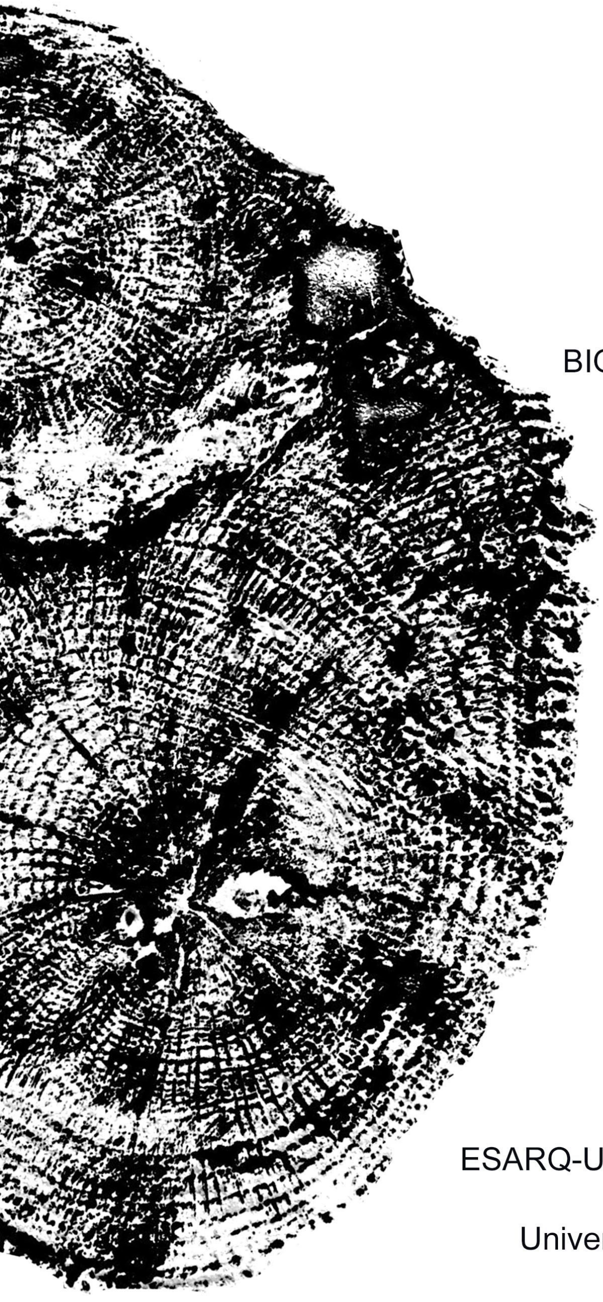
BIO-DIGITAL MORPHOGENESIS: CRAFTING THE FUTURE OF ARCHITECTURE WITH NATURE'S BLUEPRINT & MACHINE'S CANVAS

Master Thesis

by

ZEYNEP ÇOLAK



MASTER IN

BIO-DIGITAL ARCHITECTURE

September 2023

ESARQ-UIC Barcelone School of Architecture

Universitat Internacional de Catalunya

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ABSTRACT

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The field of Biodigital Architecture stands at the intersection of biology, technology, and design, forging innovative pathways toward sustainable and responsive built environments. This thesis embarks on a multifaceted exploration of Biodigital Architecture, seeking to unravel its complex tapestry by examining its profound relations with nature learning, its dynamic integration with machine learning, and an incisive analysis of these connections within the ambit of a visionary bio-digital skyscraper project by adding a new perspective. That is; biodigital architecture represents an in-depth understanding of natural processes, combined with digital precision thanks to advanced digital tools and traditional craftsmanship.

At its core, Biodigital Architecture is profoundly rooted in nature. Drawing inspiration from the innate intelligence of the natural world, architects harness biomimetic principles to reimagine the built environment. This study delves into the principles of biomorphism and biophilia, unraveling how architects learn from nature's designs, processes, and ecosystems. By aligning architectural endeavors with ecological knowledge, Biodigital Architecture offers sustainable and regenerative solutions that foster a harmonious coexistence between humans and the environment. It tracks the precedents of bio-digital architecture from different periods, from different origin places, and in different fields to pursue a complete interdisciplinary and multi-perspective method that it requires.

In a rapidly evolving digital landscape, machine learning emerges as a potential in the arsenal of Biodigital Architecture. This study examines the emerging relationship between machine learning and architectural practice, concentrating on how computational models and artificial intelligence are used to improve architectural performance and adaptability. Thus, it adds to the craftsmanship involved in this process and explores the potential of it. In this perspective, craftsmanship encompasses not just manual skills but also the knowledge of digital tools and technology that enable architects and designers to create technologically advanced designs that are inspired by nature. As architects embrace the realms of responsive and adaptive architecture, the implications of incorporating machine learning techniques are explored in this thesis in the context of achieving precision, complexity, rapid prototyping, and scalability through a case study of a bio-digital skyscraper project.

At the heart of this thesis lies a comprehensive analysis of a bio-digital skyscraper project—an emblematic intersection of nature learning and machine learning within architectural practice. Through meticulous examination, we unravel the intricate interplay between these elements, exploring their roles in shaping the skyscraper's overall form, fabrication of a scaled prototype, and functions. The inquiry extends beyond theory as the project's environmental performance, energy efficiency, and occupant experiences are evaluated. This empirical analysis encapsulates the transformative potential of Biodigital Architecture, serving as a testament to its real-world applications.

This interdisciplinary journey through the realms of Biodigital Architecture, nature learning, and machine learning unfurls as an exploration of innovation and possibility. It embodies the spirit of a rapidly evolving architectural paradigm that seeks to harmonize the built environment with the natural world while embracing the transformative potential of digital technologies. Its landscape, unearths insights, lessons, and revelations that contribute to the evolution of Biodigital Architecture, positioning it as a visionary and sustainable path forward in the dynamic landscape of architectural design and innovation.

Acknowledgments

I would like to take a moment to express my deepest gratitude to the individuals who have played tremendous roles in my academic journey and the completion of this thesis.

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I am also thankful to my professors and mentors at UIC Barcelona, whose guidance and expertise have been invaluable. Their fostered vibrant academic environment and commitment to pushing the boundaries of knowledge have had a profound impact on my intellectual growth.

This thesis is a testament to the collective effort, guidance, and support of these remarkable individuals and institutions. While the words on these pages may bear my name, they are a reflection of the collective wisdom and encouragement I have received from all those mentioned above.

With sincere gratitude,

Zeynep Çolak

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INTRODUCTION

Humanity has always been drawn to the fluidity of complex forms that are in a continuously changing movement, arranged in harmony with morphogenetic laws. An organic, continuous connection occurs when each part responds to the whole, and the whole gets reflected in those parts. When this connection exists, there are better structural and growth conditions and Gaudi described this connection as the beauty of nature or the objective beauty (Estévez, Urbano, 2020). Today, we no longer talk about architectural styles, but we talk about trends and the most obvious of them is the emerging use of computers in the design process. The computational design makes it easier to develop designs through versioning and gradual adjustment by automating parts of the process like the way mutations in nature generate biodiversity, therefore it pushes the limit of form finding in architecture and design, the reason we talk about digital morphogenesis today. Digital morphogenesis is inspired by biology, it operates through a logic of optimization, something that is learned from nature and something that can be strengthened by computation therefore today, the digital design of architectural projects can be based on computational strategies that are also morphogenetic. So the focus is on the idea of finding the most suitable form that answers specific input constraints. According to D’arcy, the form of an object is a "diagram of forces" while formation is the result of physical laws operating according to predictable mathematical patterns and he described growth and form with the study of organisms because nature and the entire universe are written in a mathematical language (Thompson, 1945). However, morphogenesis and today’s design approach are more than form; natural morphogenesis is notable for the strong relationship between the processes of materialization and formation. Instead of distinguishing between these processes, an alternative morphogenetic approach to architectural design involves unfolding morphological complexity and performative capacity from material elements. Morphogenetic design experiments explore growth processes that can be controlled with mathematics and can affect design from product scale to architectural scale in terms of form, behavior in material systems, and digital fabrication. By extending the experimental research tradition and building on design work based on physical form findings, this study aims to investigate the potential consequences of such experiments when applied to the digital realm from the physical one.

Objectives

This thesis aims to comprehensively explore the multifaceted landscape of Biodigital Architecture, underpinned by the dual pillars of Nature Learning and Machine Learning. These concepts are dissected into their constituent elements, delineating a roadmap for understanding the past, present, and future of architectural innovation. With a particular focus on a Bio-Digital Skyscraper project, this research also seeks to achieve the objectives concerning nature learning and its relation with machine learning while in every chapter focusing on form finding process, behavior, and materiality.

The first chapter is related to nature learning, this thesis aims to examine the first precedents of concepts like natural systems, forms, processes, biomorphism, and organic architecture which eventually turned out and formed the basis of bio-digital architecture in history. It investigates how architects and artists drew inspiration from nature’s diverse forms, patterns, and structures, weaving these biomimetic principles into architectural designs. Later it examines the intricate processes of natural morphogenesis, where organic systems evolve and adapt over time, and how these concepts influence architectural dynamics. Following the Unraveling of the principles of Gaudinian Parametricism, a fusion of organic design and parametric architecture that embraces the complexities of nature in computational models. Related to this subject, it explores the mathematical underpinnings of natural phenomena and their translation into architectural language, emphasizing the universal grammar of mathematics. Then investigating the historical role of artisans from different fields used the language of mathematics, nature learning, and growth and applied them in their works. The result is an overall form-finding process, rotten in deep nature learning and mathematical language of the universe reflected in different contexts and fields. Later it evolves to investigate the material behavior in nature, focusing on materiality and production, and ends with concluding how the bio-learning process works and its potential.

The second chapter aims to explore the intersection of Biodigital Architecture with machine learning techniques, particularly focusing on how artificial intelligence, computational design, generative algorithms, and digital fabrication tools are leveraged to enhance design, performance, and adaptability. Moreover, it focuses on assessing the potential for machine learning to contribute to the evolution of Biodigital Architecture, especially in the context of responsive and adaptive design solutions that can dynamically interact with their environment and occupants. Similar to the first chapter, this one revolves around investigating the form-finding process, material behavior, and fabrication process. Therefore to get in more deeply with form finding, the research analyzes generative design algorithms in architectural design, where machine learning aids in the creation of innovative and optimized forms. While giving a discussion about digitalization in general and digital avant-garde on focus and open forms by exploring the paradigm shift toward open-ended, non-arbitrary, digitally driven architectural forms. It proceeds by analyzing the integration of artificial intelligence in the architectural design process, emphasizing the role of machine learning algorithms in decision-making and design optimization. It goes on to another context which is digital fabrication and its implications for the realization of complex biodigital designs. Lastly, it gives a material computation and its relation to bio-digital architecture to address the potentials and real-world applications.

