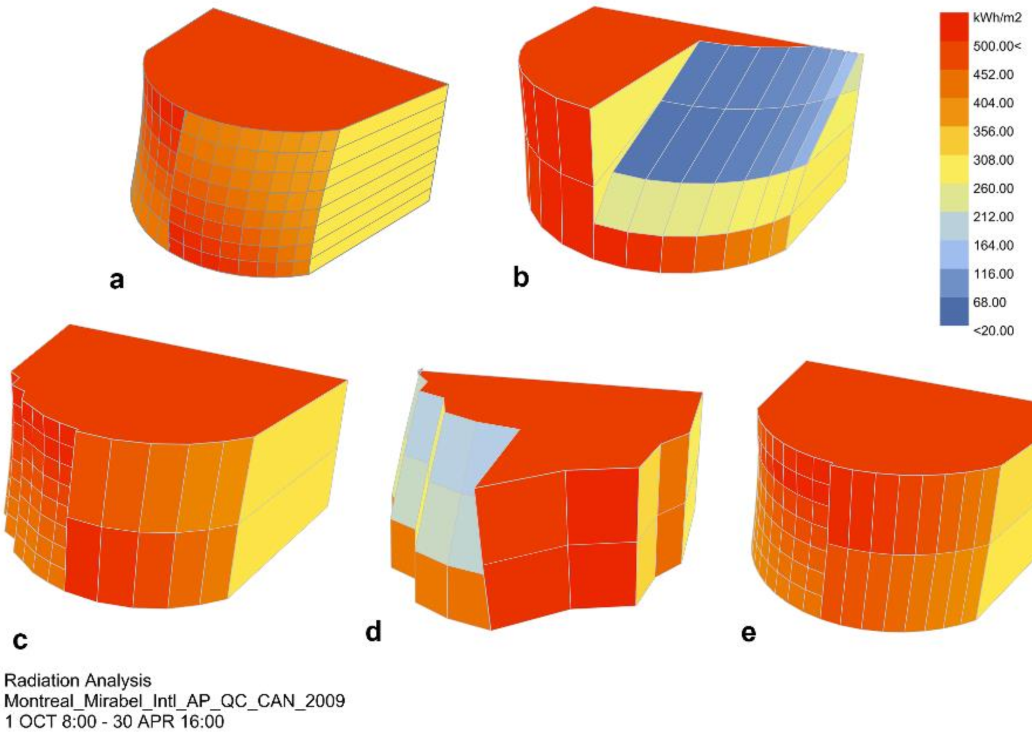

Figure VI-15: Radiation analysis results of optimal SBE under cold climate conditions generated applying: (a) generation mechanism, (b) CTA mechanism, (c) COA mechanism, (d) CTA/ COA mechanism, (e) SPP mechanism (Author, 2022).

VI.6.2 Under temperate climate conditions

In a temperate climate the optimisation consists in balancing the total received solar radiation during both hot and cold periods. Indeed, setting a trade-off consists in decreasing a performance value to upgrade the other. For Constantine city, the simulation is run during both heating and cooling periods i.e., from November to April and from June to August, corresponding to winter and summer critical months respectively. Additionally, the SUT was limited from 8 am to 4 pm. The results show that, the solar protection is enhanced, while the collection decrease comparing with the reference performance values (Table. VI- 3). Therefore, all the obtained results using different mechanisms represent trades-off between solar collection and protection under Constantine climate (Fig. VI-16). CTA mechanism gives the best trade-off between optimisation objectives. It permits the enhancement of solar protection and shape coefficient of 33.90 %, and 20.60% respectively, while the collection is decreased by 33.90%.

The space efficiency reached 98% by the implementation of CTA/COA mechanism, and is kept above 96% using the other mechanisms. Optimal SBE under temperate climate are mostly characterised by high segmentation level (Tab.VI-4). In each mechanism, specific SN values characterise optimal SBE such as 6/3 in CTA mechanism. CTA values are very close to the normal. While, COA values are low, and reach higher values such as 29° when implementing CTA/COA mechanism. Specific profile shapes combinations, such as 4/711 and 4/95 are behind the generation of optimal SBE.

Table VI-3 Optimal first ranked SBE for Constantine (temperate climate) (Author, 2022).

GSS Mechanisms	G	Optimal SBE performance values				Optimal SBE Geometric features					
		Solar radiation (kW h)	Solar radiation (kW h)	Space efficiency (%)	Shape coefficient	SN_A SN_E (M)	SN_A SN_E (A)	Date	CTA M/A (°)	COA M/A (°)	P M/A
Generation	15	229910	178260	97.5619	0.3762	6/2	7/6	28/12	/	/	/
CTA	21	243030	186000	96.2331	0.2781	5/2	6/3	2/8	86,85 /78,79,71	/	/
COA	13	225960	174440	97.5615	0.3817	2/2	3/6	20/12	/	7/4	/
CTA+COA	17	251600	188540	98.6150	0.3703	7/2	4/2	30/10	87,83 /81,83	29,21,9 /6,17	
SPP	4	230090	178160	97.5502	0.3713	6/6	4/6	26/12	/	/	4/711

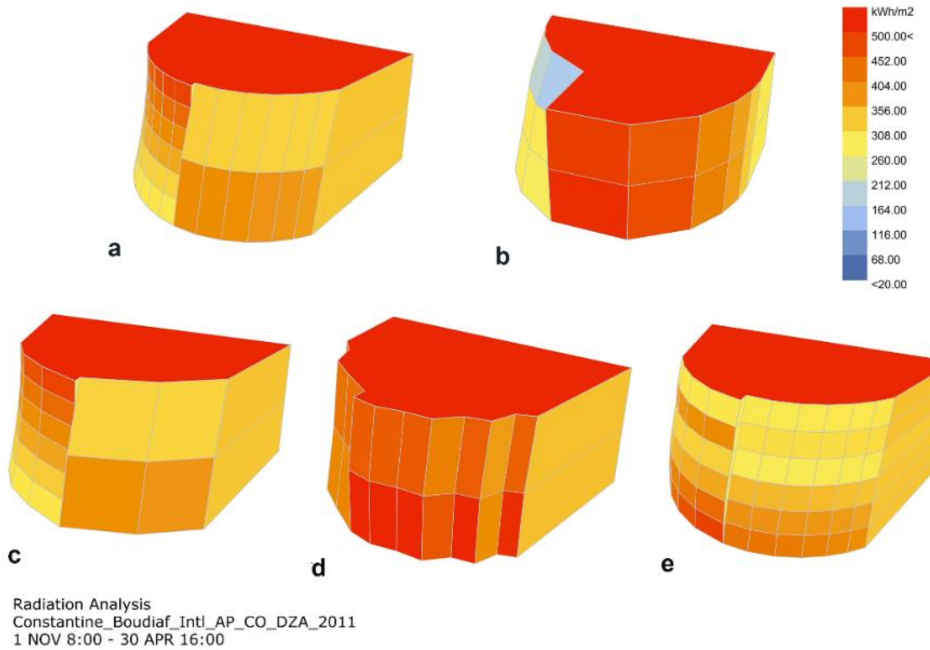

Figure VI-16: Radiation analysis results of optimal SBE under temperate climate conditions generated applying; (a) generation mechanism, (b) CTA mechanism, (c) COA mechanism, (d) CTA/ COA mechanism, (e) SPP mechanism (Author, 2022).

VI.6.3 Under hot climate conditions

Using the same approach described above, the optimal SBE for Ghardaia were generated and optimised for the cooling period, from April to October. The SUT was set from 7am to 7pm. The results indicate that, all generated optimal SBE have better performance than the reference building shape in terms of solar protection (Fig. VI-17). Precisely, the generation mechanism improves the building solar potential by 48.80% (Tab. B. 3). The total received radiation is reduced to 397670 kWh for the (4645/3646) profiles shapes combination. It allows a solar protection enhancement of 44.15%. Table. B. 3 shows that the same profiles combinations, such as 21989/3646 (Tab. B. 3) are adopted in the generation of many optimal SBE shapes. The implementation of CTA mechanism allows reducing total received radiation with 41.90% when compared with the reference building. CTA values of optimal SBE are mostly close to the normal. However, when CTA and COA are simultaneously varied the CTA values of the BFF afternoon part decrease close to 61°. A little COA variation compromised between 0° and 11° enhanced slightly the SBE solar potential. The best trade-off is achieved using CTA/COA mechanism with an enhancement of 44.90% and 34.85% in solar protection, and shape coefficient respectively, while the space efficiency is close by 97% (Tab. VI-5).

18th January is the optimal solar state for generation, COA and SPP mechanisms, and February for CTA and CTA/COA mechanisms. Optimal SEB issued from the same mechanism have generally the same segments numbers such as 6/2 in CTA mechanism. The best value of space efficiency is estimated at 98% obtained via the implementation of CTA mechanism. It is maintained above 95% in other mechanisms. CTA/COA mechanism gives the best results in terms of shape coefficient 0.21, which represents an improvement of 38.25%.

Table VI-4 Optimal first ranked SBE for Ghardaia (hot climate) (Author, 2022).

GSS Mechanisms	G	Optimal SBE performance values			Optimal SBE Geometric features					
		Solar radiation (kWh)	Space efficiency (%)	Shape coefficient	SN_A SN_E (M)	SN_A SN_E (A)	Date	CTA M/A (°)	COA M/A (°)	Paths: M/A
Generation	13	406750	96.4929	0.3739	6/6	7/3	18/1	/	/	/
CTA	9	551380	98.8428	0.3521	4/2	6/2	27/2	88,81/89,83	/	/
COA	16	451680	96.9027	0.3790	5/2	3/6	18/1	/	3 / 5	/
CTA+COA	19	413820	96.7742	0.2215	4/2	5/2	10/2	82,89/61,68	12 / 1	/
SPP	19	397670	96.3399	0.3768	7/7	3/8	21/1	/	/	4645/3646

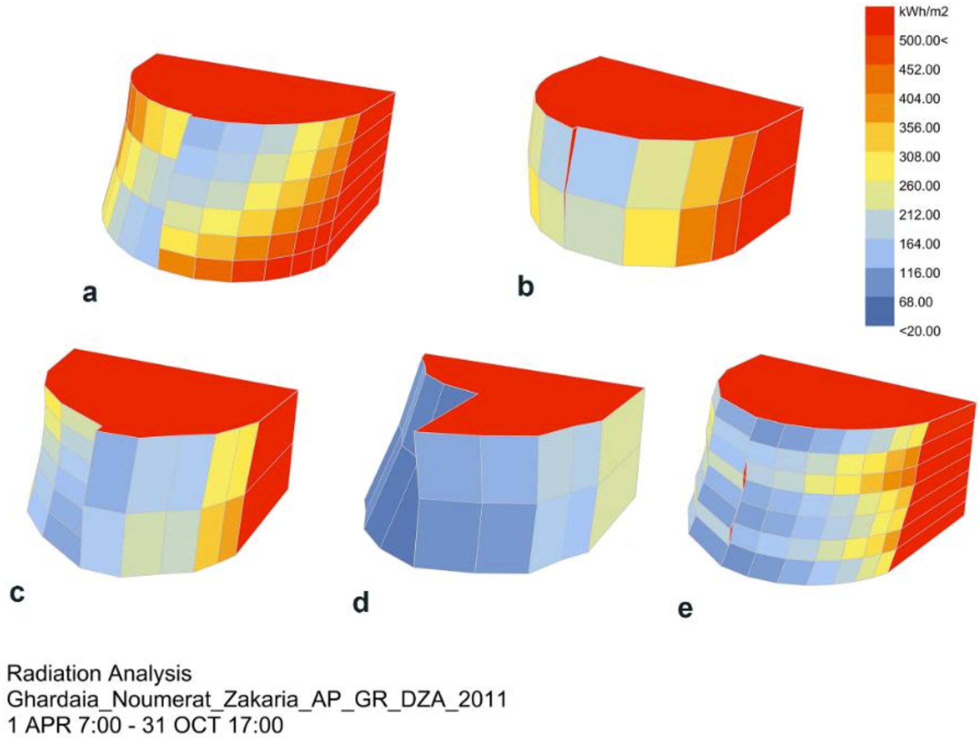

Figure VI-17: Radiation analysis results of optimal SBE under hot climate conditions generated applying; (a) generation mechanism, (b) CTA mechanism, (c) COA mechanism, (d) CTA/ COA mechanism, (e) SPP mechanism (Author, 2022).

VI.7 Conclusion

In the present Chapter, a solar morphing design method was established to enhance static building envelope ability in regulating solar exposure, with respect to enhancing shape coefficient, while keeping the building space efficiency acceptable. Getting inspiration from natural mechanism provides the designer with a road map and helps him visualise the design solution. Accordingly, a Geo-solar morphing mechanism, inspired by ‘solar-induced rock cracking’ phenomena, was adopted as a design concept in setting the Geo-solar segmentation method. The latter was implemented based on a generation, and four optimisation mechanisms, using a parametric approach and visual programming in Grasshopper. MOGA optimisation is performed to generate optimal SBE, and evaluate the method’s effectiveness under cold, temperate, and hot climates. A comparative study was carried out between optimal SBE and a rectangular-based reference building.

The results show that the effectiveness of the GSS method is limited under cold climates in terms of solar potential. However, it helps enhance the building shape coefficient of 10.30%. The GSS method can be considered as an effective tool in setting a trade-off between two contradictory solar design objectives in temperate climates. It enhances solar protection during the cooling period by 33.90%, and shape coefficient by 20.60%. While the total received solar radiation is reduced by 33.99 % in the heating period. Under hot climate, the GSS method shows better performance. The improvement of solar protection and the shape coefficient reached 44.90% and 34.85%, respectively. The space efficiency values are kept up to 95%. Therefore, the deviation reveals the ability of the morphed façade to regulate solar energy compared with a standard façade especially under hot and temperate climates.

The present study shows that combining the biomimicry approach and visual programming tools helps provide effective architectural design tools. Further, early-design stage solar morphing methods help achieving more efficient static building envelope. The use of MOGA and computational design tools allows generate a wide range of optimal design solutions and options and make it possible to set a trade-off between two conflicting solar design objectives. Therefore, GSS can be applied in the architectural design process in hot climates such as Algerian Sahara. It will help adapt local architecture to its climatic context and considerably contribute to climate change attenuation. The study offers a solar morphing method for building design; the impact neighbouring buildings is not considered and need further research. In the MOGA process, the objectives and the generations numbers were limited according to the used computer performance. For the same reason the segmentation is applied only to a building part. Otherwise, more irregular and effective shapes can be generated. Future studies should evaluate the impact on the building energy performance and overall thermal comfort of the occupant.

Additionally, the inspiration source in this study is a phenomenon observed in nature, which has not been explored previously in building morphing studies. Moreover, the method logic allows the designer to generate optimal building shape by considering multiple factors of solar geometry and shape performance indicators

VII. GENERAL CONCLUSION

General conclusion

This section summarizes the main conclusions drawn from the present thesis in order to highlight the significance of our study findings in both research and design domains. By attempting to address the questions posed and explored in the introductory chapter of this thesis, the primary findings are presented. The following conclusions are given in accordance with the structure and chapters' order. In addition, the findings are highly relevant to the study's main objective, which is to improve the ability of a static building envelope to manage its solar exposure.

The present study objective is to establish an innovative design method for building solar morphing implementing a revised top-down bio-inspired design approach. Thus, a natural solar morphing mechanism is found then transcribed into an architectural design concept. Consequently, innovative building forms are obtained by applying the established method. Hence, the addressed theoretical concepts, the development of the solar design algorithm and the application on several case studies allowed to give answers to all above highlighted questions.

The conclusions drawn from the two parts that include six chapters are presented in order to emphasize the treated questions, the study framework, the addressed concepts, and the suggested solutions. The first part of the thesis is theoretical and explains the fundamentals of an innovative approach in the architectural design field. The latter embeds different design approaches, such as parametric approaches, generative approaches, and algorithm-based approaches. The second chapter urges architects to rethink architecture and emphasizes the need for innovative design tools. However, the common origin of the above-mentioned approaches is "shape grammars theory," which relies on basic computation operations. This chapter shows that innovative design approaches emerge from a conventional theory of shape composition.

Furthermore, this section highlights the fundamentals of "shape grammars" design theory and demonstrates their simple application in achieving complex and innovative forms. This analytical approach helps designers understand that the process of innovative and creative design in architecture relies on simple shape combinations and basic geometric transformation rules. **This means that complex forms can be derived from basic shape combinations**. An algorithmic-based design approach is particularly explained in the same chapter to encourage architects to seek new forms of architectural expression.

General conclusion

The significant findings in biomimicry field are about bio-inspired design approaches. The fourth chapter explains that the study of natural systems and organisms requires knowledge from different areas. Accordingly, the study shows the interdisciplinary connection and defines the basics before starting the design process. The study demonstrates that **life sciences are mandatory in the understanding of natural phenomena** and their transcription into a design concept.

A large number of bio-design tools and methods make the choice more difficult. Additionally, the use of the same terms to explain different concepts makes the designer confused about the accuracy of the bio-design approach. For this reason, our research suggests a revised top-down bio-approach path-line, dubbed “Bio-bridge design line-path”. In fact, the embedding of Bio-bridge design concepts in the bio-inspired design process showed its effectiveness in selecting an appropriate source of inspiration. Therefore, the definition of the bio-bridges concepts helps to emphasize the main bio-approach elements and stages.

The results of the implementation of the geo-solar segmented building envelope morphing method show the effectiveness of **Bio-bridge concepts**. Thus, the analysis of the relationship between architecture and biomimicry helped outline **the most impactful design elements**. Identifying the biomimicry features and architectural aspects that affect the implementation of a bio-approach is a way to enhance design thinking, revise the existing design approaches, and make effective design line-path. Similarly, this analysis can be conducted in the other bio-design domains. The development of innovative design tools is important, but we should also revise our design thinking system to upgrade the architectural quality of buildings, especially in our country.

The differentiation between "the transcription of bio-knowledge" and "the bio-knowledge transfer" is basic. Many research studies addressed bio-knowledge transfer, with various methologies proposed. In this study, the use of the term "transcription" is chosen because the nature of information changes from a theoretical concept and functional mechanism into a shaping mechanism and then a geometry. In fact, the present study shows the importance of choosing the appropriate terms to designate the desired meaning and explain the basic ideas. This was clearly shown in revising the bio-bridge "level" by giving it a revised meaning to make it more effective in the process of searching for an appropriate source of inspiration. Moreover, the term "behaviour" was not embedded in the revised bio-approach line-path since it is considered as a general term that can be replaced by the terms

"Analogy" and "analogical functional aspect." The analogical functional aspect is more significant to describe the behavioural process.

The present research shows that it is possible to enhance architectural quality by conducting a critical analysis of the existing design methods and approaches. Thus, designers and architects should continually work to improve the quality of architectural space, its usability, and its adaptation to the user's requirements. The generation of organic and irregular building shapes that do not obey traditional architectural design shape grammars is not sufficient. These geometries must be adapted to climatic factors to mitigate the repercussions of climate change. For these reasons, innovative architectural approaches must be embedded in architectural design studies and education.

Furthermore, clarifying the foundation of innovative architectural design serves as an invitation to improve the architectural quality of future designed buildings. The quality of architectural design in Algeria is a subject that merits independent and in-depth consideration. The topic of the architecture's adaptation to its global setting, which encompasses all social, economic, and cultural factors, must be addressed **in light of environmental considerations**. The geo-solar segmented building envelope morphing method suggested in this research is a design method that helps ensure solar adaptation of the building shape. Furthermore, it can be applied to Algerian climate zones to contribute to sustainable architecture. This draws architects' attention towards the use of algorithmic-based design in order to develop algorithms that allow generating adapted geometries with respect to other climatic factors, not only solar energy.

Although the present thesis only addresses solar adaptation, further adaptation aspects can be addressed to verify the possibility of designing a multifunctional static building envelope that serves more than one purpose. In the geo-solar segmented building envelope morphing method, the building envelope surfaces are in continual interaction with solar energy. For this reason, the evaluation of the segmented building envelope SBE was done based on the cumulative behaviour of the building envelope surfaces. Consequently, the results of this study show that it is possible to develop a building envelope solar morphing method to enhance its ability to regulate solar incident radiation. Therefore, there are many research areas that are related to static building envelope functionalities that must be addressed. Furthermore, the use of biomimicry in architecture has been limited to dynamic facade systems. The dynamic aspect and the possibility of changing the façade module layout facilitate achieving the required adaptation. However, they mostly rely on active systems that consume energy to perform. For these reasons, an investigation of the possibility of a static building envelope should be conducted.

Additionally, the geo-inspiration source in this study is a phenomenon observed in nature, which has not been previously adopted in building morphing studies. Moreover, the method allows the designer to generate an optimal building shape by considering multiple factors of solar geometry and shape performance indicators (Keskas *et al.*, 2022).

The BSM method developed in this thesis help enhance the building's energy efficiency under **several climate types** by enhancing static building envelope solar exposure. This method is versatile, allowing shape exploration in several climatic regions. It can be applied in the early design stage to avoid modifications in the building shape post-construction. Thus, it saves time, energy and resources for future upgrades (Keskas *et al.,* 2022).

Furthermore, the present study shows the effectiveness of the developed method **under several climatic conditions** Trade-offs between solar protection, solar collection and shape performance indicators are achievable under a temperate climate.

Interdisciplinary connections, as defined in the current study, are required in the implementation of an innovative design approach. Thus, mathematics has an important position in architecture. Since the building's shape is a geometry that has its roots in mathematical laws, interdisciplinary research groups should be set up to conduct studies in the field of design.

In addition to being a technique to design, **parametric design** is also a method for examining and exploring geometries. Focusing on specific parameters facilitates comprehension and management of complex shapes. Parametric design approach relies on mathematics; we can't use it without math modelling.

In fact, the success of research projects dealing with **environmental building's adaptability** is dependent on the selected study elements, as detailed in Chapter 3. Therefore, the definition of the study objectives helps define the most suitable evaluation indicators. The values of the evaluation indicators depend on the manipulation of the building envelope shape by varying the parameters' values. Thus, the study **parameters** should be selected based on the functional aspect.

The combination of the bio-design approach, parametric design, and multi-objective optimisation offers five morphing mechanisms and diverse design solutions. This shows that combining innovative design approaches leads to the development of more creative design process. Another conclusion can be taken from the present thesis that concerns the researcher character. Even if the current tendency in bio-inspired design approach applied to architectural design emphasizes the design of façade systems, it was very interesting to not follow the same research axe and to undertake the design of the whole building shape, which is ignored. Biomimicry should be explored by both biologists and designers from several domains. To exchange knowledge and develop more effective bio-inspired design approaches, methods, and tools.

This study demonstrates that integrating the biomimicry with visual programming tools results in more effective architectural design tools. In addition, early-design solar morphing approaches contribute to a more efficient building envelope. The employment of MOGA and computational design tools enables the generation of a large number of optimal design solutions and possibilities and the establishment of a trade-off between two solar design objectives that are in conflict.

The present thesis contributes to clarifying and addressing the application of biomimicry in the design of the whole building shape, which is a research topic that is less treated. Moreover, the results of this study and the published paper entitled "**Geo-solar segmentation mechanism: an early-design stage method for building solar morphing" in the** "Solar Energy" journal will encourage and draw researchers' attention towards the adaptation of the whole building shape embedding natural mechanisms.

Further research works:

Many research axes and topics can be derived from the present study framework. The addressed design approach can be re-examined and explored by focusing only on one or two approaches and testing the results of their combination. We deeply believe that research and science are in permanent evolution, and innovative and revised approaches can be derived from the existing ones.

General conclusion

Algorithmic-based design should be generalised in architecture field since it helps achieve the adaptation of the building to its environment, particularly nature and climatic factors. It also helps achieve the sustainable development goals in the framework.

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Annex

Annex A:

Table A.1 Koppen world climate classification (Peel et al., 2007)

Climate zone	description	Temperature criterion
A	Tropical	$T_{cold} \geq 18$
B	Arid	$MAP < 10 \times P_{threshold}$
C	Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
D	Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
E	Polar	$T_{hot} < 10$

Annex B:

Table B.1 Optimal five ranked SBE for Montreal (Cold climate).

GSS mechanisms	G	Performance values			Optimal SBE Geometric features					
		Solar radiation (kW h)	Space efficiency (%)	Shape coefficient	SN_A SN_E (M)	SN_A SN_E (A)	Date	CTA M/A (°)	COA M/A (°)	P M/A
Generation	18	219100	98.4958	0.3701	8-8	8-6	30/12	/	/	/
	18	219280	98.5314	0.3704	3-8	8-6	20/12	/	/	/
	13	219230	98.5217	0.3698	8-7	8-5	21/12	/	/	/
	19	217560	98.4763	0.3694	8-8	8-3	18/12	/	/	/
	13	219310	98.5211	0.3698	7-8	8-5	22/12	/	/	/
CTA mechanism	20	254780	97.7612	0.3251	7-4/	6-2	16/3	88,78,60,62/ 87,89	/	/
	18	252870	97.7012	0.3266	7-4	6-2	16/3	88,77,60,62/ 87,89	/	/
	21	243300	97.9935	0.3286	5-4	4-2	10/01	84,80, 63,60/ 87,88	/	/
	17	256680	97.7026	0.3295	5-4	4-2	17/02	84,77,64,60/ 87,88	/	/
	19	247380	97.7167	0.3307	5-4	4-2	14/02	84,77,64,60/ 87,88	/	/
COA mechanism	21	221280	98.6139	0.3738	5-2	8-8	22/12	/	1,0 / 1,4,25,29	/
	21	220900	98.6163	0.3727	5-2	7-8	22/12	/	0,5 / 0,0,25,1	/
	21	221000	98.6084	0.3751	7-2	6-8	22/12	/	2,1,0 / 2,29,23,28	/
	21	221230	98.6036	0.3763	6-2	8-7	22/12	/	2,1,8 / 1,30,28,29	/
	20	218460	98.5356	0.3704	5-2	6-6	08/12	/	4,0 / 3,1,22,24	/
CTA / COA mechanism	20	193190	96.1651	0.3050	4-2	7-3	07/08	89,88/83,72,70	23,24,12,23 /2,27,23,7	/
	11	208960	96.0445	0.3024	4-2	7-3	07/08	89,84/83,74,70	23,24,12,23 /2,27,23,7	/

	15	210240	96.1547	0.3116	5/2	6-3	12/8	89,89/72,72,80	9,4,3,20 /10,26,18,14	/
	18	211250	96.2493	0.3082	3/2	7-3	12/8	89,88/72,72,82	2,2,25,12 /14,13,19,29	/
	7	209960	96.0883	0.3105	5/2	7-3	12/8	89,88/72,72,80	7,2,25,23 /14,26,18,14	/
SPP mechanism	26	219910	98.6561	0.3645	8/2	8-7	25/12	/	/	1/4798
	18	219360	98.6919	0.3649	7/2	8-5	24/12	/	/	1/114
	19	219370	98.7000	0.3650	8/2	8-5	24/12	/	/	1/113
	15	219340	98.7017	0.3649	8/2	8-5	20/12	/	/	1/112
	16	219380	98.6656	0.3647	7/2	8-5	22/12	/	/	1/118

Table B.2 Optimal five ranked SBE for Constantine (Temperate climate).

GSS Mechanisms	G	Optimal SBE performance values				Optimal SBE Geometric features					
		Solar radiation (kW h)	Solar radiation (kW h)	Space efficiency (%)	Shape coefficient	SN_A SN_E (M)	SN_A SN_E (A)	Date	CTA M/A (°)	COA M/A (°)	P M/A
Generation	15	229910	178260	97.5619	0.3762	6/2	7/6	28/12	/	/	/
	15	229530	178010	97.5510	0.3759	8/2	8/5	27/12	/	/	/
	13	229450	177970	97.5577	0.3764	7/2	7/6	15/12	/	/	/
	14	229420	177940	97.5575	0.3764	7/2	6/6	15/12	/	/	/
	14	229270	177790	97.5563	0.3766	7/2	4/6	15/12	/	/	/
CTA mechanism	21	243030	186000	96.2331	0.2781	5/2-	6/3	2/8	86,85/78,79,71	/	/
	4	235740	180200	96.2212	0.2824	5/2	3/3-	2/9	86,85/78,79,66	/	/
	5	233420	178330	96.1450	0.2836	5/2	3/3	2/9	86,85/78,78,66	/	/
	20	238550	184800	97.6304	0.3648	6/3	5/2	29/10	87,79,81/82,79	/	/
	15	238620	184870	97.6132	0.3645	6/3	5/2	27/10	87,79,81-82,79		
COA mechanism	13	225960	174440	97.5615	0.3817	2/2	3/6	20/12	/	7/4	/
	20	226720	175100	97.5516	0.3808	3/2	2/6	23/12	/	8/4	/
	19	228300	176620	97.5319	0.3800	5/2	4/7	17/12	/	15,1/10,9	/
	9	227110	175380	97.5575	0.3828	2/2	8/7	20/12	/	7/4,9,26,14	/
	6	228130	176430	97.5182	0.3803	7/2	4/6	28/12	/	17,9,9/11,9	/
CTA / COA mechanism	17	251600	188540	98.6150	0.3703	7/2	4/2	30/10	87,83/81,83	29,21, 9/6,17	/
	13	250550	187490	98.6030	0.3753	7/2	4/2	30/10	87,83/81,83	18,21, 9/30,17	/
	18	249830	187160	98.5399	0.3711	5/2	4/2	30/10	89,82/81,80	23,26/ 1,17	/
	19	248680	186680	98.4890	0.3710	7/2	6/2	30/10	87,81/81,83	30,21, 9/8,19, 29	/

	20	234540	177340	96.2879	03022	3/2	2/2	22/8	86,84/64,79	29/2	/
SPP mechanism	4	230090	178160	97.5502	0.3713	6/6	4/6	26/12	/	/	4/711
	1	229640	177920	97.5036	0.3714	5/5	7/5	26/12	/	/	4/119
	1	229600	177910	97.4501	0.3714	8/5	7/5	26/12	/	/	4/95
	1	229580	177880	97.4499	0.3714	7/5	7/5	26/12	/	/	4/95
	5	230370	178370	97.5633	0.3716	6/6	4/6	22/12	/	/	4/711

Table B.3 Optimal five ranked SBE for Ghardaia (Hot climate).