In the third chapter, this research explores bio-digital architecture in the light of its interdisciplinary nature, with math and digital morphogenesis in focus for the finding process, delving into the study of growth, behavior, and materiality as fundamental inquiries and analyzing the convergence of traditional craftsmanship with digital fabrication techniques. Later it focuses on conducting an in-depth analysis of a specific bio-digital skyscraper project, investigating how it incorporates principles of nature learning and machine learning in its design, construction, and operation. Moreover, it examines the application of bio-learning principles, employing AI in the form-finding process. Then it explains how gyroids as minimal surfaces were used in the creation of skyscrapers highlighting the math and digital morphogenesis and generative algorithms and their role in achieving complex, adaptive design. Later it presents the use of digital fabrication in realizing the skyscraper’s design, emphasizing precision. As a result, to draw meaningful conclusions about the effectiveness of Biodigital Architecture as a sustainable and technologically advanced approach to architectural design, as a living organism and to identify key lessons and insights from the case study.

Through these objectives, this thesis aims to contribute to a deeper understanding of the dynamic interplay between Biodigital Architecture, nature learning, and machine learning. It seeks to shed light on the potential of this innovative field to redefine the future of sustainable and responsive architectural design in an increasingly complex and interconnected world. Through this structured exploration, this thesis endeavors to shed light on the intricate and transformative realm of Biodigital Architecture, where the past informs the present, and both converge to shape a sustainable and innovative future in architectural design and construction.

Justification

Biodigital Architecture stands at the nexus of biological wisdom, technological innovation, and architectural evolution. As humanity grapples with pressing challenges related to climate change, mass production, resource depletion, and urbanization, it becomes increasingly crucial to explore novel avenues for sustainable and responsive architectural design. This thesis seeks to delve into the realm of Biodigital Architecture, offering a robust justification for its comprehensive exploration in a new era of "*living architecture*".

The urgency of addressing climate change and mitigating its impact on the planet is undeniable. Architecture, as one of the most resource-intensive human endeavors, plays a pivotal role in this global challenge. Biodigital Architecture, with its emphasis on ecological sensitivity and sustainability, presents a promising avenue for reducing the environmental footprint of the built environment. This thesis endeavors to shed light on how Biodigital Architecture can contribute to a sustainable future by exploring its historical roots, contemporary applications, and future potentialities to highlight the idea of "a building is an organism" rather than "a machine"[1].

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[1] In the 1920s, Le Corbusier published his own influential book, Toward an Architecture, in which famously wrote "Une maison est une machine-à-habiter" ("A house is a machine for living in")

Biodigital Architecture represents a unique fusion of nature and technology, where the design process is informed by the intricate intelligence of the natural world, and where computational tools and machine learning enhance architectural innovation. This fusion holds the promise of not only creating aesthetically compelling designs but also optimizing building performance, energy efficiency, and occupant well-being. This thesis seeks to justify its exploration by unpacking the intricate relationship between nature learning and machine learning within the context of architectural design.

Biodigital Architecture is inherently interdisciplinary, drawing from fields as diverse as biology, mathematics, art, and digital technology. It encourages collaboration between architects, biologists, mathematicians, and digital artists, transcending traditional disciplinary boundaries. This interdisciplinary nature positions Biodigital Architecture as a fertile ground for innovation and problem-solving. Thus, this thesis aims to justify its examination by highlighting the need for an interdisciplinary approach to addressing the complex challenges of contemporary architecture.

Architectural practice is undergoing a profound transformation in the digital age. Computational design, generative algorithms, and digital fabrication are reshaping the way buildings are conceived, designed, and constructed. Biodigital Architecture, with its roots in nature learning and its embrace of machine learning, represents a pivotal evolution in architectural paradigms. This thesis seeks to justify its research by offering insights into how this evolution is unfolding and how it holds the potential to redefine the future of architectural design.

In summary, this thesis on Biodigital Architecture is justified by the urgency of sustainable architecture, the fusion of nature and technology, the interdisciplinary nature of the field, the evolving architectural paradigms, and a case study project with scaled physical models that underscore its significance. Through this exploration, it aspires to contribute to a deeper understanding of Biodigital Architecture's role in addressing the complex challenges of the built environment and its potential to shape a more sustainable and innovative architectural future located at the intersection point between design, science, and art.

Methodology

The methodology employed in this thesis is designed to comprehensively investigate Biodigital Architecture, focusing on the integration of nature learning, machine learning, and AI. The research process is structured into several key stages to ensure a rigorous and systematic exploration of the subject.

The research begins with an extensive literature review encompassing the roots of Biodigital Architecture, nature learning in architecture in the past, and biomimicry. This phase aims to establish a strong theoretical foundation, identify key concepts, and gain insights into current trends and practices in the field by tracking the precedents based on different contexts and exploring the interdisciplinary characteristics it possesses from the beginning.

Building on the insights gained from the literature review, a conceptual framework is developed. This framework serves as a guiding structure for the research and helps in formulating research questions, objectives, and hypotheses. It also assists in delineating the interplay between nature learning and machine learning in Biodigital Architecture.

The research employs computational tools and software to conduct in-depth analyses. Large datasets are processed and analyzed using machine learning algorithms to identify patterns and predict the performance of architectural performance. Machine learning algorithms are used to process and analyze large datasets, uncover patterns, and make predictions related to architectural performance. Parametric design software is employed to explore generative design possibilities inspired by nature. Digital fabrication methods and tools are also used to make prototypes of design and scaled physical models of case projects. Thus, AI was employed in certain cases, such as in the form of finding processes and creating visual representations and renderings. Therefore in the end a comparative analysis is carried out to evaluate the performance and design outcomes of the case studies concerning their utilization of AI, machine learning, and nature learning. This analysis aims to identify best practices, innovative solutions, and potential areas for improvement.

Based on the findings from the case studies and computational analyses, a synthesis phase is initiated. This phase involves the development of design propositions that integrate AI, machine learning, and nature-learning principles into architectural design. These propositions serve as conceptual models for future Biodigital Architecture projects. The research concludes by summarizing the key findings, highlighting the significance of AI, machine learning, and nature learning in Biodigital Architecture, and offering recommendations for future research and practical applications.

This methodology employs a holistic approach that combines theoretical exploration, empirical analysis, and computational modeling to investigate the integration of nature learning, machine learning, traditional craftsmanship, and employing AI in Biodigital Architecture. It seeks to advance our understanding of how these elements can contribute to sustainable, innovative, and responsive architectural design.

Background

Nature's forms have long been applied symbolically and metaphysically in ancient architecture. Nature has always been something we observe, worship, and represent. Today's architects are investigating potential uses for high-performance materials that can grow, repair, and decompose on their own like biological organisms. We should consider the current built environment to be damaged and in need of repair. Restoration and transformation should take priority over irresponsible expansion into more rural regions. Nature offers an endless source of precedents that have evolved through the years to offer optimal solutions to the numerous challenges of life and survival. The effective solutions found in nature are perceived as beautiful to our senses, and these sophisticated natural systems stimulate our thoughts. The creative brain is inspired by these biological creations, while the analytical brain attempts to comprehend nature's guiding laws and principles. For those seeking innovation and beauty, nature provides an infinite source of inspiration for efficient and effective design.

New tools and design approaches are needed for complex architectural forms that combine digital morphogenesis, computer-aided manufacturing, parametric modeling, and material self-organization. Current CAD applications now offer generative design methods so the designer can create parametric relationships between features, approaches, and functions in a way that encourages experimental design methodologies. But at the moment, *geometrical limitations* are primarily what motivates this liberation. Approaches for generative performative modeling have been developed that combine principles of engineering with form-finding. Nevertheless, material organization and behavior are already predetermined design restrictions thus, form finding in the digital realm is limited to the interaction between geometry and structure and it typically excludes the expression of material characteristics, organization, and behavior. Therefore form-finding experiments with self-organizational materials and systems that are recorded in a set of geometric dependencies and relations remain to be explored. We live in an era today in which new architecture and design must be necessarily provided by new materials, new tools, and new processes. Thus, today's industrial age came with another design thinking

Because of the assembly line, the Industrial Revolution gave rise to a particular form of design thinking in which we frequently construct cities, buildings, wearables, and even products out of parts. We must investigate alternate, in line with nature, methods of construction and manufacturing; “growth as opposed to assembly. In other words, a system that gradually varies its functionality by varying elasticity” (Oxman, 2015). A new design paradigm was found between an organism and a machine, a system between growth and assembly. The human body isn't made of parts and is not assembled, our skin covers our whole body with varying functions. That is to say; while the skin on our backs is thicker and has smaller pores, the skin on our faces is thinner and has larger pores. Both of these functions are performed by the same skin, while one functions as a filter the other acts as a barrier, and yet it has no parts or assembly.

I. NATURE LEARNING

Humans have always been closely connected with nature for the entire time of existence on Earth, humans have an instinctive, primitive attraction to it. The constant yearning for a closer relationship with nature has been giving architecture and design a starting point from the beginning of time. Harmony and organic connections lie in nature and this is the result of each part responding to each other and the whole reflects on these parts. Every singular element in nature can be understood as part of a whole system thus when observed, designers can link complexity, organic connections, and coexistence in this system to be used in today's architecture with the sensitivity it requires. In the end, nature is the ultimate designer by being an architect, an engineer, and an artist which taught humans everything we know since the beginning. Nevertheless, architecture is the pure combination of aesthetics, structural principles, and mathematical precision and can be enhanced by learning from nature´s efficiency. The designs created by nature work in a way with the minimum amount of energy cost and materials possible. Nature, however, does not seek it out in the same way that architects and designers do, favoring or discarding living beings based on their beauty, but only on their functional efficiency. Despite this, we feel attracted to nature´s continuity and flow and we find it beautiful. Our perception of beauty is linked to the forms in the natural world, however, nature's efficiency doesn't lie only in forms but also in the material behavior of every organism.

Humans found living forms to be particularly fascinating among other natural phenomena, and ever since biology emerged in the early 19th century, many designers have drawn inspiration from its discoveries (van Eck, 2007). The main idea behind the "organicism" school of thought was the practice of using what is learned from nature to design beautiful architecture. The tight relationship between live nature and architecture is one of the architectural theory's most recurrent and enduring concepts. Some designers have interpreted biological motifs artistically, as ornaments and decorations. Others have used the symbolic meanings of it as the intellectual, figurative, or spiritual underpinnings of their practice.

Pragmatically, many designers have tried to use the organization of natural structures to inform their designs, and more recently, a growing number of practitioners and researchers are attempting to comprehend and reinterpret naturally occurring functionalities, behaviors, and processes of growth and natural selection. The fascination with natural systems among these architects coexists with a greater fascination with biomimicry or bioinspiration as fundamentally different approaches to nature[2]. In light of these, this chapter explores the methods of form-finding in nature with examples from other parts of the world. Moreover, it investigates the characteristics of different organisms to understand material behavior in nature and how they differ in functions. Lastly, it discusses how designers can combine them and perform efficiency and true bio-learning to inspire and form today's design perspective.

1.1 FORM FINDING

1.1.1 Biomorphism

What is a human being’s first sensation? The first perception of humans is the ”feeling of space”, being nested in space, wrapped up in the womb. Although this concept of the first perception of humans is not a direct application of “*biomorphism*[3]”, it does have significant connections to biomorphic design. It's a biomorphic space, it is warm, comfortable, and growing. It is the initial sensory experience of the surrounding environment that we encounter from the origin of our nature before any art movement, design paradigms, or form-finding efforts and

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[2] According to Steadman [29, pp. xvi, 260], earlier initiatives with comparable goals were carried out as "biotechnique" or "biotechnics" in the 1920s and 1930s as well as "bionics" or "biomimetics" that started in the 1950s.