GSS Mechanisms	G	Optimal SBE performance values			Optimal SBE Geometric features					
		Solar radiation (kW h)	Space efficiency (%)	Shape coefficient	SN_A SN_E (M)	SN_A SN_E (A)	Date	CTA M/A (°)	COA M/A (°)	Paths : M/A
Generation	13	406750	96.4929	0.3739	6/6	7/3	18/1	/	/	/
	18	411730	96.5566	0.3741	6/6-	7/4-	18/1	/	/	/
	15	364690	96.4905	0.3741	6/6	5/3	18/1	/	/	/
	21	411550	96.5558	0.3742	6/6	6/4	18/1	/	/	/
	6	411650	96.6126	0.3742	7/4	7/4	18/1	/	/	/
CTA mechanism	9	551380	98.8428	0.3521	4/2	6/2	27/2	88,81/89,83	/	/
	18	548990	98.8476	0.3520	3/2	6/2	27/2	89,80/89,83	/	/
	17	545560	98.7148	0.3522	4/2	6/2	27/2	88,79/89,83	/	/
	11	544220	98.7120	0.3528	4/2	4/2	27/2	88,79/89,83	/	/
	17	552660	99.1227	0.3650	6/2	8/2	26/1	80,88/89,88	/	/
COA mechanism	16	451680	96.9027	0.3790	5/2	3/6	18/1	/	3,9/5	/
	20	452590	96.9045	0.3793	3/2	4/6	18/1	/	9/0,6	/
	8	452290	96.8976	0.3793	5/2	3/6	18/1	/	3,9/4	/
	13	444230	96.8795	0.3837	2/2	3/6	18/1	/	9/1	/
	12	445920	96.8489	0.3837	3/2	3/6	18/1	/	10/11	/
CTA / COA mechanism	19	413820	96.7742	0.2215	4/2	5/2-	10/2	82,89/61,68	12,0/1,17	/
	17	406790	96.6519	0.2220	4/2	5/2-	10/2	81,88/61,68	12,0/1,18	/
	9	409990	96.4978	0.2228	7/2	3/2	24/2	82,89/61,66	12,20,23/1	/
	4	411110	96.7311	0.2272	3/2	5/2	6/2	89,88/61,60	11/27,8	/
	19	373300	95.9146	0.2194	4/2	3/3	29/2	82,74/62,75,83	5,8/2	/
	19	397670	96.3399	0.3768	7/7	3/8	21/1	/	/	4645/3646

SPP mechanism	9	399780	96.7622	0.3723	7/8	3/8	21/1	/	/	21989/3646
	13	437740	96.7444	0.3744	2/8	6/8	21/1	/	/	21989/3646
	16	439530	96.7006	0.3722	2/7	4/7	19/1	/	/	1475/3254
	13	392770	96.7880	0.3775	7/7	3/4	20/1	/	/	2597/1

Annex C:

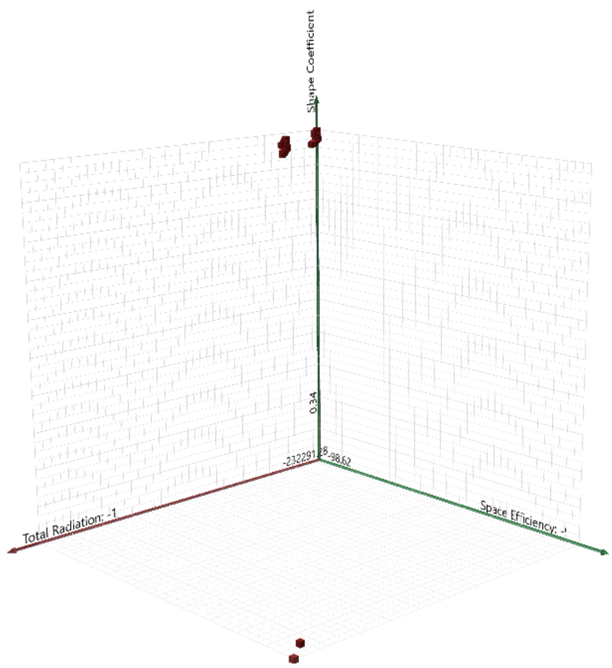

Fig. C.1. Pareto front set of segmented building envelope for Montreal using generation mechanism.

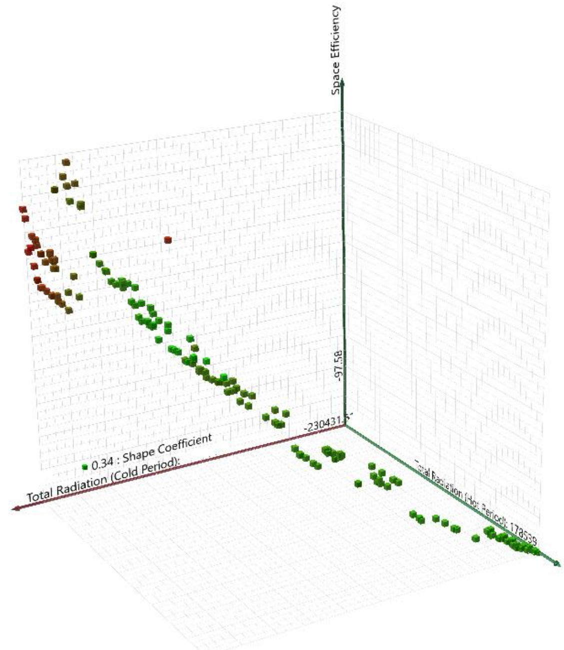

Fig. C.2. Pareto front set of segmented building envelope for Constantine using generation mechanism.

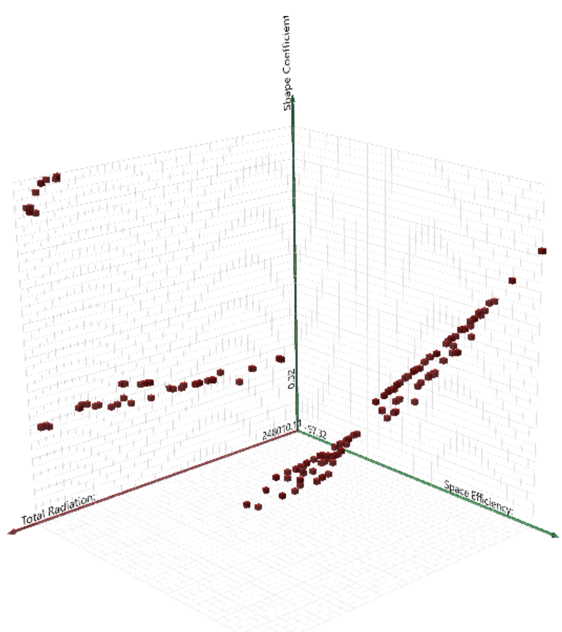

Fig. C.3. Pareto front set of segmented building envelope for Ghardaia using generation mechanism.

Annex D published article

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Geo-solar segmentation mechanism: An early design stage method for building solar morphing

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A R T I C L E I N F O

Keywords:
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Building shape performance
Design trade-off

A B S T R A C T

Building envelope shape plays a crucial role in determining the building energy performance, by regulating its solar exposure and the incident solar radiation. However, there are limited solar morphing tools that allow the generation of static building envelope. Besides solar potential, building shape performance indicators need to be considered, such as space efficiency and shape coefficient. Therefore, the present study proposes the 'geo-solar segmentation' morphing method that can help architects and engineers generate a range of optimal building shapes based on received solar radiation, shape coefficient and space efficiency in the early design stage, under different climate conditions. Accordingly, based on the top–down biomimetic approach, the solar-induced rock cracking mechanism is adopted as a source of inspiration to generate an architectural design concept. It is then, transcribed into a solar design generation and optimisation algorithms using visual programming in Grasshopper within the Rhinoceros software. Octopus, an evolutionary solver is used to perform the multi-objective genetic algorithm optimisation. A comparative study is conducted between optimal solar segmented building envelopes and a reference rectangular-based shape. The results demonstrate that under hot climate, optimally segmented building envelopes are 44.90% more effective in terms of solar protection than rectangular-based ones, and allow a trade-off between solar protection and collection under temperate climates. Moreover, the method helps reduce the shape coefficient by at least 10.30% for any climatic location, while ensuring a minimum space efficiency of 95%. The suggested method can be used as an early design-stage tool to enhance static envelope energy performance.

1. Introduction and literature review

The effects of climate change can be seen around the world, and it is accelerating and affecting people's health and life. According to the fifth assessment report of the Intergovernmental Panel on Climate Change(IPCC), atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have considerably increased since the 18th century due to the intensity of energy consumption and human activities. According to the current greenhouse gas emissions rates, the global average temper- ature could increase by 1.4 to 2.6 °C above pre-industrial levels by 2065. It is recommended by scientists and policymakers to limit global warming to below 2 °C within the present century (IPCC, 2014) to avoid significant and potentially catastrophic impacts to the planet.

In order to remedy the current situation, engineers, architects and building planners are working together to reduce buildings' energy consumption and enhance their performance. Embedding solar conscious strategies into the architectural design via solar morphing tools allows achieving energy-efficient buildings and comfortable living environments (He et al., 2021), and consequently, attenuating climate change impacts. Indeed, regulating static building envelope solar exposure is recognised as an influential factor affecting building's solar potential and energy performance. Building solar morphing (BSM) strategies allow designers to control incident solar radiation and achieve desired indoor conditions. Moreover, based on the available solar radi- ation, physical properties of the building envelope, such as G-values, are defined to help in further optimising solar heat gains (Ménard & Sou- viron, 2020). The resulting temperature difference between indoor and outdoor environment can drive convective air flow, thereby assisting in ventilation (Kolokotsa et al., 2012) (Bekkouche et al., 2013), andpossibly causing heat losses that can be limited by choosing appropriate U-values of the envelope materials (Lee et al., 2013). Thus, building solar morphing strategies are the major factor in regulating incident solar radiation, defining appropriate envelope materials, and

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Nomenclature

BSM	Building solar morphing
SMA	Shape memory alloy
SBE	Segmented building envelope
GSS	Geo-solar segmentation
SUT	Solar useful time
MOGA	Multi-objective genetic algorithm
S	Shape coefficient
E	Usable space
I	Total received solar radiation
BBF	Building Back-face
B_H	Building height
BFF	Building front face
SN_A	Azimuthal segment number
SN_E	Elevation segment number
CTA	Combined tilt angles
COA	Combined orientation angles
E/NBF	East-north building face
W/SBF	West-north building face
S_S	Solar state
D_H	Horizontal distance
D_V	Vertical distance

consequently, optimising the heat transfer between indoor and outdoor spaces.

Furthermore, integrating BSM strategies in early design stages in-creases the feasibility of installing solar energy harvesting systems, ensuring higher yields. In particular, proper orientation of the building's wings, roof tilt angle, and building height can help maximize the output of photovoltaic panels. For instance, Hachem et al. (2011a) notes that,by adjusting the angle between the wings of an L-shaped building, the peak electricity generation potential of the building integrated PV panels increased. Similarly, Xu et al. (2021) showed that a single storey urban block can achieve almost double the solar energy potential of a high-rise block, in terms of both the installation potential as well as technical feasibility. Their study showed the significant impact of theblock shape on its solar potential. Therefore, implementing BSM passive strategies enhances building integrated solar energy system efficiency, and allows adjusting the building shape in the early design stage. We will accordingly focus more on the passive solar shape morphing stra- tegies in the review of the literature.

Building solar morphing (BSM) strategies are solar design generation methods and tools applied within the building design process to opti- mize the building's solar potential. Numerous studies have applied solar morphing strategies for rectangular-based shape buildings acting on the geometry of the facades' elements and the roof. Shan (2014) tried to find a compromise between indoor thermal comfort and natural lighting in a single office room throughout the year. The design generation is basedon the window grid dimensions and the shading system depth variation. The results demonstrate that a 500 lx illuminance level is achievable in the early design stage. Konis et al. (2016) established a building shape optimisation method by adjusting the building orientation and win- dows' shape to daylight requirements. The results demonstrate that the suggested method reduces energy use intensity (EUI) by 17% and en- hances daylight performance by 65%. Fang and Cho (2019) optimised the day-lighting quality and energy performance of a small office building by manipulating skylights and windows dimensions, buildingdepth, and roof ridge location. This optimisation strategy is tested under Miami, Atlanta, and Chicago climate. The results show that the most impactful geometric variables are the skylight width and length.

Moreover, researchers have explored how the geometric form canoptimize the amount of solar radiation falling on the building facades. Okeil (2010) proved that morphing the solar profiles in a conventional residential block enhances the received solar energy amount on its fa- çades and reduces it on the roof during winter. Furthermore, the building wings configuration (L, U, H and T form) determines its solar potential and ability to generate electricity according to the shadow and light zones projected on the building envelope (Hachem et al., 2011). Xuet al. (2021) assessed the solar and technical potentials of installing PV modules on industrial blocks in a representative Chinese town. Seven types of industrial blocks are identified based on their geometric fea- tures. The results show that the geometric form of the studied industrial blocks determines their solar and technical potentials. Furthermore, the less tall geometries are more effective.

Solar radiation on the roof can largely influence the building thermal performance. Kämpf and Robinson (2010) developed a building energy performance optimisation method based on maximising annual received solar radiation, varying the orientation and the tilt angle of the roof faces. Compared with the reference shape, the annual radiation of the optimised roof shape is increased by up to 20%. Lobaccaro et al. (2016) suggested a solar exposure optimisation process for a traditional Nor- wegian house roof shape in Trondheim (Norway). The process involves testing multiple roof panels' sizes and tilt angles values. The results indicate an improvement in the roof solar potential by around 30%, compared with the initial roof shape.

In fact, BSM methods for the whole building shape generation are applied in different locations and for different building types. (Yi & Malkawi, 2009) elaborated a building envelope solar exposure optimi- sation based on a geometric control system, including "agent" and "child" points. The method allows the generation of irregular building shapes starting from a rectangular-based one. The results indicate that the implemented geometric control system helps generate more efficient building shapes by modifying the building plan and the three- dimensional shape. Taleb et al. (2020) developed an early design stage tool that enhances the building solar protection efficiency. It works by changing the tilt angle of the initial parallelepiped's meshes to manipulate the shape. The results show that the optimisation of the whole building shape ameliorates its solar exposure during the hot period by providing up to 48% less insolation. Fokaides et al. (2017) optimised the whole building shape to increase the building annual and seasonal solar heat gain. The results show that the optimal building shape varies according to the climate type; for instance in Athens, the optimal shape of the building's southern part is quasi-rectangular, whileit is isosceles trapezoid in London.

Other studies have explored curved building shape solar morphing. Adamski (2007) conducted optimisation study of the southern part of a cylindrical building. The obtained results show that the oval-based building shape is more effective than the circular-based one andsignificantly better than the square-based one. Zhu et al. (2019) pro-posed a solar exposure optimisation method for curved building shapes by introducing energy utilisation parameters and stress distribution. The optimal solar curved shape is obtained by defining the most appropriate structure. Based on total received solar radiation and two additional shape performance indicators: space efficiency and shape coefficient, Zhang et al. (2016) conducted a solar optimisation of free-form building shape. The method consists in manipulating the cylindrical building shape using four control points. The results show that under North China's cold climate, the optimisation enhances the building solar po- tential and shape coefficient by 30–53%, and 15–20% respectively. The space efficiency is decreased by about 5%.

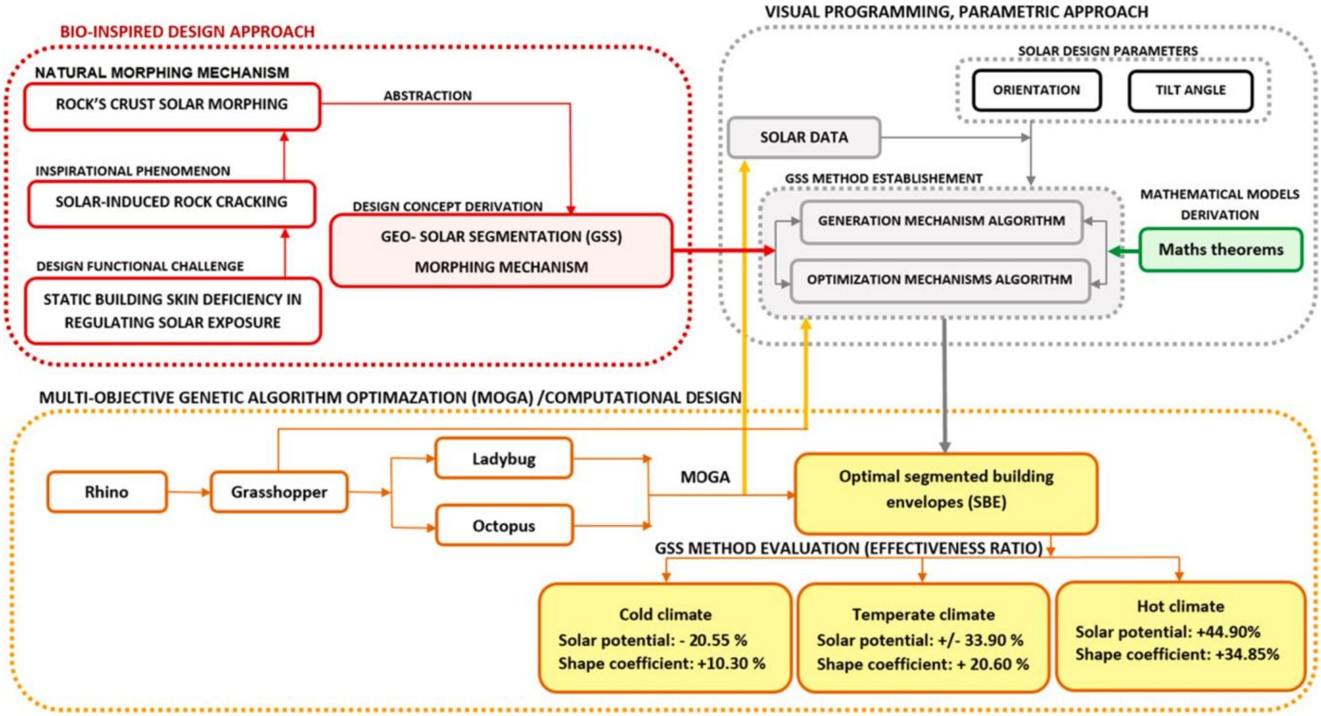

Fig. 1. Conceptual framework of the study.

1.1. Bio-inspired solar morphing strategies in architectural design

Nature imitation has been applied in the design process throughout human history, either consciously or unconsciously. The establishmentof biomimicry as a discipline that supports the bio-inspired design, was coined by the American scientist Janine Benyus, who defined it as the imitation of nature's intelligent systems (Pandremenos et al., 2012). From a technical viewpoint, biomimicry provides humans with solutions to real-world problems by emulating models and systems from the natural world (Benyus, 1998). As in many fields, the bio-inspired design approach has been introduced in architectural design (Tavsan et al., 2015). Particularly, it enhances the building solar morphing effective- ness in the early design stage. Thus, studies, which employed bio- inspired solar morphing methods for building envelopes, are discussedin the present section.

Khosromanesh and Asefi (2019) used a biomaterial to design a sec- ond building envelope inspired by ice plant seed capsules. The results show that the bio-inspired mechanism allows the façade modules to undergo deformations according to dry/wet conditions due to their hydro-actuated texture. It therefore helps manage sunlight penetration and reduce building energy consumption. Park and Dave (2014) designed a passive roof system inspired by the optics of reflecting su- perposition eyes. It works by manipulating the inclination and the orientation of the facade modules to help control the illuminance con- ditions. The results show that the designed system improves the build- ing's ability to regulate solar energy penetration and protection. Thus, indoor illuminance reaches a much higher level than the minimum required level, reducing energy consumption. Sheikh and Asghar (2019) designed bio-inspired façade modules that change the configuration via solar-based axial folding mechanism to improve solar protection in highly glazed buildings. The façade is inspired by *Oxalis oreganada* leaf that has the ability to adjust its position according to the sun movement. The established system is tested on a 20-story office building in hot and humid climate Lahore, Pakistan. The results indicate that the optimised building energy load decreased by 32%. Additionally, the lighting levelis kept within the recommended range of 500–750 lx in 50% of the interior space with minimal reduction in visual comfort.

Other researchers developed bio-inspired solar morphing mecha-nisms inspired by dynamic solar adaptation mechanisms such as:deployable structures and kinetic patterns. Pesenti et al. (2015) designeda deployable shading system for adaptive façade, which is manipulatedthrough the variation of geometric parameters using Shape MemoryAlloy (SMA) actuators. Kuru et al. (2019) created a façade shadingsystem inspired *by Echinocactus Grusonii*, a golden barrel cactus that canregulate light via the change in surface temperature induced by the ar-eoles opening-closing mechanism that ensures self-shading via spines.The shading system is inspired by modular origami geometry and worksusing SMA springs, which are sensitive to the temperature variationsthat change the glazing shaded area according to solar irradiance levels.Schleicher et al. (2011) established a façade shading system based on hinge-less flapping mechanism inspired by the bird-of-paradise plant.The system is further enhanced by adapting its geometry to curved façade panels based on Aldrovanda vesiculosa's trapping mechanism. Hosseini et al. (2021) developed an interactive-kinetic facade that al-lows regulating daylight and improving visual comfort according to sun- timing position and different user positions in the office, using dynamic transitory-sensitive material. The opening-closing movement of plant's stomata inspired the dynamic mechanism. The results show that the developed system is very effective on the south facade and achieve an average spatial daylight autonomy of 60.5%, useful daylight illumi- nance of 90.47%, and exceeds useful daylight illuminance of 2.94%.

Besides its interaction with living organisms, solar radiation is a major factor shaping the earth's surface and the various relief features, through weathering phenomenon. This led us to geo-inspired science (Butcher & Corfe, 2021), in other words 'geo-derived developments' (Speck et al., 2017), which is a biomimicry's sub-field that supports designer inspiration from the natural dead world (geology), based on its non-bio-concepts. According to Butcher and Corfe (2021), geo-inspired science was proposed by William Whewell, and developed by the En-glish geologist James Hutton, then popularised by Charles Lyell who considered that future innovative solutions reside in the geological past. This sub-field relies on biomimicry approaches.

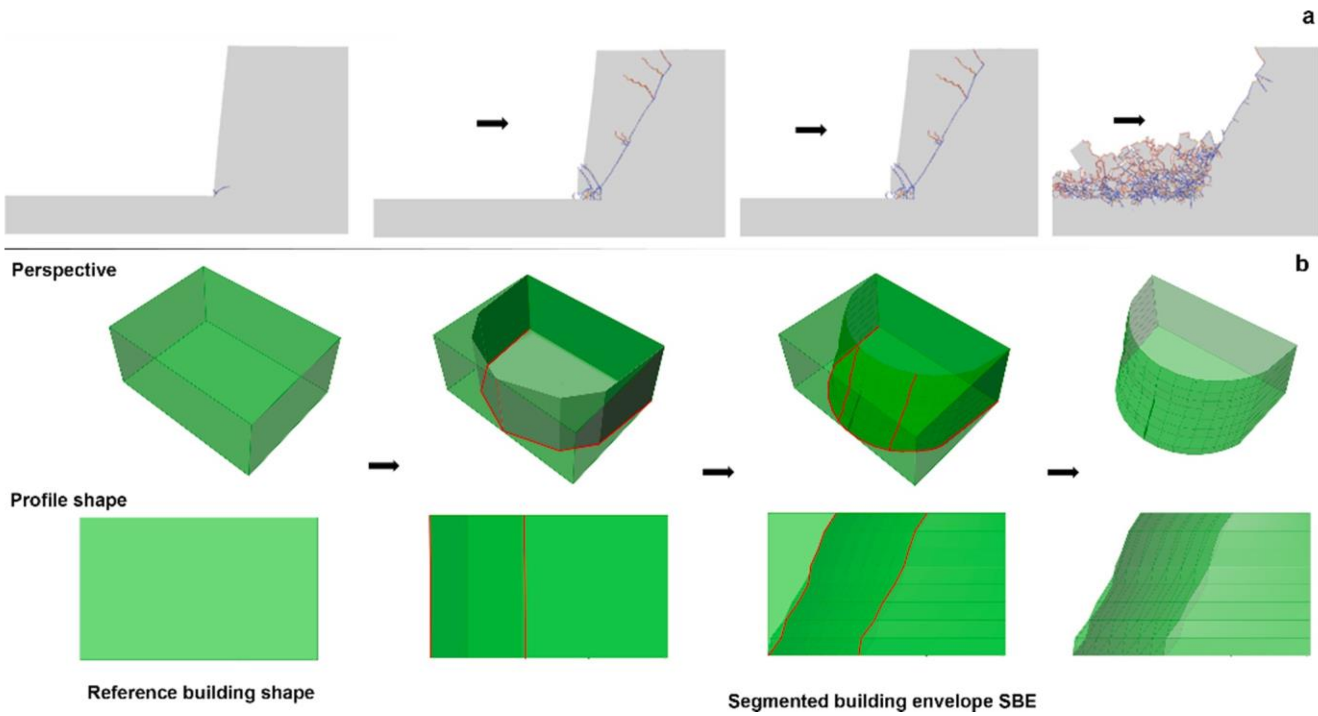

Fig. 2. (a) Rock thermal cracking process (Sun et al., 2022), (b) geo-inspired design concept.

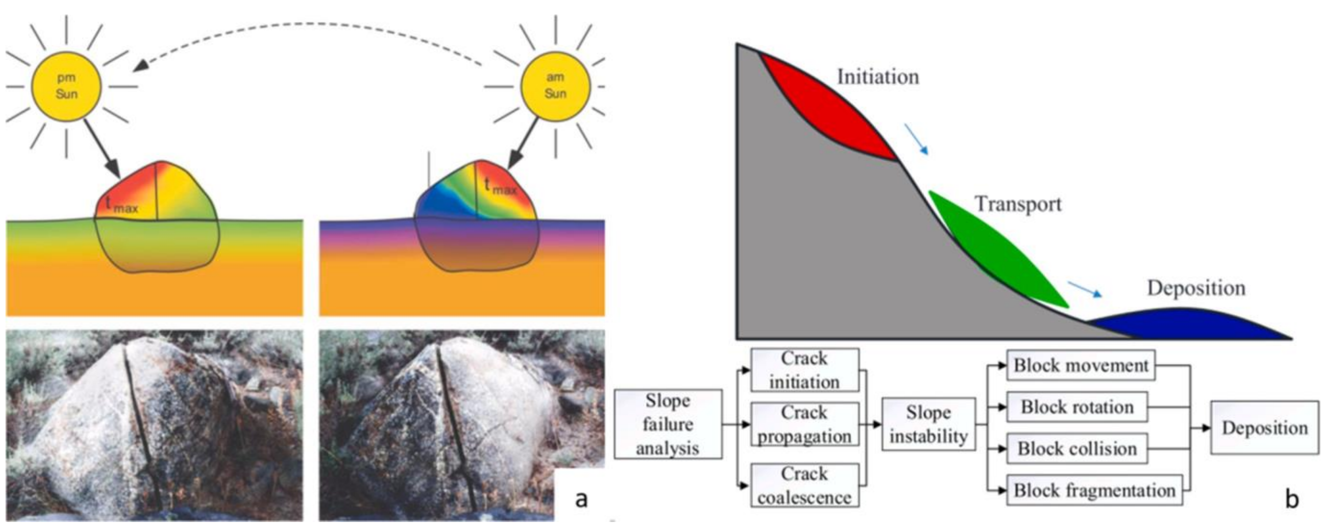

Fig. 3. (a) Temperature fluctuation (McFadden *et al.*, 2005), (b) Rock cracking process (Sun et al., 2022),

1.2. The aim and the objectives of the study

Based on the review of existing literature on bio-inspired BSM stra- tegies, it can be observed that most of the BSM studies focused on bio- inspired façade dynamic systems, while the bio-inspired static build- ing envelopes are rarely addressed. Accordingly, the present study aims to develop a BSM method that enhances static building envelope solar exposure. This method is versatile, allowing shape exploration in several climatic regions. It can be applied in the early design stage to avoid modifications in the building shape post-construction. Thus, it saves time, energy and resources for future upgrades. Additionally, the geo- inspiration source in this study is a phenomenon observed in nature,which has not been explored previously in building morphing studies. Moreover, the method allows the designer to generate optimal building shape by considering multiple factors of solar geometry and shape performance indicators.

2. Methodology

In the literature, the application of BSM strategies is mostly limitedto envelope optimisation. However, in the current paper, the suggested method is applied to generate a building envelope as well as optimise its performance, i.e., regulating the total solar radiation received by the building envelope. The methodology section describes the sequence of solar morphing steps and the tools used to generate optimal segmented building envelope SBE, as shown in Fig. 1. Initially, applying the top–-down design approach, a naturally occurring phenomenon is identified, and a bio-inspired design concept is derived from it, to respond to solar constraints (section 2.1) (Fig. 2).

In the next phase, the geo-inspired design concept is transcribed intoa design algorithm, i.e., a visual computer program on Grasshopper, based on mathematical models to generate solar building shapes. Then,a multi-objective genetic algorithm optimisation is conducted to find a

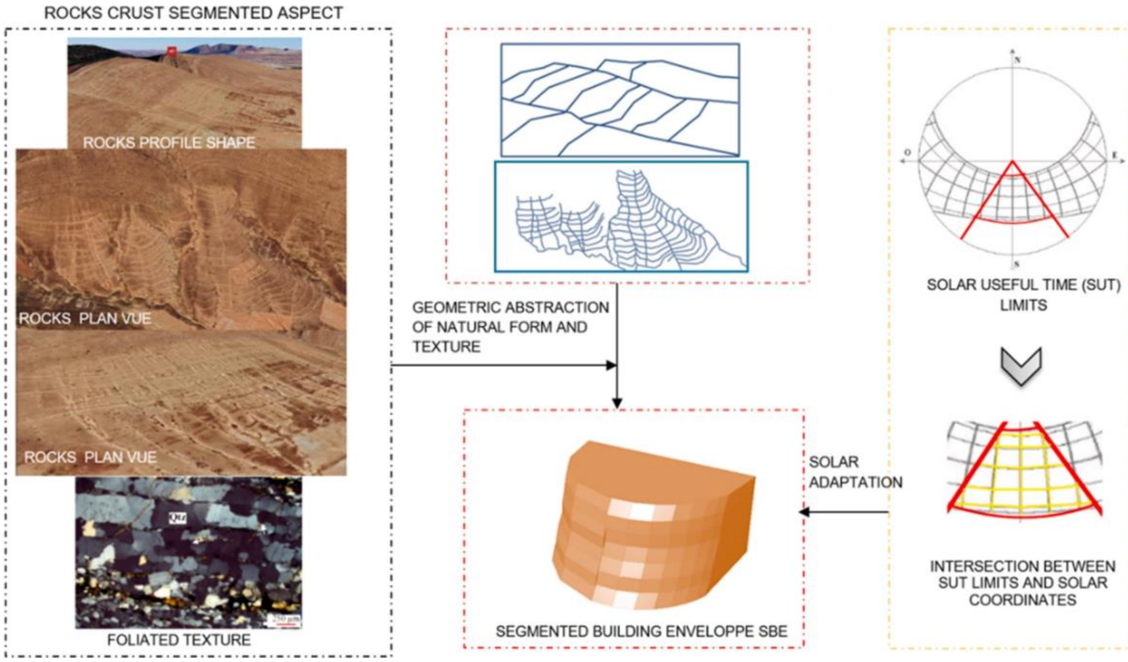

Fig. 4. Rock structure and texture geometric abstraction and solar adaptation of the design concept (https://www.google.com/intl/fr/earth/; Ganguly et al., 2020).

trade-off between the building solar potential, its compactness, and space efficiency, using the plug-in Octopus (https://www.food4rhino.com/en/app/octopus), which is a multi-objective evolutionary solver, developed based on a genetic algorithm. The next section compares the performance of the various generated design alternatives. Eventually, the conclusion summarises the learning from this study and the appli- cability of the method in other context.