[3] Biomorphism is an art movement that began in the early 20th century and focused on organic shapes and forms. However The term “biomorphism” was first used by biologist Julian Huxley in his 1930 book Evolution: The Modern Synthesis. He defined it as “the process by which living organisms become more complex in structure and function; also applied to non-living things.”

aesthetic reasons came along. Today, biomorphic architecture takes inspiration from natural forms, shapes, patterns, and organic systems found in nature and it tries to mimic them in the design. Biomorphic architecture can be seen as the 21st-century avant-garde movement known as *digital organicism*[4], and both can be seen as precedents of *genetic architecture*[5] . However, architecture has been always taken its inspiration from nature and living beings making it *biomorphic* since the beginning of time. Humans constructed primitive “nests” to survive and protect themselves from unsuitable climate conditions yet, those first precedents of human constructions were made up of branches, bones, or leaves around the form or created by carving into rock formations.

The first known temple and construction site Gobekli Tepe located in southeastern Turkiye dates back to approximately 9600 BCE (Haklay, Gopher, 2020). Gobekli Tepe exhibits biomorphic architecture characteristics when the concept didn't exist yet. The most striking feature of Gobekli Tepe is its arrangement of massive, intricately carved T-shaped pillars which include abstract symbols as well as numerous animals (including foxes, lions, oxen, hyenas, scorpions, spiders, various reptiles, insects, and birds, particularly vultures), the site's creators must have worked on them with extreme diligence. An example of one of these anthropomorphic figures, a fox, is seen in Figure 1. While this is not a direct representation of organic forms, the anthropomorphic carvings could be seen as the early forms of biomorphic design, as they draw inspiration from human and possibly animal shapes. Also as the way they attempt to connect religious or ritualistic activities with the natural world that is a fundamental aspect of biomorphic design, as it seeks to evoke a sense of harmony between the built environment and the organic world. In Göbeklitepe’s case, it was used as a temple, a sacred place; where each figure would represent something, deliver a message that can be perceived by for for

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[4] Digital organicism is the part of organic architecture and design that uses the latest cybernetic-digital resources in its design and/or production. the avant-garde of architecture and design. (Estevez, 2015)

[5] Genetic architecture is architecture that applies genetics, taking objects into account.

1. Genetics may be applied to architecture in a *real and natural way*. This would be the real genetic architecture, requiring the combined effort of architects and geneticists.
2. Genetics may be applied to architecture metaphorically and artificially. This would be genetic architecture only by extension or similarity with genetic definitions and processes.

for everyone and guide them. To achieve this, the people who built Göbeklitepe looked at nature, as the common ground known and understood by everyone. What they found was resembling constellations of animal figures so everyone could track them. Therefore it can be said that nature helped to form the communication from the first phases of civilization on the Earth and *biomorphism* became their language.

Figure 1: The pillars in Gobekli Tepe. Specifically focusing on one of the fox figures and showing it as the projection constellation[6] (photo by Z. Çolak)

Other than these; the site's layout, the arrangement of the pillars, and their positioning relative to each other can be seen as an attempt of biomorphic architecture as they integrate with the natural landscape and respond to the natural context (fig.2). A series of rings or enclosures make up the Göbekli Tepe site as seen in the figure. The two gigantic, T-shaped monolithic limestone pillars that are present at the center of each one and are between 3 and 6 meters tall, together with smaller pillars that are similar in shape but not as large as the central ones, are what they have in common. Thus, some of the enclosures seem to be oriented towards the Sun rising at the summer solstice or setting at the winter solstice while others are

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[6] The fox figure appears to be an assemblage of mainly Leo with the tail extending out to Spica. Albeit perhaps not established as convincingly as the stars represented by this figure, it does fit at least to assume it appears somewhere within a space not already represented within the other stones, and that it bears some semblance to the configuration of Leo. The Lesser Fox is made up primarily of the constellation Lepus and the star Sirius, while the angle appears to be representative of the horizon and the Milky Way (Gobekli Tepe Constellations – Myths Mysteries & Wonders, n.d.)

thought to be oriented toward the moon when it was in its lower standstill or it is suggested by others that the enclosures in the site are oriented toward the setting point of the star Deneb (α Cyg) (Lorenzis & Orofino, 2015). In every scenario, this leads us to the conclusion that not only the civilization that built Göbeklitepe at the end of the Ice Age era were capable of building this complex architectural site with intricate details for representations and metaphors, but also they were highly knowledgeable of observing the sky and calculating star maps and using them to depict dates and important events. They were well aware of the power of nature, construction, and precise calculations.

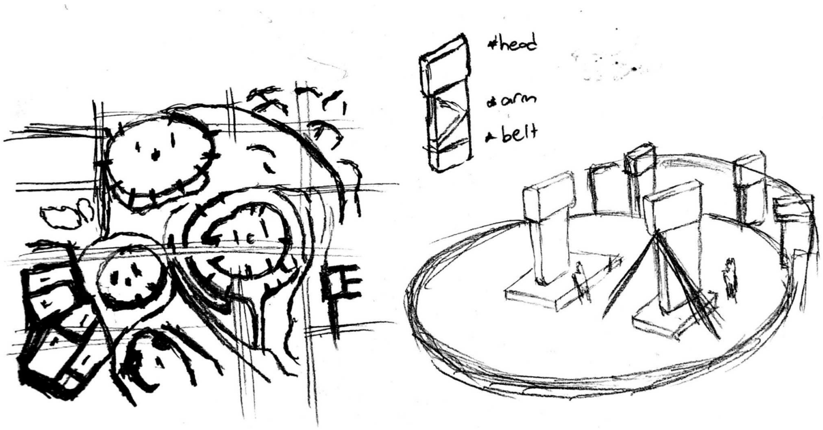

Figure 2: The site layout, plan, and sketch of Gobekli Tepe. (By Z. Çolak)

Another example is from the “Fairy Chimneys[7]”, the primitive cave dwellings of Cappadocia, Turkiye. These dwellings were carved into the soft volcanic rock formations and seamlessly blend with the natural landscape, mimicking the surrounding geological features (fig.3). Cappadocia exhibits biomorphic characteristics through its close integration with the natural environment, its use of organic forms and materials, and its adaptability to the landscape. Moreover, the process of carving the dwellings often followed the flow of the rock, leading to curved walls, arched doorways, and rounded spaces, resulting in organic interior architectural marvels. However, the community living there wasn't concerned about mimicking nature for aesthetic or symbolic reasons; in fact, they were trying to take advantage of natural insulation and thermal mass for temperature regulation to keep

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[7] Fairy Chimneys are geomorphological structures created from soft rock of sedimentary origin. Volcanic eruptions created this surreal moonscape when the lava flows formed tuff rock, winds, and rain sculpted into sinuous valleys with curvy cliff faces and pointy fairy chimneys.

the interiors cool in summer and warm in winter. This integration of natural materials and forms for climate control aligns with the biomorphic concept of designing with nature to enhance efficiency.

Figure 3: The landscape and fairy chimneys from Ürgüp, Cappadocia. (photos by Z. Çolak)

By observing first human constructions and vernacular architecture such as Göbekli Tepe and Cappadocia we can gain a deeper appreciation for the timeless human impulse to engage with and draw inspiration from the natural world in architectural and artistic endeavors. The primitive dwellings embraced an inherent connection with the land, creating a symbiosis between human habitation and geological formations. This coexistence with the environment embodies the biomorphic principle of fostering a harmonious relationship with nature.

Other examples of biomorphic design can be seen in the later eras, where human construction was at the peak point in history considering aesthetics and structure. The ancient Greeks drew inspiration from the human body and observed the natural world around them, which influenced the proportions and forms of their architectural elements. Their awareness of proportion ultimately led them to recognize the proportions of the greatest piece of art: the human body. In the classical Greek period, columns consisted of a “base, shaft and capital” but what they were symbolizing was “feet, body, and head” (Vitruvius,1960) (fig.4). In his work “De Architectura” (The Ten Books On Architecture), Vitruvius is renowned for suggesting that a structure must possess the three qualities of “firmitatis, utilitatis, and venustatis”, or stability, utility, and beauty. These are also known as the Vitruvian

Triad or the Vitruvian Virtues. Having these anthropomorphic aspects makes these architectural elements also biomorphic.

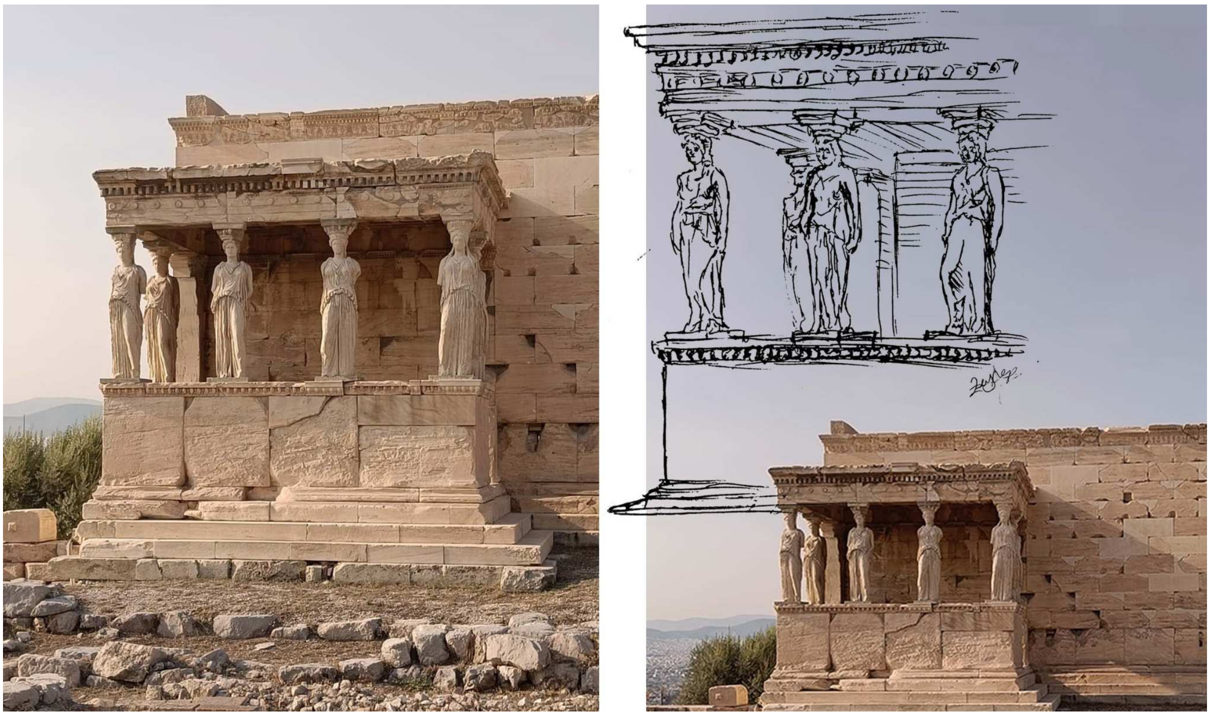

Figure 4: Caryatids Columns in Athens and the sketch of Caryatids (photo by Z. Çolak)

Architecture, in Vitruvius' view, is an imitation of nature. Humans constructed dwellings out of natural materials, similar to how birds and bees build their nests, to shelter themselves. His inspiration guided the ancient Greek era and led them to take biomorphic images which are curved, soft, and have fluid forms, and use them either abstractly or directly. Greeks, as they perfected the craft of construction according to these principles, created the Doric, Ionic, and Corinthian architectural orders. Each of them has different aspects such as the Doric column having a simple, plain capital while the Ionic column’s capital consists of volutes, which are spiral scroll-like elements on each side that give the Ionic order a more decorative and graceful appearance and the Corinthian column have the most ornate capital of the three orders. The capital is decorated with acanthus leaves and small volutes above the acanthus leaves which made Greeks resemble Corinthian order to a young girl, Ionic to a mature woman, and Doric to the head of a man.