2.1. *Establishment of the geo-solar segmentation generation mechanism*

A naturally occurring solar morphing phenomenon is first identified following a top–down bio-design approach to respond to the design challenge. The daily and seasonal variation of solar radiation results in temperature fluctuations and induces thermo-mechanical stress on rock mass (Marmoni et al., 2020). The rock's mass is cracked under solarenergy effect generating a new surface with new profiles shape as shown in Fig. 3 (Sun et al., 2022). Although the solar induced cracking of rock surface is a dynamic process, we considered the resulting rock's shape as static assuming it is kept so, for a long time. This makes the solar- induced rock morphing mechanism a potential inspiration source for static building envelope design. Both the rock surface and building en- velope are exposed to solar energy and enclose internal volume, which is in continuous heat exchange with the external environment. Accord- ingly, the design concept in the present study is derived from the solar- induced rock-cracking phenomenon, and involves morphing the refer- ence building volume based on solar data to generate new profiles shape.

The solar-induced rock-cracking phenomenon can geometrically be perceived as the generation of a new rock's surface according to solar-segmented profiles. This surface exhibits lineated structure and texture with parallel layers organisation and lattice shape (Winter et al., 2020). According to the previous structural characteristics, the 'geo-solar seg-

mentation' morphing concept is set (Fig. 4). It generates a segmented

building envelope based on the solar useful time (SUT) representing the time during which direct normal solar radiation affect dry bulb tem-

peratures. Moreover, it represents the interval of the best orientations. geo-solar segmentation (GSS) method is applied in the design of the building face included between the azimuth coordinates of the SUT limits, called the building front face (BFF). The next section explains the implementation of the GSS generation mechanism at plan and elevation levels and the corresponding mathematical models.

2.1.1. *Azimuthal segmentation at the plan level*

The reference building has a rectangular footprint, with a length of L and width of W. A line is then drawn parallel to the initial rectanglelength and at a depth of 1/3 W from the backside. To generate the segmented envelope, an arc of radius R 2/3 W is drawn from the mid- point of this line. This ensures that the new building area is maintained within the initial footprint. The corresponding sun-path diagram is then centred along the arc centre (Fig. 5. a). The same point is afterwards, joined with the SUT limits azimuthal coordinates (Fig. 5. a). Eventually, the intersection points of the arc with the SUT azimuthal limits are joined to the building back-face (BBF) to draw the north east N/EBF and the north west N/WBF building faces (Fig. 5).

Given that, until noon, the sun traces an upward path in the sky followed by a downward path until sunset, the BFF is divided into morning and afternoon parts based on the respective solar data (Fig. 5.b). SBE shapes were generated based on direct normal radiations, since they greatly affect the building solar potential (Caruso & Kämpf, 2015). In order to generate the BFF surfaces, each of the morning and the af- ternoon SUT intervals is divided into sub-intervals of minimal durationof half an hour (Fig. 5. c). Then, between the intersection points of each sub-interval limits and the arc, the surface length, which is the normal segment to the bisector of the sub-interval angle θn is drawn, applyingthe tangent trigonometric law (Byrne, 1847) Eq. (2). The bisector rep- resents the direct normal radiation at sub-interval mid-time (Fig. 5. d).So that, azimuthal sub-interval angle (θ_n) equals:

$$\theta n = \theta n_{end} - \theta n_{beginning} \quad (1)$$

According to the above-mentioned trigonometric law (Fig. 5. d), we deduce that:

$$\sin\frac{\theta_n}{2} = \frac{\frac{SRF_L}{2}}{R} \quad (2)$$

$$\frac{SRF_L}{2} = \sin\frac{\theta_n}{2} * R \quad (3)$$

Where:

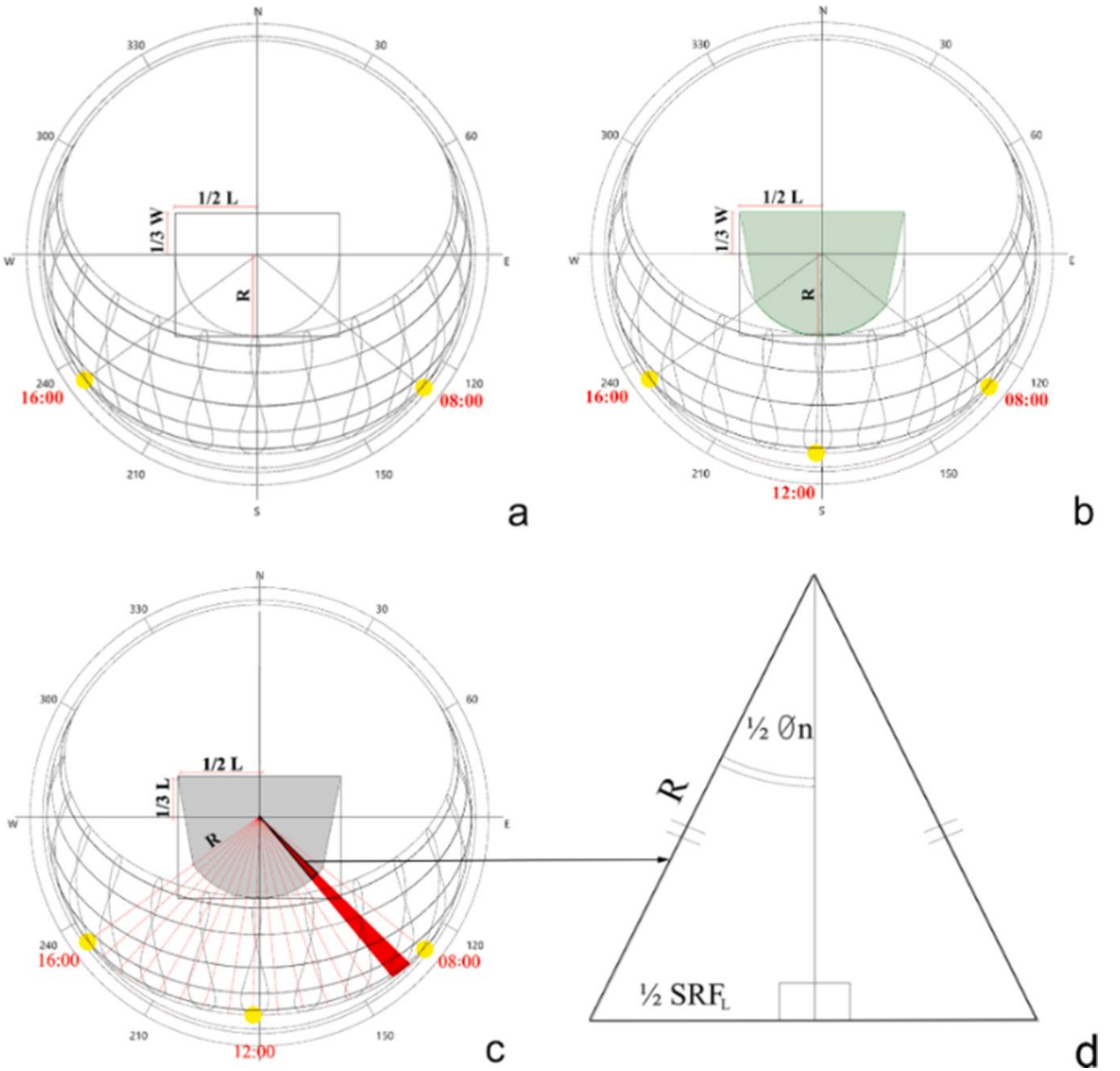

Fig. 5. Azimuthal segmentation steps sequence; (a) the intersection of the SUT limits and the arc, (b) joining the building front and back faces, (c) drawing the sub-intervals, (d) geometric rule of azimuthal segmentation.

n: a specific sub-interval.

SRF_L: the length of each of the BFF surfaces and the corresponding azimuthal segment.

$\theta_{n\ end}$: azimuth coordinate of the end of the sub-interval (n).

$\theta_{n\ beginning}$: azimuth coordinate of the beginning of the sub-interval (n).

2.1.2. Elevation segmentation at the profile level

Both of the BFF profiles are generated based on the plan segmented line (Fig. 5). The building height is first divided equally according to the vertical segments number to create a lattice with the horizontal lines, drawn based on horizontal D_H and vertical D_V distances (Fig. 6). EachBFF surface is normal to direct radiation at the corresponding sub- interval mid-time (Fig. 6). According to the triangle angles sum theo-rem Eq. (4) we have in the ABC triangle (Fig. 6):

$$A + B + C = 180^\circ \text{ So, } C = 180^\circ - (A + B) \tag{4}$$

$$= 180^\circ - (A + 90^\circ) \tag{5}$$

$$= 180 - 90 - A \tag{6}$$

$$C = T = 90^\circ - A \tag{7}$$

According to the theorem of two parallel lines (w) and (y) cut by a transversal line (K), A and H angles are equal since they are congruent (Eq. (8)) (Byrne, 1847). We have then:

$$A = H_{mid} \tag{8}$$

From Eq. (7) and Eq. (8), we deduce that:

$$T = 90^\circ - H_{mid} \tag{9}$$

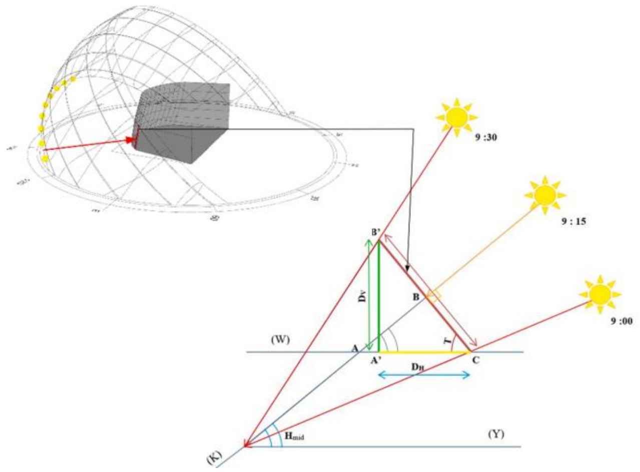

Fig. 6. Geometric rules of elevation segmentation.

Table 1
Geo-solar segmentation method parameters.

Parameters groups	Parameter notation	Description
Static parameters	Building Back-face BBF	The initial footprint northern edge
	Building height B_H	The building's total stories height, with 3 m story height
Dynamic parameters	Building front face BFF	The building envelope part included between SUT limits.
	Azimuthal segment number SN_A	There are two: morning $\mathbf{SN_A}$ and afternoon $\mathbf{SN_A}$, with: $2 < \mathbf{SN_A} < 8$.
	Elevation segment number SN_E	There are two: morning $\mathbf{SN_E}$ and afternoon $\mathbf{SN_E}$, with: $2 < \mathbf{SN_E} < 8$.
	Combined tilt angles CTA	The BFF surfaces tilt angles, resulting from a given solar state. CTA (α_1°, α_2°...) their number depends on $\mathbf{SN_E}$.
	Combined orientation angles COA	The BFF surfaces orientation angles, resulting from a given solar state. COA (β_1°, β_2°...) their number depends on $\mathbf{SN_A}$.
	Segmented building envelope SBE	Specific segmented building envelope generated using solar GSS for a given solar state. It is characterised by specific CTA (α_1°, α_2°...) and CTO ($\beta1^{\circ}$, β_2°...). Their configuration and dimensions depend on the BFF configuration.
	East-north building face E/NBF	
	west-north building face W/SBF	
Independent variables	Solar state S_S	A specific day solar data in a given location. It comprises all of studied location, latitude, and the solar data
	Horizontal distance D_H	The projected distance between each two successive azimuthal segments Fig. 6
	Vertical distance D_V	The vertical distance between each two successive elevation segments Fig. 6

According to triangle trigonometry formulas applied to the A′B′C triangle, we have:

$$\sin T = \sin C \frac{D_V}{SRF_W} \tag{10}$$

$$SRF_W = D_V / \sin T \tag{11}$$

In addition:

$$\cos C = \cos T = \frac{D_H}{SRF_W} \tag{12}$$

$$\text{So}: D_H = SRF_W \, \omega \cos T \tag{13}$$

From (Eq. (11)) and (Eq. (13)) we deduce that:

$$D_H = \left(\frac{D_V}{\sin T}\right) \omega \cos T \tag{14}$$

$$D_H = D_V \left(\frac{\cos T}{\sin T}\right) \tag{15}$$

The GSS mathematical models are derived from trigonometric laws. They describe the geometric relationship between the surfaces of the BFF and direct normal solar radiation.

2.2. Determining geo-solar segmentation parameters

Based on the categorization of solar optimization parametes suggested by Zhang et al. (2016), the GSS method parameters and variables are classified into three groups as shown in Table 1. Static parametersare kept the same, while dynamic ones vary during the optimisation process to obtain diverse parameters combinations. Indeed, each BFF part has its own Azimuthal SN_A and elevation SN_E segment numbers that range between 2 and 8. Besides segment numbers, dynamic parameters include new established geometric characteristics of SBE, such as, solar state S_s, obtained from the weather data (epw) file, 2004–2018

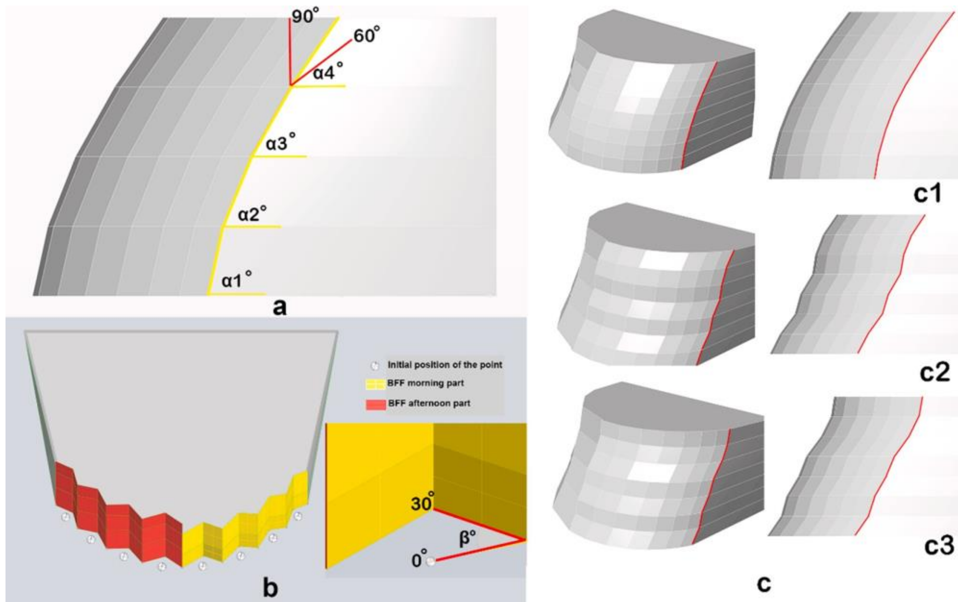

Fig. 7. Geometric manipulation principles of GSS optimisation mechanisms; (a) CTA, (b) COA, (c) SPP.

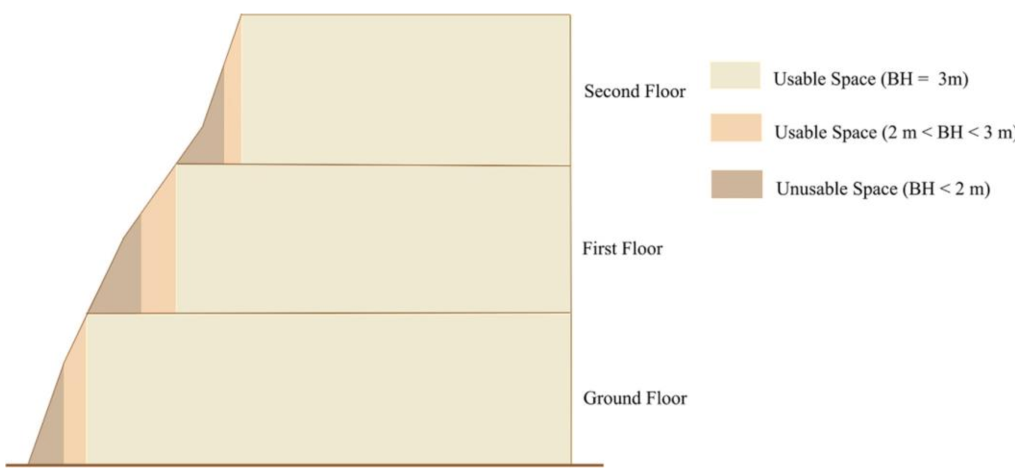

Fig. 8. Segmented building envelope's usable space.

Table 2

Reference building performance values for the studied locations.

Location		Reference building shape performances		
		Solar radiation (kW h)	Space efficiency (%)	Shape coefficient
Montreal		323,090	100	0.34
Constantine	Cold period	367,620		
	Hot period	281,230		
Ghardaia		712,040		

(https://climate.onebuilding.org/), combined orientation angles COA, combined tilt angles CTA (Table 1). These parameters facilitate the discussion of the simulation results. The third group consists of independent variables of the GSS generation data such as: vertical D_V and horizontal D_H distances (Fig. 6). Therefore, the novelty in the present study resides in elaborating a geo-inspired solar morphing method and new corresponding parameters.

2.3. Geo-solar segmentation optimisation mechanisms

Taking into consideration only the direct normal radiation effect on SBE potential is not sufficient to enhance the building solar potential. Consequently, the iterative cracking process that modify the rock'ssurface over time inspired us to set optimisation mechanisms. The resultant rock's crust is a multi-faceted surface characterised by het- erogenic tilt angles (Román-Sánchez et al., 2019) and orientations. Additionally, many solar morphing optimisation methods (Hosseini et al., 2019), (Yadav & Chandel, 2013) rely on the variation of building faces' tilt angle and orientation. Accordingly, four optimisation mechanisms are established, then implemented in the GSS method.

The first and the second mechanisms are based on the variation of combined tilt angles (CTA) and combined orientation angles (COA)

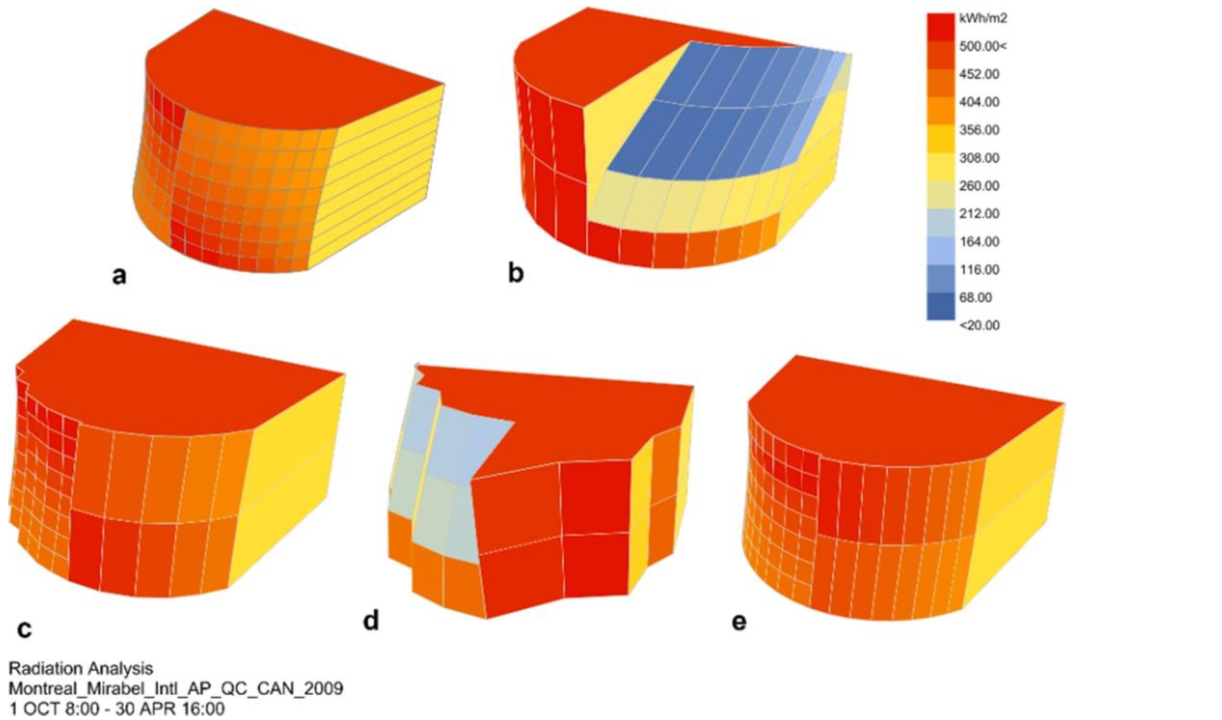

Fig. 9. Radiation analysis results of optimal SBE under cold climate conditions generated applying: (a) generation mechanism, (b) CTA mechanism, (c) COA mechanism, (d) CTA/ COA mechanism, (e) SPP mechanism.

Table 3
Optimal first ranked SBE for Montreal (cold climate).

GSS mechanisms	G	Performance values			Optimal SBE Geometric features					
		Solar radiation (kW h)	Space efficiency(%)	Shape coefficient	SN_A SN_E (A) (M)	SN_A SN_E	Date	CTA M/A (°)	COA M/A (°)	P M/A
Generation	18	219,100	98.4958	0.3701	8–8	8–6	30/12	/	/	/
CTA	20	254,780	97.7612	0.3251	7–4	6–2	16/3	88,78,60,62/87,89	/	/
COA	21	221,280	98.6139	0.3738	5–2	8–8	22/12	/	1,0/ 1,4,25,29	/
CTA + COA	20	193,190	96.1651	0.3050	4–2	7–3	07/08	89,88/83,72,70	23,24,12,23/ 2,27,23,7	
SPP	26	219,910	98.6561	0.3645	8/2	8/7	25/12	/	/	1/4798

Table 4
Optimal first ranked SBE for Constantine (temperate climate).

GSS Mechanisms	G	Optimal SBE performance values				Optimal SBE Geometric features					
		Solar radiation (kW h)	Solar radiation (kW h)	Space efficiency (%)	Shape coefficient	SN_A SN_E (M)	SN_A SN_E (A)	Date	CTA M/A (°)	COA M/A (°)	P M/A
Generation	15	229,910	178,260	97.5619	0.3762	6/2	7/6	28/12	/	/	/
CTA	21	243,030	186,000	96.2331	0.2781	5/2	6/3	2/8	86,85/78,79,71	/	/
COA	13	225,960	174,440	97.5615	0.3817	2/2	3/6	20/12	/	7/4	/
CTA + COA	17	251,600	188,540	98.6150	0.3703	7/2	4/2	30/10	87,83/81,83	29,21,9/ 6,17	
SPP	4	230,090	178,160	97.5502	0.3713	6/6	4/6	26/12	/	/	4/711

respectively, while keeping the building orientation fixed (Fig. 7). The minimal COA angle is fixed at 30° to avoid having a plan shape with acute angles (Fig. 7. b). The third mechanism CTA/COA is based on a simultaneous variation of CTA and COA. Eventually, the irregular rock's profiles shape inspired a fourth optimisation mechanism, called 'the segments position permutation' SPP. It is implemented in the GSS using the factorial of the elevation segment number SN_E!. The SPP mechanism allows to evaluate the effectiveness of numerous SBE profiles

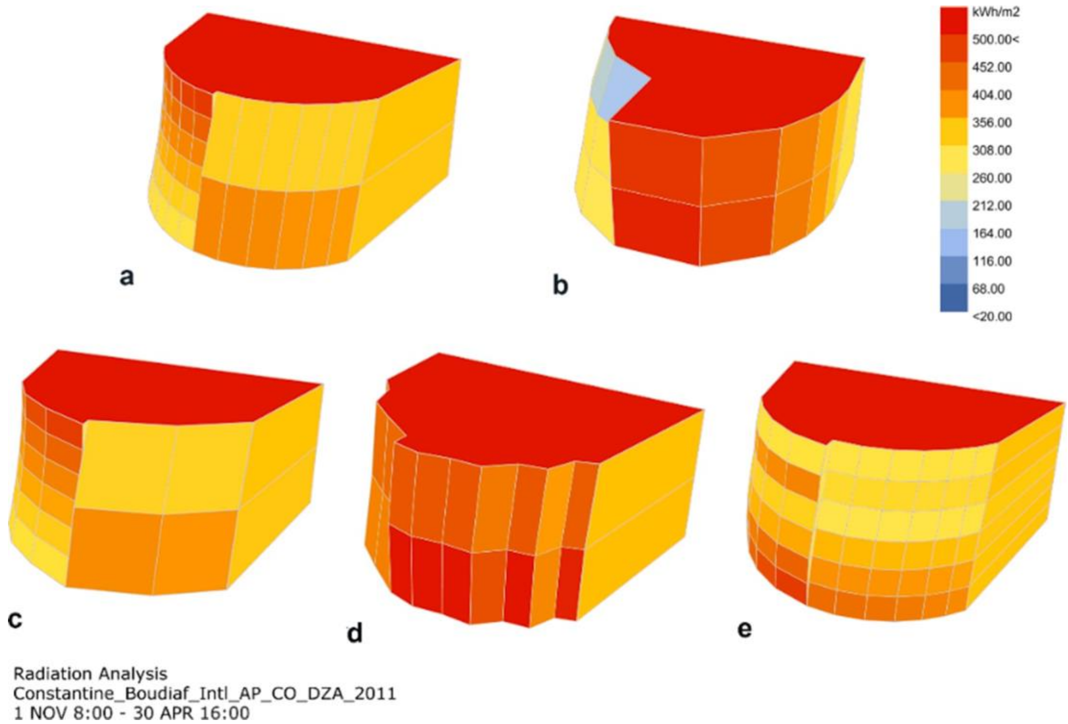

Fig. 10. Radiation analysis results of optimal SBE under temperate climate conditions generated applying; (a) generation mechanism, (b) CTA mechanism, (c) COA mechanism, (d) CTA/ COA mechanism, (e) SPP mechanism.

Table 5
Optimal first ranked SBE for Ghardaia (hot climate).

GSS Mechanisms	G	Optimal SBE performance values			Optimal SBE Geometric features					
		Solar radiation (kW h)	Space efficiency (%)	Shape coefficient	SN_A SN_E (M)	SN_A SN_E (A)	Date	CTA M/A (°)	COA M/A (°)	Paths: M/A
Generation	13	406,750	96.4929	0.3739	6/6	7/3	18/1	/	/	/
CTA	9	551,380	98.8428	0.3521	4/2	6/2	27/2	88,81/89,83	/	/
COA	16	451,680	96.9027	0.3790	5/2	3/6	18/1	/	3/5	/
CTA + COA	19	413,820	96.7742	0.2215	4/2	5/2	10/2	82,89/61,68	12/1	/
SPP	19	397,670	96.3399	0.3768	7/7	3/8	21/1	/	/	4645/3646

configurations ($SN_E!$), as shown in Fig. 7. C.

$$SN_E! = SN_E*(SN_E - 1)*(SN_E - 2)*(SN_E - 3)*\cdots*1 \quad (16)$$

2.4. Studied locations

GSS mechanisms are tested under different climate conditions, according to which the solar morphing objective is set. Indeed, solar collection and protection optimisation are sought in cold and hot climate regions respectively. Under temperate climate, a trade-off between solar exposure and protection should be set. Considering the above-mentioned design objectives and temperature factor, three climate zones are defined based on Koppen world climate classification: cold, temperate and hot (Carver et al., 2002)(Table A1). Two Algerian towns: Constantine (36 N°) and Ghardaia (32 N°) that represent temperate and hot locations respectively are selected, and Montreal (45 N°) taken as cold location. This selection is restrained by the availability of climate data and short-day duration in cold regions. The latter is taken into account when defining the SUT for critical months, since the values of solar coordinates, which are the main GSS algorithm inputs, are null during night-time. Hence, the effectiveness of GSS method is assessed for critical months during which direct normal solar radiations are available and the temperatures are out of comfort range.

Optimal SBE shapes are generated based on the same dimensions of the reference building shape, which has a rectangular plan with a size of 15 m × 20 m. It is a three-story building with 3 m story height.

3. Multi-objective genetic algorithm optimisation (MOGA)

In recent years, multi-objective genetic algorithm optimisation (MOGA) has been used with BSM methods, to define optimal design solutions. It involves defining a set of optimal solutions, based on design parameters and performance indicators. Furthermore, genetic algorithm

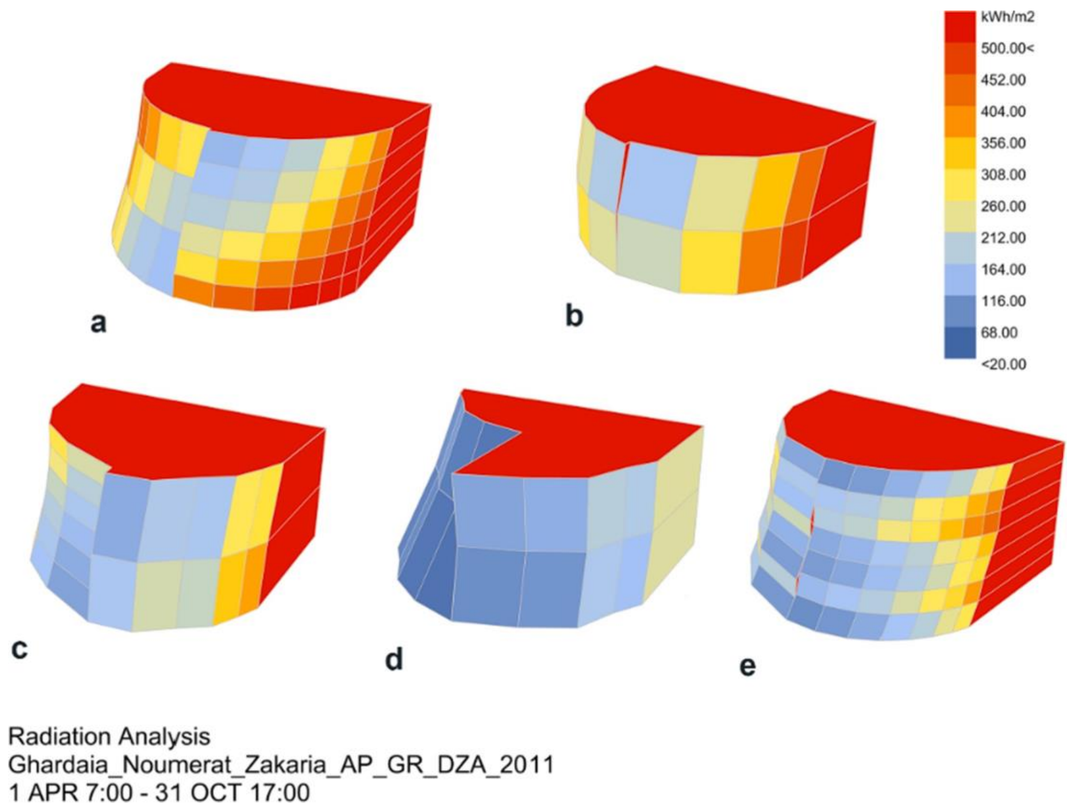

Fig. 11. Radiation analysis results of optimal SBE under hot climate conditions generated applying; (a) generation mechanism, (b) CTA mechanism, (c) COA mechanism, (d) CTA/ COA mechanism, (e) SPP mechanism.

iteration principles allow exploring large solutions′ domain and lead to effective design. The combination of MOGA and parametric design approach (Yi & Malkawi, 2009), (Jin & Jeong, 2014), (Fokaides et al., 2017) has shown its usefulness in building solar morphing. For these reasons, MOGA is performed to generate optimal SBE shapes.