Figure 5: The capitals of the Corinthian column are adorned with intricate acanthus leaves and other patterns resembling the foliage of plants and ivy. (Photo by Z. Çolak)

1.1.2 Morphogenesis

The organic, continuous connection can be seen in every part of nature, each part is interrelated with the whole and the whole is a reflection of those parts. Morphogenesis happens to the forms in nature to create this beauty.

Morphogenesis is a phenomenon in nature that is described as the biological process in which organisms develop their intricate structures and form in the natural world. Since it is typical for living organisms, the process includes cell division, growth, self-healing, differentiation, and aging guided by genetic instructions and environmental forces. From the precise arrangement of feathers in a bird's wing to the intricate branching patterns of a tree, and nature’s designs are a testament to the elegance of this process. At its core, *natural morphogenesis* relies on three things; genetic information guides the formation of structures while cell communication ensures coordination and mechanical forces, both internal and external, shape the tissues and sculpt the final forms (Bourgine & Lesne, 2010). Understanding this process not only deepens our appreciation of nature's beauty but also holds the potential for inspiring innovative solutions in fields ranging from biology to art, engineering, and design. In light of this, morphogenesis´ relation with design in the past and today will be explored.

This fundamental principle, morphogenesis, lies in nature and has deeply influenced the evolution of architecture. Throughout history, humans observed and learned from the morphogenetic processes of the natural world, leading to the creation of architectural forms that were not only functional and adaptive but also aesthetically pleasing, even if it wasn't something they were specifically trying to achieve in the primitive era. At its basis, morphogenesis in nature is generally the process through which organisms grow following specific patterns and forms. These growth patterns were frequently imitated even in primitive architecture and they continued to develop until today's advanced architecture. For instance, the curved, flowing, and interconnected passageways of the ancient underground cave city *“Derinkuyu*[8]*”* in Cappadocia (fig.6) resonated with the growth patterns of plant roots while they also mimicked the natural morphology of cave systems, integrating human habitation with the earth. In addition to that, morphogenesis allows organisms to adapt to their surroundings, and like all primitive architecture, Fairy Chimney dwellings and Derinkuyu underground city in Cappadocia were inherently linked to their environment, with designs tailored to local climate, topography, and available resources. Moreover, morphogenesis mainly involves the transformation of materials as organisms grow and evolve. In primitive architecture, materials like adobe, wood, and stone transformed shaping, carving, and assembly, resulting in architectural forms that echoed the morphogenesis process.

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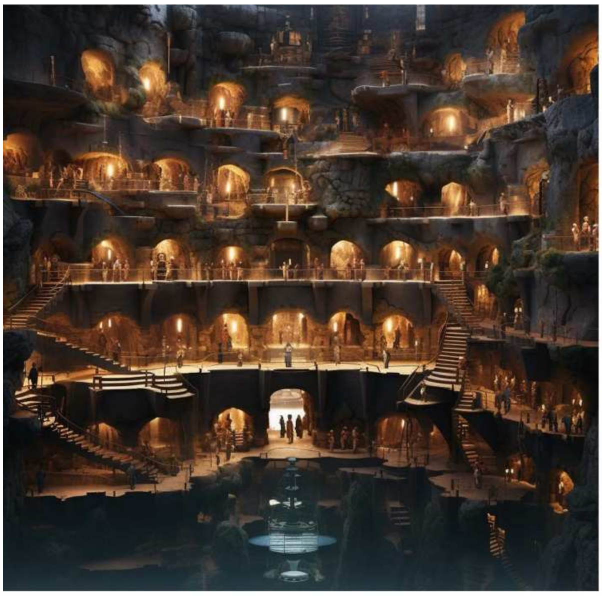
[8] The ancient city of Elengubu, known today as Derinkuyu burrows more than 85 m below the Earth's surface, encompassing 18 levels of tunnels. The largest excavated underground city in the world.



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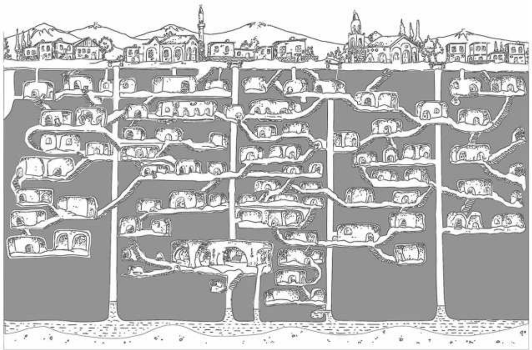

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Figure 6: Derinkuyu generated with AI according to the real images and drawings **Figure 7:** Actual drawing of Derinkuyu (Jacobs, 2022) **Figure 8:** Images Of Derinkuyu generated with AI

To sum up, the connection between morphogenesis in nature and primitive architecture emphasizes how early civilizations possessed an instinctive awareness of the intricate processes that take place in the natural world and it highlights the remarkable synergy between human creativity and the inherent patterns of the organic world. Primitive architects constructed built environments that seamlessly blended with their surroundings and cultural contexts by observing and mimicking growth patterns, structural efficiency, and adaptive methods found in nature. This legacy still serves as a source of inspiration for contemporary architecture, which uses an understanding of morphogenetic principles to balance sustainability, aesthetics, and functional design. The interaction between natural morphogenesis and primitive architecture shows the close relationship between human creativity and the biological environment, leading to structures that harmonize with their surroundings.

1.1.3 Gaudinian Parametricism

To comprehend and mimic nature, humans have always tried. Some people saw biological forms and shapes as ornaments and decorations appealing to the eye, others used the interpretations of its symbols as the philosophical, figurative, or spiritual underpinnings of their practice. But none of it came close to actually creating forms by learning from nature because we've heard these words for the last decades; "Form follows function[9]" and "A house is a machine to live in[10]" form-finding process that stays away from nature. With industrialization coming into our lives, we 'grew apart' from nature and centered on the ideas of machines,

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[9] The phrase was coined by the architect Louis H. Sullivan in 1896 in an article titled The Tall Office Building Artistically Considered, though he later attributed the core idea to the Roman architect, engineer, and author Marcus Vitruvius Pollio, who first asserted in his book "De Architectura" that a structure must exhibit the three qualities of firmitas, utilitas, venustas—that is, it must be solid, useful, and beautiful. Sullivan actually wrote "form ever follows function," but the simpler and less emphatic phrase is more widely remembered.

[10] Refers to the famous quote stated in 1927, 'The house is a machine for living in.' by Le Corbusier.

technology and anything artificial would ‘function better’. In the end, we were convinced that advanced machines were the ultimate solution to everyday modern problems until we started to see the results of the massive damage they made on our Earth. Although architecture in the last century was massively affected by the idea of industrialization, some designers chose to use the tools and knowledge of the technology they were offering, yet they were following the principles of nature. The results were exquisite architectural designs inspired by natural elements while functioning in the most efficient and sustainable ways thus they were the pioneers of something far more advanced in their times. One of these genius minds was the Catalan architect Antoni Gaudi.

At a period when the terms ecology and sustainability did not even exist, Gaudi was the first environmental and ecological architect. He was the first to use nature's immediate inspiration for architecture and design in a way that went beyond its purely formal applications, which is something that architects and designers occasionally do. His outstanding forms were not just aimed at the aesthetic and organic beauty of nature but also aimed at the utilization of minimum necessary material and energy costs in construction just like nature itself. Real and profound bio-learning of nature is concealed behind the forms of his architecture. Gaudi was working with scaled models made of chains or weighted strings which are called *“catenary arches[11]”* which enabled him to explore endless iterations of organic forms. This process is similar to today’s one of the most trending styles; parametric architecture. Today, by changing any parameter we can update the whole drawing set or three-dimensional digital model with parametric architecture, however, Gaudi accomplished this without any computationally aided software or computer, but with

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[11] The Catenary arch was Gaudi’s own construction system. He made string models, hung them from the ceiling, tied sandbags to them to determine their weight concerning the actual construction, and then took pictures of them. The most structural and effective building structure was revealed when the model's photograph was turned on its side. As the catenary arch is the most consistent with the natural function of structures, only engineers who use mathematics and physical science in the construction of bridges, and railway stations as well as Catalan masons who use centuries of tradition and common experience, have attempted it. With their resemblance to parabolas, catenary arches, along with the corresponding vaults of ruled geometry and resulting inclined pillars, follow the natural line of thrust of the loading. As in nature, they generate the ideal structural work in buildings usingleast amount of material and the least amount of energy.

his catenary arches. Therefore describing his style as *“Gaudinian Parametricism[12]”* wouldn't be wrong in fact, the spectacular organic continuity he achieved with this method is currently reflecting on digital organicism, which was established as the first vanguard of the twenty-first century before evolving into biodigital architecture. In his masterpiece La Sagrada Familia, he used three-dimensional forms composed of ruled surfaces such as hyperboloids, parabolas, helicoids, spirals, and conoids which have a direct correspondence with math.