3.1. Solar potential indicators evaluation

Solar potential evaluation indicators are categorised by Nault et al. (2015) into three groups: geometry-based metrics, external solar and

geometry-based metrics, full climate and geometry-based metrics. Additionally, building solar morphing is based on the manipulation of two parameters types: continuous and discrete parameters. Continuous

parameters include all building shape geometric parameters. Whilst, discrete ones consist of values that define the building envelope characteristics such as: material thickness (Lobaccaro et al., 2016). GSS method relies on the variation of continuous parameters design and the geometry-based metrics. Therefore, the present study aims to keep an acceptable space efficiency and enhance the building compactness. Therefore, the following indicators are calculated during the optimisa- tion process to evaluate the SBE shapes.

3.1.1. Usable shape evaluation

Building space efficiency is generally discussed in slopped and free form buildings envelope that both reduce the building usable space. SBE shapes are generated using plate sloped surfaces that give irregular aspect to the building profiles shape. Beyond its functional aspect, the space efficiency ratio is considered as an energy performance indicator, even if it is rarely used (Zhang et al., 2016). Since the building volume is heated and conditioned during winter and summer periods respectively,a building shape with low space efficiency ratio results in excessive energy consumption (Zhang et al., 2016). High space efficiency ratio indicates more usable space inside the building, and better energy per-formance. Usable space can be evaluated by calculating the usable floorarea (Chan and Sherman, 2004). In the present study, it is calculated byapplying the same rule Eq. (17) used by (Zhang et al., 2016). Accord- ingly, the space efficiency ratio of a building is the ratio between the usable space volume V_u and the whole building volume V_0. Where n is the building's total stories, and i is the number of stories.

$$E = \frac{\sum_{i=1}^{n} (Vu)_i}{V} \quad (17)$$

Usable shape in the present study is related to CTA values (Fig. 8), which affects the variation of the building usable space. Low CTA values make the internal space near the BFF non-accessible due to the low height ($H < 2$ m). Thus, BFF combined tilt angles CTA values range between 90° and 60° (Fig. 7. a).

3.1.2. Building shape compactness

Building shape compactness has been used by many researchers as an energy performance indicator (Caruso & Kämpf, 2015). BSM strategies aim to increase the building compactness by minimising its external envelope area while increasing the internal building volume (Zhang et al., 2016). In fact, reducing shape coefficient decreases heat transfer between indoor and outdoor environment (Filippín et al., 2005), which affects the indoor climate and energy consumption (Bekkouche et al., 2013). Moreover, building shape compactness offers an economic advantage by reducing the building envelope area and consequently materials needs. It is described using shape coefficient S, representing the ratio between the building envelope area F_0 and its volume V_0.

$$S = \frac{F_0}{V} \tag{18}$$

3.2. Visual programming and parametric modelling approach

In the present study, the implementation of the parametric approach required the use of computational design tools. Therefore, Grasshopper, rhino visual programming environment is used to establish the GSS generation mechanism, which is a parametric design algorithm devel- oped by making connections between components according to the previously presented mathematical models. Optimisation mechanisms are afterwards implemented by embedding the corresponding dynamic parameters and the necessary Grasshopper components that govern them.

3.2.1. Genetic algorithm settings

As shown in the study framework (Fig. 1), Octopus is a multi- objectives evolutionary solver, developed based on the genetic algo- rithm SPEA-2 and HypE (https://www.food4rhino.com/en/app/octo- pus). It is a Rhino plugin for Grasshopper, used to perform simulation, and MOGA optimisation. The Pareto 80/20 optimisation is extensively used in MOGA optimisation. It allows generating two solutions types:the dominated solutions that are more effective in one or more of the study objectives, and the non-dominated ones that represent the Pareto frontier set. The latter gathers the best trade-offs between the study objectives. The MOGA optimisation is an open-ended process; thedesigner can stop it once the needed goals are met. For each mechanism, about 20 to 26 generations were explored, starting by initial population of 200. Respecting a crossover rate of 0.8 and mutation probability ratio of 0.2, the breeding process is performed by keeping the best solutions of each generation and crossing them with the individuals of the next generation to explore possible trades-off (Chore & Magar, 2017). After generating the Pareto frontier set, the non-dominated solutions (i) were ranked from 0 to 100 using Eq. (19) in order to select the optimal ones, based on maximal (max) and minimal (min) performance indicators values. The high objective function Y value characterises the best solution.

$$y = (I_i - I_{min})C_1 + (E_i - E_{min})C_2 + (-1)(S_i - S_{min})C_3 \tag{19}$$

$$C_1 = \frac{100}{I_{max} - I_{min}}$$

$$C_2 = \frac{100}{E_{max} - E_{min}}$$

$$C_3 = \frac{100}{S_{max} - S_{min}} \tag{22}$$

4. Results and discussion

The assessment of the GSS mechanisms is carried out by comparingthe total received solar radiation by optimal SBE against the reference building shape. To account for the change in the geometry and energy performance of optimal SBE, the shape coefficient and space efficiencyare calculated. Based on objective function value (Y) Eq. (19), fiveoptimal solutions are presented for each location to show different design performances trades-off (Appendix. B). Additionally, optimal SBEshapes are selected with respect to the reference building volume limits.To analyse the obtained optimal SBE shapes, their geometric features are outlined. Each of optimal SBE belongs to a given generation (G). It is characterised by the solar state (S_S) date according to which it is generated, and optimal segments numbers: SN_A and SN_E of both BFF morning (M) and afternoon (A) parts. The optimal SBE obtained from optimisation mechanisms are characterised by specific features such as CTA values, COA values and SPP combinations. The first generated SBE performances are compared with the optimal SBE issued from optimi- sation mechanisms, then with the reference performance values (Table 2).

4.1. Under cold climate conditions

For the cold climate of Montreal, optimal SBE shapes (Fig. 9) are assessed for the heating period, extending from October to April; for this period, the SUT was kept constant from 8 am to 16 pm. Table 3 showsthe optimal SBE performances obtained when applying GSS mecha- nisms. It can be seen that, the first generated SBE receives a total solar radiation of 219100 kW h, which is amplified by nearly 254780 kW h, when varying CTA. This represents an improvement of 16.30%. Any further optimisation using the other mechanisms leads to a slight improvement in total received radiation comparing with the first generated SBE performance (Fig. C1). Nevertheless, the SBE solar po- tential remains less than the reference value, estimated at 323090 kW h. Moreover, it is observed that the implementation of COA and SPP mechanisms provides the best results in terms of space efficiency 98%, which is maintained up to 96%, over optimisation process. The shape coefficient is decreased to 0.30 using the CTA mechanism, which rep- resents an enhancement of 10.30% (Table B1).

The optimal solar state's month changes according to the imple- mented mechanism; it is December in both generation and COA mech- anisms and August for CTA/COA mechanism. It varies between the three first months of the year: January, February and March in the CTA mechanism. Therefore, the solar state's month varies as a function of the manipulated geometric parameters. Optimal SBE obtained from the generation and COA mechanisms are characterised by high segmenta- tion levels (SN 08) contrary to those reached in applying the CTA/ COA mechanism, which are of lower segmentation level (03 < SN < 07) (Fig. 9). It is noticed that the CTA values of the lower segments of theBFF Morning part are mostly close to the normal, about 88°. Whilst, the highest ones are close by 60°. Therefore, the segments generated ac- cording to early morning solar data are nearly vertical to face the low sunrays. Table B1 shows that the combination of the first profile shape of the BFF morning part with 112, 113, and 114 profile shapes of the BFF afternoon part offered optimal SBE under Montreal climate.

Therefore, the results indicate that, under cold climate the GSS method's effectiveness is limited in terms of solar potential, with less effectiveness of 20.55% than the reference building (Table B1). How- ever, it can be used to enhance the building shape coefficient. The CTA optimisation mechanism is the most effective, which means that the tilt angle is a crucial design parameter in the GSS method.

4.2. Under temperate climate conditions

In a temperate climate location, the optimisation involves balancing the total received solar radiation during both hot and cold periods. Indeed, setting a trade-off consists in decreasing a performance value to upgrade the other. For Constantine city, the simulation is run duringboth heating and cooling periods i.e. from November to April and from June to August, corresponding to winter and summer critical monthsrespectively. Additionally, the SUT was limited from 8 am to 4 pm. The results show that, the solar protection is enhanced, while the collection decrease comparing with the reference performance values (Table 4). Therefore, all the obtained results using different mechanisms represent trades-off between solar collection and protection under Constantine climate (Figs. 10, C2). CTA mechanism gives the best trade-off between optimisation objectives. It permits the enhancement of solar protection and shape coefficient of 33.90%, and 20.60% respectively, while the collection is decreased by 33.90% (Table B2).

The space efficiency reached 98% by the implementation of CTA/COA mechanism, and is kept above 96% using the other mechanisms. Optimal SBE under temperate climate are mostly characterised by high segmentation level (Fig. 10). In each mechanism, specific SN values characterise optimal SBE such as 6/3 in CTA mechanism. CTA values are very close to the normal. While, COA values are low, and reach higher values such as 29° when implementing CTA/COA mechanism. Specific profile shapes combinations, such as 4/711 and 4/95 are behind thegeneration of optimal SBE.

4.3. Under hot climate conditions

Using the same approach described above, the optimal SBE for Ghardaia were generated and optimised for the cooling period, from April to October. The SUT was set from 7 am to 7 pm. The results indicate that all generated optimal SBE have better performance thanthe reference building shape in terms of solar protection (Table 5, Fig. 11). Precisely, the generation mechanism that improves the build-ing solar potential by 48.80% (Fig. C3, Table B3). The total received radiation is reduced to 397,670 kWh for the (4645/3646) profiles shapes combination. It allows a solar protection enhancement of 44.15%. Table B3 shows that the same profiles combinations, such as 21989/3646 are adopted in the generation of many optimal SBE shapes. The implementation of CTA mechanism allows reducing total received ra-diation with 41.90% when compared with the reference building. CTA values of optimal SBE are mostly close to the normal. However, whenCTA and COA are simultaneously varied, the CTA values of the BFF af- ternoon part decrease close to 61°. A little COA variation that rangesbetween 0° and 11° enhanced slightly the SBE solar potential. The best trade-off is achieved using CTA/COA mechanism with an enhancementof 44.90% and 34.85% in solar protection, and shape coefficientrespectively, while the space efficiency is close to 97%.

18th January is the optimal solar state for generation, COA and SPP mechanisms, and February for CTA and CTA/COA mechanisms. Optimal SEB issued from the same mechanism have generally the same segments numbers such as 6/2 in CTA mechanism (Table B3). The best value of space efficiency is estimated at 98% obtained via the implementation of CTA mechanism. It is maintained above 95% in other mechanisms. CTA/ COA mechanism gives the best results in terms of shape coefficient 0.21, which represents an improvement of 38.25%.

5. Conclusion and future works

In the present paper, a building solar morphing method was estab- lished to enhance static building envelope ability in regulating solar exposure, with respect to enhancing shape coefficient, while keeping the building space efficiency acceptable. Getting inspiration from natural mechanism provides the designer with a road map and helps visualisethe design solution in early design stage. Accordingly, a Geo-solar morphing mechanism, inspired by 'solar-induced rock cracking' phe- nomenon, was adopted as a source of inspiration in setting the geo-solar segmentation method. The latter was implemented based on a genera- tion, and four optimisation mechanisms, using a parametric approach and visual programming in Grasshopper. MOGA optimisation is per- formed to generate optimal segmented building envelopes (SBE), and evaluate the method's effectiveness under cold, temperate, and hot cli- mates. A comparative study was carried out between optimal SBE and a rectangular-based reference building.

The results show that the effectiveness of the GSS method is limited under cold climates in terms of solar potential. However, it helps enhance the building shape coefficient up to 10.30%. The GSS method can be considered as an effective tool in setting a trade-off between two contradictory solar design objectives in temperate climates. It enhances solar protection during the cooling period by 33.90%, and shape coef- ficient by 20.60%. While the total received solar radiation is reduced by 33.99% in the heating period. Under hot climate, the GSS method shows better performance. The improvement of solar protection and the shape coefficient reached 44.90% and 34.85%, respectively. The space effi- ciency values are kept up to 95%. Therefore, the deviation reveals the ability of SBE to regulate solar energy compared with a rectangular- based building form especially under hot and temperate climates.

The present study shows that combining the biomimicry approach and visual programming tools helps provide effective architectural design tools. Further, early-design stage solar morphing methods canhelp achieve more efficient static building envelope. The combination of MOGA and bio-design approach allows generate a wide range of optimal design solutions and options and make it possible to set a trade-off be- tween two conflicting solar design objectives. Therefore, GSS can be applied in the architectural design process in various climates like inAlgerian Sahara. It will help adapt local architecture to its climatic context. The study offers a solar morphing method for building design; the impact neighbouring buildings is not considered and need further research. In the MOGA process, the objectives and the generations numbers were limited according to the used computer performance. For the same reason the segmentation is applied only to a building part. Otherwise, more irregular and effective shapes can be generated. Future studies should evaluate the impact on the building energy performance and overall thermal comfort of the occupant.

VIII.Declaration of Competing Interest

The authors declare that they have no known competing financialinterests or personal relationships that could have appeared to influence the work reported in this paper.

IX.Acknowledgement

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X.Appendix A

Table A1.

Table A1
Koppen world climate classification (Peel et al., 2007).

Climate zone	Description	Temperature criterion
A	Tropical	$T_{cold} \geq 18$
B	Arid	$MAP < 10 \times P_{threshold}$
C	Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
D	Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
E	Polar	$T_{hot} < 10$

XI.Appendix B

Tables B1-B3.

Table B1
Optimal top five ranked SBE for Montreal (Cold climate).

GSS mechanisms	G	Performance values			Optimal SBE Geometric features					
		Solar radiation(kW h)	Space efficiency(%)	Shape coefficient	SN_A SN_E(M)	SN_A SN_E (A)	S_S Date	CTA M/A (°)	COA M/A (°)	P M/A
Generation	18	219,100	98.4958	0.3701	8–8	8–6	30/12	/	/	/
	18	219,280	98.5314	0.3704	3–8	8–6	20/12	/	/	/
	13	219,230	98.5217	0.3698	8–7	8–5	21/12	/	/	/
	19	217,560	98.4763	0.3694	8–8	8–3	18/12	/	/	/
	13	219,310	98.5211	0.3698	7–8	8–5	22/12	/	/	/
CTA mechanism	20	254,780	97.7612	0.3251	7–4/	6–2	16/3	88,78,60,62/ 87,89	/	/
	18	252,870	97.7012	0.3266	7–4	6–2	16/3	88,77,60,62/ 87,89	/	/
	21	243,300	97.9935	0.3286	5–4	4–2	10/01	84,80, 63,60/ 87,88	/	/
	17	256,680	97.7026	0.3295	5–4	4–2	17/02	84,77,64,60/ 87,88	/	/
	19	247,380	97.7167	0.3307	5–4	4–2	14/02	84,77,64,60/ 87,88	/	/
COA mechanism	21	221,280	98.6139	0.3738	5–2	8–8	22/12	/	1,0/ 1,4,25,29	/
	21	220,900	98.6163	0.3727	5–2	7–8	22/12	/	0,5/ 0,0,25,1	/
	21	221,000	98.6084	0.3751	7–2	6–8	22/12	/	2,1,0/ 2,29,23,28	/
	21	221,230	98.6036	0.3763	6–2	8–7	22/12	/	2,1,8/ 1,30,28,29	/
	20	218,460	98.5356	0.3704	5–2	6–6	08/12	/	4,0/ 3,1,22,24	/
CTA / COA mechanism	20	193,190	96.1651	0.3050	4–2	7–3	07/08	89,88/83,72,70	23,24,12,23/ 2,27,23,7	/
	11	208,960	96.0445	0.3024	4–2	7–3	07/08	89,84/83,74,70	23,24,12,23/ 2,27,23,7	/
	15	210,240	96.1547	0.3116	5/2	6–3	12/8	89,89/72,72,80	9,4,3,20/ 10,26,18,14	/
	18	211,250	96.2493	0.3082	3/2	7–3	12/8	89,88/72,72,82	2,2,25,12/ 14,13,19,29	/
	7	209,960	96.0883	0.3105	5/2	7–3	12/8	89,88/72,72,80	7,2,25,23/ 14,26,18,14	/
SPP mechanism	26	219,910	98.6561	0.3645	8/2	8–7	25/12	/	/	1/4798
	18	219,360	98.6919	0.3649	7/2	8–5	24/12	/	/	1/114
	19	219,370	98.7000	0.3650	8/2	8–5	24/12	/	/	1/113
	15	219,340	98.7017	0.3649	8/2	8–5	20/12	/	/	1/112
	16	219,380	98.6656	0.3647	7/2	8–5	22/12	/	/	1/118

Table B2
Optimal top five ranked SBE for Constantine (Temperate climate).

GSS Mechanisms	G	Optimal SBE performance values				Optimal SBE Geometric features					
		Solar radiation (kW h)	Solar radiation (kW h)	Space efficiency (%)	Shape coefficient	SN_A SN_E (M)	SN_A SN_E (A)	S_S Date	CTA M/A (°)	COA M/A (°)	P M/A
Generation	15	229,910	178,260	97.5619	0.3762	6/2	7/6	28/	/	/	/
	15	229,530	178,010	97.5510	0.3759	8/2	8/5	27/ 12 12	/	/	/
	13	229,450	177,970	97.5577	0.3764	7/2	7/6	15/ 12	/	/	/
	14	229,420	177,940	97.5575	0.3764	7/2	6/6	15/ 12	/	/	/
	14	229,270	177,790	97.5563	0.3766	7/2	4/6	15/ 12	/	/	/
CTA mechanism	21	243,030	186,000	96.2331	0.2781	5/2-	6/3	2/8	86,85/78,79,71	/	/
	4	235,740	180,200	96.2212	0.2824	5/2	3/3-	2/9	86,85/78,79,66	/	/
	5	233,420	178,330	96.1450	0.2836	5/2	3/3	2/9	86,85/78,78,66	/	/
	20	238,550	184,800	97.6304	0.3648	6/3	5/2	29/ 10	87,79,81/82,79	/	/
	15	238,620	184,870	97.6132	0.3645	6/3	5/2	27/ 10	87,79,81–82,79		
COA mechanism	13	225,960	174,440	97.5615	0.3817	2/2	3/6	20/ 12	/	7/4	/
	20	226,720	175,100	97.5516	0.3808	3/2	2/6	23/ 12	/	8/4	/
	19	228,300	176,620	97.5319	0.3800	5/2	4/7	17/ 12	/	15,1/10,9	/
	9	227,110	175,380	97.5575	0.3828	2/2	8/7	20/ 12	/	7/4,9,26,14	/
	6	228,130	176,430	97.5182	0.3803	7/2	4/6	28/ 12	/	17,9,9/11,9	/
CTA / COA mechanism	17	251,600	188,540	98.6150	0.3703	7/2	4/2	30/ 10	87,83/81,83	29,21,9/ 6,17	/
	13	250,550	187,490	98.6030	0.3753	7/2	4/2	30/ 10	87,83/81,83	18,21,9/ 30,17	/
	18	249,830	187,160	98.5399	0.3711	5/2	4/2	30/ 10	89,82/81,80	23,26/1,17	/
	19	248,680	186,680	98.4890	0.3710	7/2	6/2	30/ 10	87,81/81,83	30,21,9/ 8,19,29	/
	20	234,540	177,340	96.2879	03,022	3/2	2/2	22/8	86,84/64,79	29/2	/
SPP mechanism	4	230,090	178,160	97.5502	0.3713	6/6	4/6	26/ 12	/	/	4/ 711
	1	229,640	177,920	97.5036	0.3714	5/5	7/5	26/ 12	/	/	4/ 119
	1	229,600	177,910	97.4501	0.3714	8/5	7/5	26/ 12	/	/	4/95
	1	229,580	177,880	97.4499	0.3714	7/5	7/5	26/ 12	/	/	4/95
	5	230,370	178,370	97.5633	0.3716	6/6	4/6	22/ 12	/	/	4/ 711

Table B3
Optimal top five ranked SBE for Ghardaia (Hot climate).

GSS Mechanisms	G	Optimal SBE performance values			Optimal SBE Geometric features					
		Solar radiation(kW h)	Space efficiency(%)	Shape coefficient	SN_A SN_E(M)	SN_A SN_E(A)	S_S Date	CTA M/A (°)	COA M/A (°)	Paths: M/A
Generation	13	406,750	96.4929	0.3739	6/6	7/3	18/1	/	/	/
	18	411,730	96.5566	0.3741	6/6-	7/4-	18/1	/	/	/
	15	364,690	96.4905	0.3741	6/6	5/3	18/1	/	/	/
	21	411,550	96.5558	0.3742	6/6	6/4	18/1	/	/	/
	6	411,650	96.6126	0.3742	7/4	7/4	18/1	/	/	/
CTA mechanism	9	551,380	98.8428	0.3521	4/2	6/2	27/2	88,81/89,83	/	/
	18	548,990	98.8476	0.3520	3/2	6/2	27/2	89,80/89,83	/	/
	17	545,560	98.7148	0.3522	4/2	6/2	27/2	88,79/89,83	/	/
	11	544,220	98.7120	0.3528	4/2	4/2	27/2	88,79/89,83	/	/
	17	552,660	99.1227	0.3650	6/2	8/2	26/1	80,88/89,88	/	/
COA mechanism	16	451,680	96.9027	0.3790	5/2	3/6	18/1	/	3,9/5	/
	20	452,590	96.9045	0.3793	3/2	4/6	18/1	/	9/0,6	/
	8	452,290	96.8976	0.3793	5/2	3/6	18/1	/	3,9/4	/
	13	444,230	96.8795	0.3837	2/2	3/6	18/1	/	9/1	/
	12	445,920	96.8489	0.3837	3/2	3/6	18/1	/	10/11	/
CTA / COA mechanism	19	413,820	96.7742	0.2215	4/2	5/2-	10/2	82,89/61,68	12,0/1,17	/
	17	406,790	96.6519	0.2220	4/2	5/2-	10/2	81,88/61,68	12,0/1,18	/
	9	409,990	96.4978	0.2228	7/2	3/2	24/2	82,89/61,66	12,20,23/1	/
	4	411,110	96.7311	0.2272	3/2	5/2	6/2	89,88/61,60	11/27,8	/
	19	373,300	95.9146	0.2194	4/2	3/3	29/2	82,74/ 62,75,83	5,8/2	/
SPP mechanism	19	397,670	96.3399	0.3768	7/7	3/8	21/1	/	/	4645/ 3646
	9	399,780	96.7622	0.3723	7/8	3/8	21/1	/	/	21989/ 3646
	13	437,740	96.7444	0.3744	2/8	6/8	21/1	/	/	21989/ 3646
	16	439,530	96.7006	0.3722	2/7	4/7	19/1	/	/	1475/ 3254
	13	392,770	96.7880	0.3775	7/7	3/4	20/1	/	/	2597/1

XII. Appendix C

Fig. C1-C3

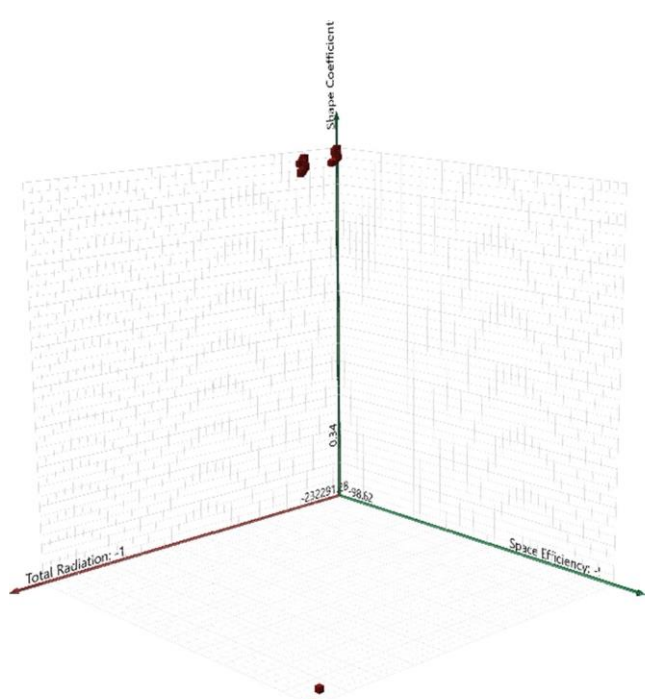

Fig. C1. Pareto front set of segmented building envelope for Montreal using generation mechanism.

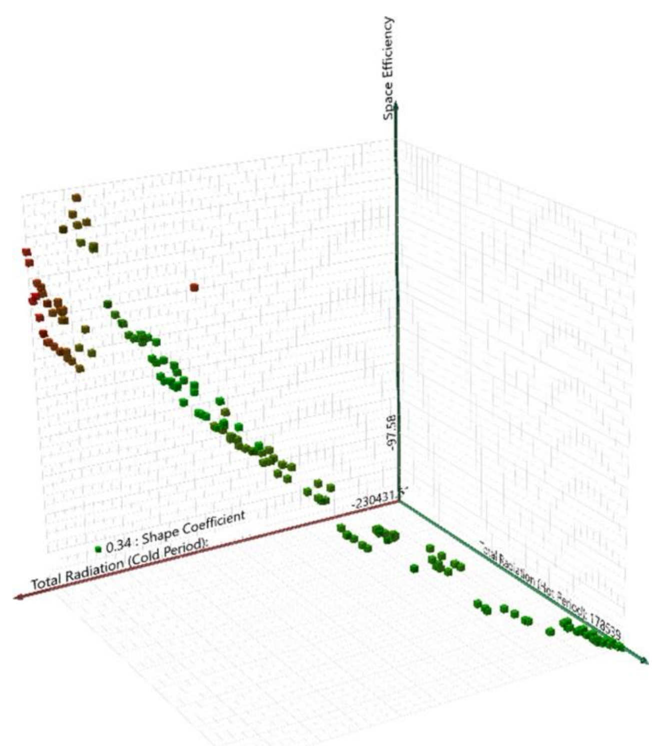

Fig. C2. Pareto front set of segmented building envelope for Constantine using generation mechanism.

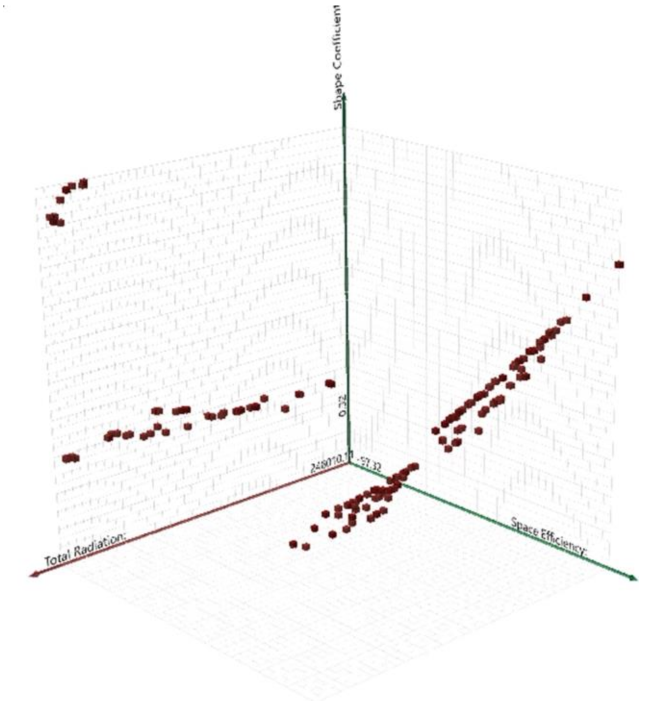

Fig. C3. Pareto front set of segmented building envelope for Ghardaia using generation mechanism.

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ABSTRACT

Building envelope shape plays a crucial role in determining the building energy performance, by regulating its solar exposure and the incident solar radiation. However, there are limited solar morphing tools that allow the generation of static building envelope. Besides solar potential, building shape performance indicators need to be considered, such as space efficiency and shape coefficient. Therefore, the present study proposes the 'geo-solar segmentation' morphing method that can help architects and engineers generate a range of optimal building shapes based on received solar radiation, shape coefficient and space efficiency in the early design stage, under different climate conditions. Accordingly, based on the top–down biomimetic approach, the solar-induced rock cracking mechanism is adopted as a source of inspiration to generate an architectural design concept. It is then, transcribed into a solar design generation and optimisation algorithms using visual programming in Grasshopper, within the Rhinoceros software. Octopus, an evolutionary solver is used to perform the multi-objective genetic algorithm optimisation. A comparative study is conducted between optimal solar segmented building envelopes and a reference rectangular-based shape. The results demonstrate that under hot climate, optimally segmented building envelopes are 44.90% more effective in terms of solar protection than rectangular-based ones, and allow a trade-off between solar protection and collection under temperate climates. Moreover, the method helps reduce the shape coefficient by at least 10.30% for any climatic location, while ensuring a minimum space efficiency of 95%. The suggested method can be used as an early design-stage tool to enhance static envelope energy performance.

Keywords building solar morphing, geo-inspiration, static building envelope design, multi-objective genetic algorithm-optimisation, building shape performance, design trade-off.

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