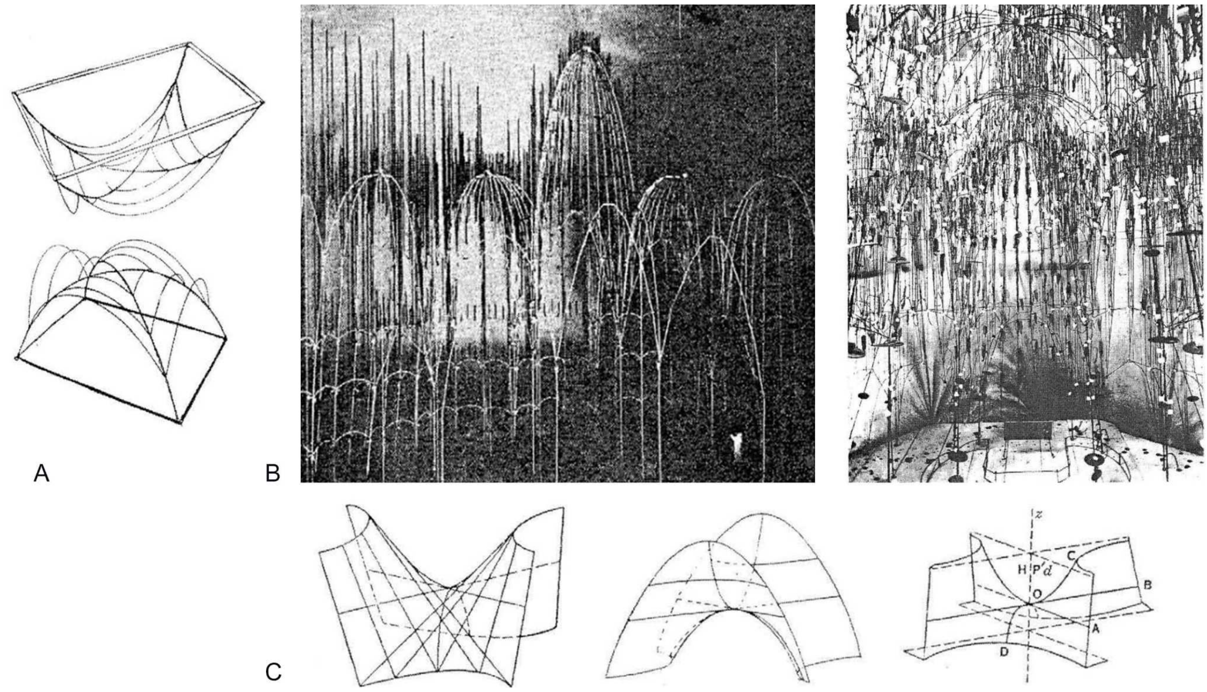

Figure 9: Gaudinian Parametricism. A; hanging model of a gothic cross vaul. B; hanging models Gaudi made for Colonia Güell. C; hyperbolic paraboloid surfaces seen in Gaudi’s works (Huerta, 2006)

Gaudi´s conceptual understanding and the continuous organic work as its result which appeared to be generated by a coherent system that reflects on all parts of the whole, led him to physical recomputation[13], in today's terms ´grasshopper´. His

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[12] Gaudinian Parametricism is a term referred to by the author as a result of Gaudí's use of advanced mathematical techniques, including hyperbolic geometry, is echoed in parametric design, which heavily relies on mathematical algorithms to generate complex architectural forms. However, Gaudí's architecture was developed in the late 19th and early 20th centuries, well before the advent of computer-aided design tools and parametric modeling software. Therefore, any direct influence such as the term *‘Gaudinian Parametricism’* is more a retrospective consideration rather than a direct historical connection.

[13] Physical recomputation refers to a concept in computing and information theory where physical processes, often in the form of physical systems or materials, are used to perform computational

morphogenetic complexity and certain geometries in a harmonious symphony were actually naturally inherited one because even though he didn't know the existence of computational design he had an amazing teacher; nature. Because nature and the entire universe are written in mathematical language, as Galileo Galilei suspected. There are growing patterns in nature, and there are transitions in nature which are all explained by morphogenetic processes.

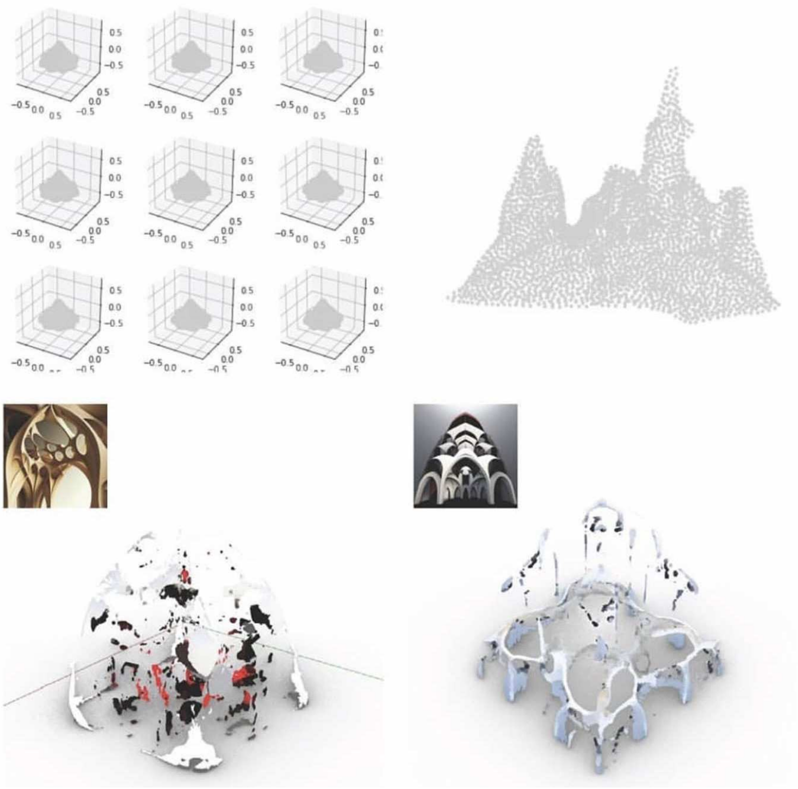

Figure 10: Scans & Point cloud models of Sagrada Familia (Lorenzo-Eiroa, 2023)

1.1.4 Mathematical Language of The Universe

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tasks. Unlike traditional digital computers that rely on electronic circuits and binary logic gates, physical recomputation explores the use of physical phenomena and processes to perform calculations and process information.

Mathematics offers a precise and universal framework for articulating patterns, relationships, and phenomena, hence it is frequently used to describe and understand nature and the cosmos. Plant growth, arrangement of leaves, and fractal patterns found in mountain ranges are one of many features of the natural world that may be described and predicted using mathematical equations. The relation of the Golden Ratio with harmony and aesthetics has given it historical relevance in art and design. It's essential to recognize that its use has varied throughout many cultures and time periods and has been a question of artistic preference rather than a rigid guideline. Some see it as having inherent beauty and balance, while others see it as merely one example among many in the enormous field of artistic expression.

The golden ratio[14] , a mathematical constant seen in nature, art, and architecture, is most closely resembled by the ratio of two successive Fibonacci numbers[15]. The golden ratio was the rule of aesthetics in art. In the natural world, the Golden Ratio is commonly observed, including in tree branches and sunflower spirals. Greek mathematicians and architects like Pythagoras and Euclid are thought to have used the Golden Ratio in their geometric studies and architectural masterpieces. It is claimed to have had an impact on the dimensions of facades, windows, and the interiors of famous buildings like the Parthenon in Athens. However, in a more modern case, Le Corbusier's architecture from the 20th century is one of the notable examples. Moreover, the Golden Ratio was accepted by Renaissance painters and architects like Leonardo da Vinci, Michelangelo, and Albrecht Dürer in their creations. For instance, the Vitruvian Man by Leonardo is frequently used as an illustration of how the Golden Ratio affects human proportions. The Golden Ratio has been utilized to set focal point placement and canvas proportions in sculpture and art. The ratio is frequently used by artists as a guide for object placement within compositions to achieve harmony and balance.

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[14] The golden ratio, also known as the divine proportion, golden mean, or golden section, is a number often encountered when taking the ratios of distances in simple geometric figures such as pentagons, pentagram, decagon, and dodecahedron.

[15] As the Fibonacci numbers get bigger, the ratio between each pair of numbers gets closer to 1.618033988749895. This number is called Phi. It can also be represented by the symbol Φ, the 21st letter of the Greek alphabet. Phi is the Golden Ratio.

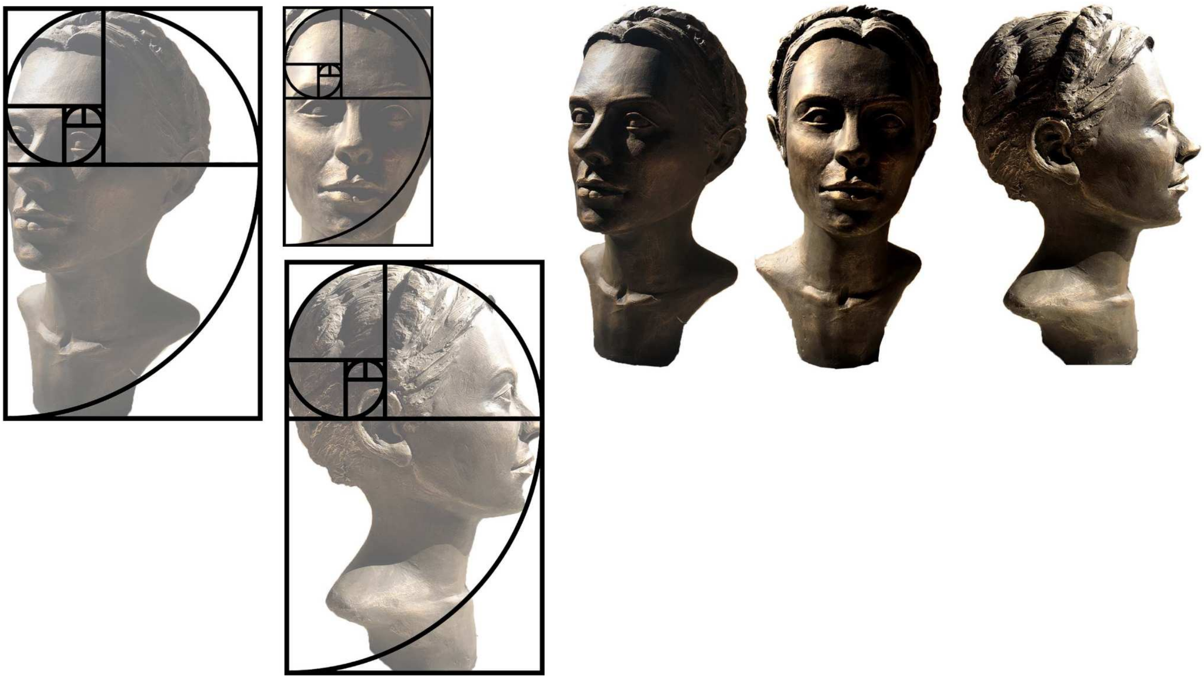

Figure 11: Sculpture Work *“Amara”* (2020) by Zeynep Çolak. On the left, artworks relate to the golden ratio, on the right the original sculpture is shown.

Another mathematical pattern, the Fibonacci sequence[16], that is also related to the forming of the golden ratio is found in various natural phenomena, such as the arrangement of leaves on plants or the spirals of a pinecone, flower petals, pineapple scales, shells, hurricanes and even in animal reproduction. That is to say in sunflowers, you may frequently count spirals that are successive Fibonacci numbers going both clockwise and counterclockwise. The number of spirals in one way of the pinecone scale patterns is a Fibonacci number, and the number of spirals in the other direction is the following number in the sequence as you progress along the patterns. Or chambers in shells, like those of the nautilus, are structured in a logarithmic spiral that can be approximated by Fibonacci numbers. Moreover, hurricanes and cyclones frequently have overall shapes and structures that resemble spirals with Fibonacci numbers. Most interestingly reproduction and population expansion in some animal groups can follow patterns resembling the Fibonacci sequence which relates Fibonacci to genetics and bio-digital architecture simultaneously. This reference guides us to one of the most important mathematics

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[16] The Fibonacci sequence is a series of numbers in which each number is the sum of the two that precede it. Starting at 0 and 1, the first 10 numbers of the sequence look like this: 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, and so on forever. Some say it’s the “nature’s secret code” as it's found in many places in nature.

and biology links as we want to understand more of the genetic code for organisms that are encoded in a molecular language that can be expressed mathematically by nucleotides (A, T, C, G). Researchers can better comprehend genetic mutations and inheritance using mathematical modeling. However, to explore more about genetics, fractal patterns in mathematics are a better fit as fractal-like patterns can be seen in many biological systems, such as the branching of blood vessels, neurological systems, and the circulatory system.

Figure 12: Object created with AI showing Fibonacci sequence in nature and giving reference to genetics and bio-digital architecture (by Z. Çolak)

Fractals are mathematical patterns that display self-similarity, or the property of having the same or similar structures at various scales and self-similarity in genetics can be seen in the DNA's hierarchical structure. Since genes are made up of nucleotide base pairs, which make up DNA molecules, chromosomes are a further division of genes. This hierarchical organization in genetic information shows a type of self-similarity. Therefore a genetic fractal can be used to describe the incredibly complex information that is encoded in DNA. Thus, genes contain shorter nucleotide sequences, which in turn contain codons and other repeating genetic motifs and DNA sequences exhibit repeating patterns at various scales. Moreover, genetic algorithms, a type of optimization technique inspired by the principles of natural selection and genetics, can be used to optimize fractal structures in various applications, such as antenna design or complex network layouts. The intricate, self-similar patterns seen in genetic information and the mathematical concepts of fractals are fascinating linkages and similarities, even though genetics and fractals are two separate areas. These links shed light on the complex and effective mechanisms by which biological systems transmit genetic information, store genetic information, and adapt to their surroundings. One of those popular fractals is known as the Mandelbrot set[17] , which is generated using a simple iterative equation and exhibits intricate complex patterns.

To sum up, the actual external world can ultimately be understood only in terms of precise mathematics. Everything around us in various scales, from the trunk of a tree to our blood vessels and DNA can be explored through the lens of mathematics.

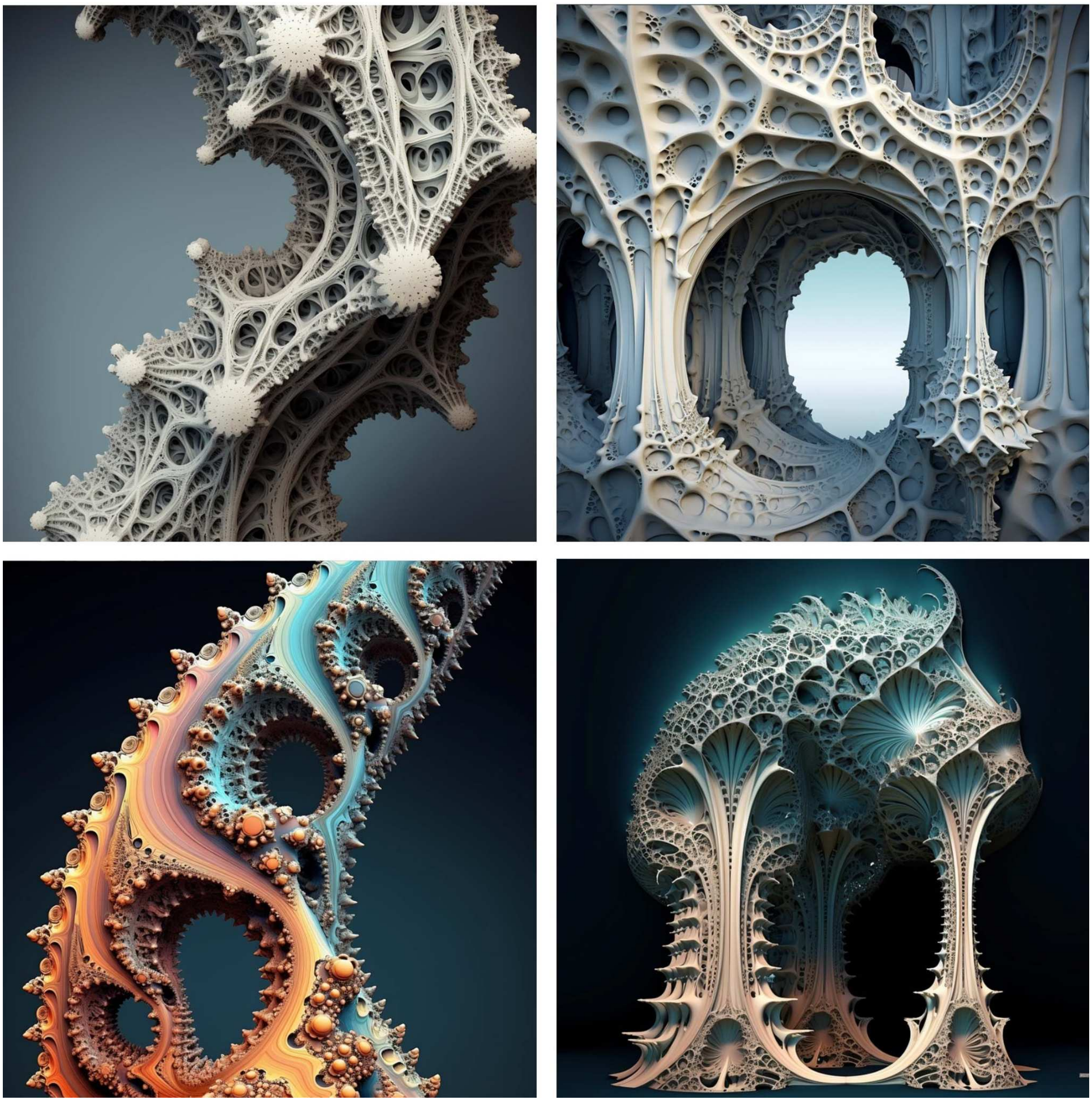

Figure 13: Architectural column designed with Mandelbrot set in AI, showing complex fractals (by Z. Çolak)

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[17] The Mandelbrot set is a two-dimensional set with a relatively simple definition that exhibits great complexity, especially as it is magnified. It is popular for its aesthetic appeal and fractal structures. And it is generated by iteration.

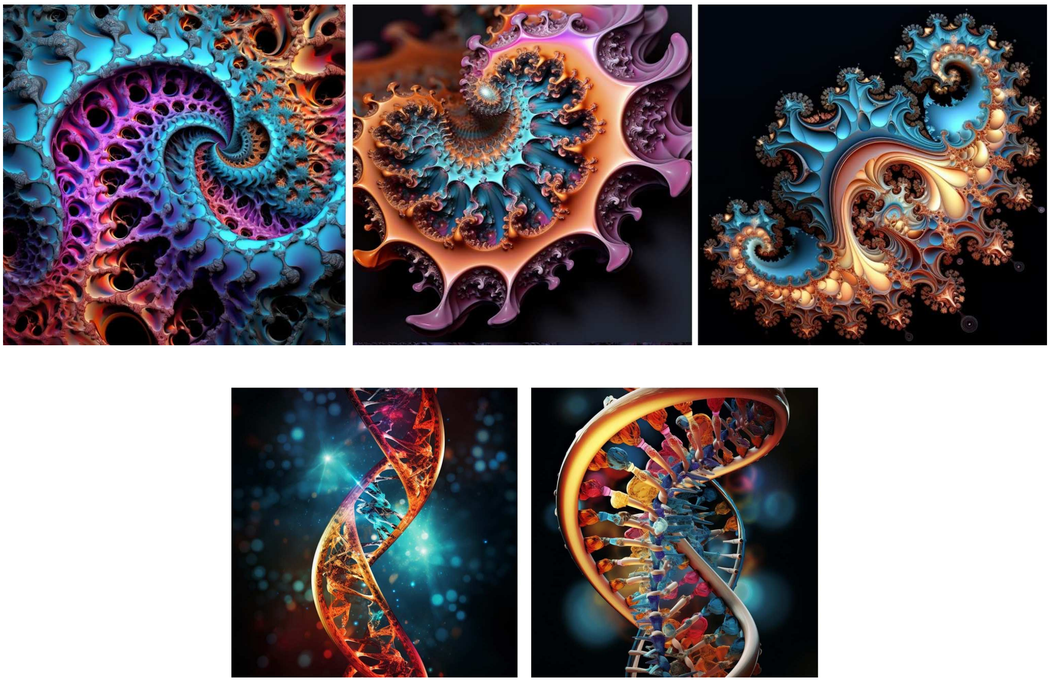

Figure 14: (Above) Images created an object made with a Mandelbrot set. (Below) Images showing the fractals in DNA. Both are made with AI to show complex fractals. (by Z. Çolak)

1.1.5 Artisans of Nature

Art has assisted in the advancement of architectural investigations and offers numerous potential routes for progress away from the passive and mute massing of the present built environment to more active, responsive, atmospheric, and responsible practice. Artisans have derived inspiration from nature and incorporated natural forms, patterns, and structures into their works of art. Moreover, they have employed mathematical concepts to create harmonious compositions, achieve balanced proportions, and capture the organic forms and patterns found in the natural world. Their experimentations with biomorphic forms and motifs prompted cross-disciplinary exchange. For instance, sculpture-making has frequently been compared to the mathematical language of nature, with artists applying mathematical ideas to guide their designs and produce aesthetically beautiful and harmonious sculptures. Various artistic movements, such as Surrealism, Art Nouveau, and Abstract Expressionism, embraced biomorphic elements in their works. Many great names such as Salvador Dali, Joan Miro, and Jean Arp incorporated organic shapes, fluid lines, and imaginative forms that later influenced biomorphic design. However, even before that artisans were using the potential in nature and exploring it with depth.

Leonardo Da Vinci studied the mathematical laws of nature in great detail and used them in his works based on geometric shapes and the Golden ratio. Drawings and diagrams from his notebooks show his intense interest in the mathematical laws guiding nature. Leonardo's scientific studies and artistic works were influenced by his detailed observations of plant growth, water flow patterns, and human anatomy serve as examples of how he has applied mathematics to both art and science. Similarly M.C. Escher's piece "Metamorphosis II[18]" demonstrates his interest in mathematical transformations by showing a continuous transformation of shapes. Closer to our day, Helaman Ferguson, a Mathematician and sculptor made intricate sculptures using mathematical concepts like fractals and minimal surfaces[19]. His sculptures, which are frequently formed of materials like stone and bronze, visually depict complex mathematical equations and natural formations.

These artisans show how the use of the mathematical language of nature may enhance artistic expression and foster a closer bond between art, mathematics, and the natural world. They paved the way for architects and designers to integrate similar principles into their creations. Their creations serve as examples of the elegance and beauty that result from the fusion of artistic imagination and mathematical concepts. However, the most crucial aspect of this was being interested in genetics and getting inspiration from it in the case of Bio Digital design to develop afterward. Therefore the closest art movement to Bio Digital design was Surrealism, which aimed to convey the workings of the subconscious. It was distinguished by strange imagery and the juxtaposition of seemingly unrelated subjects. The master of it, Salvador Dali created a vision, “Dalinian Dream (Estévez,

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[18] Metamorphosis II is a woodcut print by the Dutch artist M. C. Escher. In it, he depicts the transition of the small town of Atrani via geometrically rigid patterns into a freestanding figure (Metamorphosis I, II, III | Museum Escher in the Palace, n.d.).

[19] A typical Helaman sculpture has layers of titles, ranging from a colloquial expression such as "eightfold way" at the top to precise mathematical symbols and syntax such as x 3 y + y 3 z + z 3 x = 0 deeper down (Ferguson, H. & Ferguson, C. 1999).

2021)" and it was known for its ability to blend reality with the subconscious, creating fantastical and imaginative compositions that evoke the mysteries of the natural world. His works didn't just inspire architecture, in fact, the surrealist creative process itself became a course of action for architecture and design, which are formed with biological and/or digital tools and which can be developed today thanks to current cutting-edge technology. This reconstruction in an emerging architecture with such alien features is made possible by the surreal metamorphosis and this relates genetics to Dalinian discourse.

Dali was fascinated by genetics from the start and included it in some of his works such as "Galatea of the Spheres[20]". Portrait of his wife, Gala, is composed of spherical shapes that give it a three-dimensional texture that is almost cellular. A sense of life and vitality is evoked by the usage of spheres and how they are arranged, which alludes to the organic structure of cells and molecules. It reflects Dali's curiosity about the underlying patterns and enigmas of nature, which also extends to the study of genetics and atomic particles, and mathematics. His unique fusion of surrealism and scientific inspiration created a distinctive and captivating body of artwork that intrigued and inspired BioDigital Architecture.

Figure 15: *"Galatea Of The Spheres"* by Salvador Dali. Today, this painting is located in Dalí's Theatre-Museum in Figueres. (Photo by Z. Çolak)

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[20] The oil artwork on canvas was created by Salvador Dalí in 1952 located in Dalí Theatre-Museum in Figueres, Spain. It is the outcome of a Dalí impassioned by science and for the theories of the disintegration of the atom. Gala's face is made up of a discontinuous, fragmented setting, densely populated by spheres, which on the axis of the canvas takes on a prodigious three-dimensional vision and perspective (*Galatea of the Spheres* | *Collection* | *Salvador Dalí Work* | *Fundació Gala - Salvador Dalí*, n.d.)

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1.2 MATERIAL BEHAVIOR IN NATURE

Nature showcases a diverse range of material behaviors, from elasticity to viscosity, and from conductivity to biodegradability. Material behavior in nature highlights how different substances adapt to their environments and serve specific functions. Each organism in the natural world has distinctive characteristics of its own. Their behavior, structure, form, pattern, and material all exhibit such characteristics. This varies not just from species to species, but also within a single species. In light of this, Art and architecture have always drawn inspiration from the material behavior of nature. Different structures and works of art have been impacted by the design, construction methods, and aesthetics of natural materials and their inherent characteristics. That brings us to the question: what does a brick want to be?[21]. Famous architect Louis Kahn used to advise his students to ask their material for counsel if they ever needed inspiration. The highlight of this topic is to seize the aspects of the material, analyze them, and find the most suitable function it can serve for and the form it is able to transform into. In architectural history, material behavior phenomenon has always shown itself.

The intricate stone tracery and ribbed vaults of Gothic cathedrals, such as Chartres Cathedral in France, were inspired by the branching patterns seen in trees and plants since the structural innovations in these cathedrals allowed for greater height and light penetration. Moreover, Gaudí's architecture is renowned for its organic forms and use of materials like ceramics and stone for cooling down and ventilation; such as his typical colorful “trencadís[22]” made with small ceramic tiles. Although other examples include using passive cooling systems inspired by termite mounds or designing energy-efficient facades based on the principles of photosynthesis in leaves, material behavior is more extended than an inspiration and with the advance,

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[21] You say to the brick, “What do you want, brick?” Brick says to you, “I like an arch.” If you say to the brick, “Arches are expensive and I can use a concrete lintel over an opening. What do you think of that, brick?” Brick says: “I like an arch.” (Louis Kahn, 1971)

[22] Trencadís is a Catalan term that literally means “chopped”. It is also the technique to make mosaics with irregular forms, generally with glazed ceramics, which you can decorate and cover flat and curved surfaces with, containing different dimensions. Park Güell and Casa Batlló are some of the places to see the application of it. Throughout the park you’ll find the distinctive art form of Trencadís-covered spheres, columns, and buildings too.

technology offers a sea full of possibilities today. Such advances in materials science have led to the development of smart materials that respond to environmental conditions. These materials, inspired by nature's adaptive behaviors, can change shape, color, or transparency. They are used in responsive facades and kinetic sculptures (Addington & Schodek, 2005).

The material behavior in nature is associated with its primary characteristic, *plasticity*[23] and it refers to the inherent flexibility, adaptability, and dynamic qualities found in the natural world. In essence, the plasticity of nature serves as a metaphorical and conceptual framework for architects and designers to approach material selection, structural design, sustainability, and aesthetics in a way that draws inspiration from the adaptability and beauty of the natural world. Plants exhibit plasticity in their growth patterns, adjusting their size, shape, and orientation of leaves and branches in response to variations in light, nutrients, and competition with neighboring plants. Also, many animals demonstrate plasticity through adaptive behaviors, such as changing their coloration or physiology to blend into their surroundings (camouflage) or altering their diet in response to food availability. Moreover, some species exhibit dramatic morphological changes during their life cycle. For example, certain insects undergo metamorphosis, transforming from larvae to adults with entirely different body structures.

However, nature is not alone in having plasticity characteristics; plastic language is a way of communication and a method for action and all fields of arts share it (Çolak, 2023). Like nature's use of diverse materials and forms for adaptation, artists experiment with a wide range of materials, from traditional paints and sculptures to digital media and unconventional materials, to express their artistic ideas. Thus, both nature and art can convey the concepts of change and impermanence. Artists may create artworks that evolve over time, decay, or interact with their environment, echoing the dynamic nature of the natural world. Plasticity in nature and art share common themes of adaptability, transformation, and creative expression. Artists often find inspiration in the malleability and resilience of the natural world, using

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[23] In its most enduring and generalized sense, plasticity refers to the capability of, or susceptibility to, being molded, shaped, modified, or otherwise changed. As such, the concept of plasticity has occupied important positions in theories of ontogenetic development, phylogenetic evolution, and neuronal development and adaptation, and psychological aging.”

these concepts to explore a wide range of artistic ideas and themes. This connection between nature's plasticity and artistic creativity highlights the profound influence of the natural world on human culture and artistic expression.

Although plasticity is a crucial part of the spectrum, the study of material behavior involves a broader spectrum of physical phenomena and properties that play a significant role in shaping the natural world and therefore, offers the best possibilities for us to learn from it. For instance, the bones in an animal's body are strong yet flexible, enabling mobility and support while rubber shows the resilience and adaptability of certain natural materials with its repeatable energy absorption and release process. In addition to these, complex material behaviors are exhibited by living organisms. Examples of biological materials responding to stimuli include plant stems bending toward light, muscles contracting and relaxing, and the extraordinary tensile strength of spider silk (El-Mahdy & Gabr, 2017). Some of these material behaviors of elements found in the natural world have been inspiring engineering solutions and architecture depending on the external and internal conditions. In other words, several natural materials show composite architectures with variable characteristics in different regions. Take into account the mechanical behavior of wood, which is influenced by the combination of strong fibers and a softer matrix.

For many scientific and engineering disciplines, such as geology, biology, physics, and materials science, it is essential to comprehend how materials behave in nature. It advances our knowledge of geological processes, the development of new materials, and the design of structures and technologies that interact harmoniously with the natural world. In the case of bio-digital architecture, this relation is even stronger; bio-digital architecture embraces the idea of adaptive design, where buildings and structures can respond to changing environmental conditions. This aligns with nature's plasticity, where organisms adapt to their surroundings. Also, bio-digital architecture often integrates innovative materials, including biodegradable or bioresponsive materials, echoing nature's use of materials optimized for specific functions. For instance, buildings might incorporate living materials that can grow or self-repair over time, similar to how some organisms adapt and heal. Therefore biodigital architecture embraces plasticity and creates buildings that evolve, respond, and thrive in changing environments, much like the natural world.

1.3 BIO-LEARNING

In the previous chapters, many examples were analyzed through different fields and from various artists and designers in which a real and deep nature-learning was seen in the forms and shapes of their works. However, to conduct a broader and more precise analysis, biolearning and nature learning should be described and should be perceived more deeply. Although they are related, there are distinct concepts within the context of architecture and design. Nature learning encompasses a broader range of natural phenomena and systems and involves studying not only living organisms and biology but also ecological systems, climate patterns, geological processes, and more. Therefore, nature learning often involves interdisciplinary approaches, bringing together knowledge from various scientific fields such as biology, ecology, geology, and meteorology to understand the holistic functioning of the natural world. Thus, nature learning provides design inspiration by observing and abstracting patterns, forms, and processes found in the natural environment. The examples that were covered in the last chapters showed how architects and designers used these inspirations to inform their creations, drawing on the beauty, efficiency, and functionality of natural systems. In these cases, it is seen that natural learning has always been present in architectural history, although it may not always have been explicitly recognized as such. This is the result of drawing inspiration from natural forms and mimicking them (biomimicry), environmental adaptation to local climate and conditions, integrating biophilic design principles to recognize the psychological and physiological benefits, and emphasizing sustainability by using locally sourced materials and construction techniques that minimize environmental impact. Although nature learning was one of the primal inspirations and teachers in the past, architects and designers can now look into the future more deeply with the advanced tools they have access to today, and bio-learning can take the lead.

Bio-learning specifically centers on living organisms, biology, genetics, and biotechnology. It delves deeply into the study of life processes, adaptation, and the potential integration of biological principles into design. Therefore it also often involves the exploration of biotechnological advancements and the potential use of living organisms, cells, or biological materials in architectural or design solutions that can include biofabrication, bioluminescence, or bio-responsive systems. Bio-learning also aims to integrate biological elements into design in a way that blurs the line between the living and built environments. It explores how buildings can incorporate living systems for functions such as air purification, energy generation, or even structural support. Moreover, bio-learning encourages innovation by pushing the boundaries of what can be achieved through biotechnology and genetic engineering. It explores the creation of novel materials and systems inspired by, or directly derived from, biology. Lastly, biolearning aligns with the concept of regenerative design, where buildings and urban environments are designed to enhance ecosystems and promote biodiversity which makes his approach increasingly valued in the face of ecological crises.

Overall, while nature learning has a broader scope and focuses on drawing inspiration from the natural world, bio-learning narrows its focus to living organisms and explores the integration of biological elements into design. However, for both cases, biomorphism is an important step, although today's biomorphism is more concerned with methods than with forms. Therefore the final stage of biomorphic architecture is connected to genetic architectures, which directly use genetics to design and construct structures that can support habitable living organisms. Because, it should be remembered that both nature learning and bio-learning approaches share a commitment to sustainability, adaptation, interdisciplinary collaboration, and the appreciation of nature's aesthetics and functionality in design. Biodigital architecture, which combines digital technologies, biology, and ecological principles, is a field that relies heavily on biolearning. It seeks to create buildings that are not only sustainable but also capable of actively interacting with and benefiting the natural environment by applying genetics, which offers great potential to art and architecture. Because in the biological world, if we treat DNA like biological software, and in the digital world if we treat software like digital DNA (Estévez, 2021). This is because DNA and software are both natural or manufactured chains of information that generate self-organizing, autonomous development, process, and emergency orders for the emergence of structure, form, and skin. In the end, designers end up with a digital DNA that is self-designing and self-producing. However, the architecture of DNA has an unusual organization known in mathematics as a fractal. Therefore we require a comprehension of fractal structures, which is currently possible thanks to machine learning.

II. MACHINE LEARNING

The Design process and architectural conception have been significantly changed by computers. With the emergence of computers and the integration of digital technologies, a revolution was born in the way architects and designers conceive, develop, visualize, and communicate their ideas. We started to be able to create and manipulate digital representations, drawings, and calculations to become more accurate and precise, the way physical models and prototypes were created changed with digital fabrication tools, and most importantly, the generative design was born. Today, designers have access to tools they never had before; we are in a place where we can automatically update the complete model or drawing set based on small changes in any parameters to enable a flexible design thanks to advanced technology and computers making it easier to create designs through versioning and gradual adjustment. It is similar to the way that *biodiversity* is created by natural mutations. This access leads us to the idea that "software is a tool for the mind" (Estévez, 2021) in the conception of the design, in other words, the main idea behind *machine learning*. Therefore, the challenge now starts with finding the most suitable form that fulfills particular input constraints has come into focus.

According to D´arcy Thompson “..the form of an object is a ´diagram of forces´..” (Thompson, 1945) and formation was the result of physical laws operating according to predictable mathematical patterns. He additionally addressed growth and form concerning the study of organisms. His controversial Theory of Transformations attempted to show the mathematical relationships between related species by 'transforming' them into one another through basic distortions. All of these references come from one ultimate source, nature. Before machines and digital culture, the most complex designs were created by nature.

Today, the heart of digital culture is complexity. The paradigm shift is mostly related to complexity, namely the possibilities that computers provide for the concept, visualization, and management of extraordinarily complex geometries that would otherwise be unthinkable and unsolvable. With the use of generative design, parametric modeling, and artificial intelligence (AI), complex designs can now be produced using computational tools and algorithms. For a variety of applications, including architecture, engineering, and materials science, machines may construct complex architectural forms, optimize structural designs, and replicate natural processes. Computers have also made it possible to calculate incredibly complicated systems of loads and computerized robots can now control the positioning and assembly of the customized structural elements. In other words, the development of successively more complex architectural arrangements is made possible by procedural, parametric, and generative computer-supported approaches combined with mass customization and automated fabrication.

In that sense, digital fabrication became a more established discipline day by day as we observe today's architecture. Digital fabrication carries the possibilities of a new aesthetic. Even though digital fabrication is still at the beginning of the architecture practice, it has the power to take over the imagination and creativity of us designers and architects. There are two main paradigms throughout almost every industry; one paradigm is what can you design, what can you compute or analyze and the other paradigm is what can you physically construct or what can you build. Today, there is a process of creating an object with computer-aided programs, taking it from *virtual design*, sending it through 3D printing, and making it a *physical object*. Therefore there is the potential for architecture also to move more fluidly between design and construction. Foundations of design, construction, and material fabrication might need to be completely rethought if we’re to go beyond bricks and mortar to engage the challenges of the next century. The future of manufacturing is sophisticated algorithms and modeling that link directly to sophisticated manufacturing machines and they allow both new efficiencies and new possibilities in new formal complexities.

What came out as a result of the software becoming tools for the mind is that architects and engineers don’t have to create the end product. They design the process; the process to achieve the form, the process to create a system for functioning, and the process to take the virtual design and transform it into the physical world by fabricating it. Because an algorithmic way of thinking is necessary for generative design therefore designers create algorithms or sets of rules that specify the design parameters and restrictions rather than manually creating the final design. These algorithms then automatically produce a variety of design possibilities. However, generative design often involves collaboration between designers, engineers, and software developers. In summary, generative design has transformed the design process by emphasizing algorithmic thinking, exploration, and optimization. Designers now view the design process as an ongoing exploration of possibilities within defined parameters, fostering creativity and innovation while also improving efficiency and performance. This shift aligns with the broader trend of using computational tools and data-driven insights to inform design decisions in various fields, from architecture to product design to engineering.

Considering all of these today, nature still continues to provide very clever and complicated designs that are frequently challenging for computers or human-designed systems to fully mimic. The main factor that shouldn’t be forgotten is that nature has created complex and highly efficient designs at a variety of scales, from the molecular level to ecosystems, over the course of billions of years. Examples include the organization of DNA, tree branching patterns, and bird wing aerodynamics so it is difficult to replicate the efficiency, adaptability, and sustainability that nature's designs frequently display with man-made systems but not impossible with the advanced technology and the tools we have today. Advancements in technology and AI continue to push the boundaries of what is possible in design and engineering. Researchers and designers are constantly exploring the interface between nature-inspired design and computational tools to create innovative and sustainable solutions.

2.1 Digital Avant-Garde

In art history, the avant-garde was originally ‘fully oppositional type’ and it uniquely focused on the category of art and aesthetic form while creating a relation between culture and society. However, like every other field, the digitalization era has affected it too. The digital age has been inviting artists to explore/advocate new ideas, new forms, and new aesthetics so when the digital avant-garde arrived after it, it also brought new aesthetics and new tectonics together. In today’s terms, "digital avant-garde" denotes a modern and cutting-edge method of artistic expression and creativity that is influenced and facilitated by digital technologies. The digital avant-garde aims to push the limits of conventional artistic forms and question norms, much as the traditional avant-garde movements that first appeared in the early 20th century. But it achieves this through making use of digital tools, platforms, and software.

The power of digital avant-garde and its effect on modern architecture and computational design, can not be overlooked. Exploration of new mediums, embracing new technological advancements, dynamic and evolving creations, and offering an interdisciplinary approach are just a few of the aspects of that and helped to form bio digital architecture after. The new mediums created by digital technology, such as digital art, computer-generated imagery (CGI), interactive installations, and generative algorithms, are explored and experimented with by digital avant-garde artists. The most recent technical developments are frequently embraced by digital avant-garde artists and incorporated into their creative processes. Utilizing advanced software, programming languages, data visualization tools, and cutting-edge hardware like 3D printers. Digital artworks have the potential to be fluid and ever-evolving, enabling dynamic creations that react to real-time data, user input, or environmental factors. Lastly, the boundaries between many artistic disciplines are regularly blurred by the digital avant-garde, which combines elements of visual art, sound, design, animation, and even coding to offer multifaceted and immersive experiences.

Examples of the digital avant-garde can be found in a variety of fields, such as digital art installations in galleries, immersing virtual reality experiences that place users in new worlds, and generative art that investigates the relationship between algorithms and creativity. It's crucial to highlight that as technology advances and artists discover new ways to express themselves artistically using digital tools, the idea of the digital avant-garde keeps evolving. Today, artists are using artificial intelligence and machine learning algorithms to create art and writers use algorithms to generate poetry and literature. The work of Alison Parrish, who creates poetry using Python code, is a fascinating example (Allison Parrish: Recent and Selected Work, n.d.) Even the internet itself has turned out to be a canvas for avant-garde artists.

Moreover, the designers are using digital tools to create avant-garde fashion designs that exist primarily in virtual spaces. Brands like The Fabricant create digital-only clothing and experiences (*Deep / The Fabricant*, n.d.). Other than this, musicians and sound artists experiment with algorithms and code to generate unique and unconventional music. What can affect architecture deeply is the fact that artists and designers are exploring immersive technologies like VR and AR to create new forms of storytelling and interactive experiences. And they use data to create visually stunning and thought-provoking works. All of these examples are the result of using algorithms and code to create anything that evolves and changes over time.

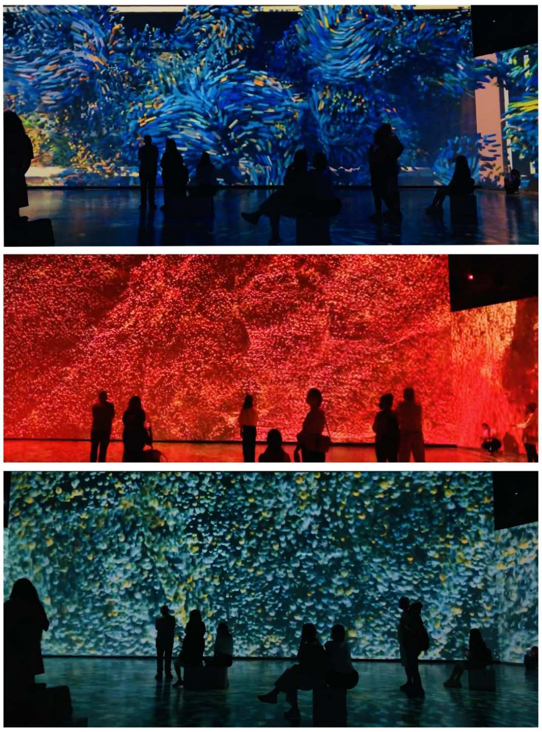

Figure 16: Parallel Universe AI Exhibition by Refik Anadol in Istanbul, 2021 (Photos by Z. Çolak)

Digital avant-garde has the potential to significantly impact architecture and design today and in the future by introducing innovative approaches and pushing the boundaries of what's possible. Digital avant-garde techniques, such as parametric design, allow architects and designers to create complex, dynamic, and adaptive forms. This can lead to more efficient use of materials and resources in construction, as well as the ability to design structures that respond to environmental conditions. Virtual reality (VR) and augmented reality (AR) technologies enable architects and designers to create immersive experiences that allow clients and users to explore designs in a more tangible way. Refik Anadol, a new media artist, integrates media arts with architecture using data and artificial intelligence for paintings, sculptures, and other types of public art. Images from two different exhibitions of his showcase different aspects of digital avant-garde; figure 16 shows the exhibition in Istanbul, 2021 in a gallery projected on the walls, floors, and ceilings. The artworks created a sequence of experiences and formed the architectural spaces around the person by becoming the architectural elements. However, the figure 17 is from the “Living Architecture” projected on the facade of Casa Batlló, even though it didn't form the spaces in this case, creating a sequence of experiences was still valid, and the fact that the artwork has become the architectural element. In light of these aspects, architecture can evolve in huge amounts for instance; collection and analysis of data from building sensors can inform design decisions, leading to more user-centric and responsive spaces and smart buildings can adjust lighting, temperature, and other factors based on user behavior.

As a result, digital avant-garde techniques can seamlessly integrate art and architecture, blurring the lines between the two disciplines. This can result in buildings that are not only functional but also works of art. Innovations such as AI-driven design assistants, advanced robotics in construction, and biologically inspired design principles are likely to reshape the field. Additionally, as technology continues to evolve, architects and designers will have access to more powerful tools for creativity and problem-solving, allowing them to address complex challenges in new and exciting ways.

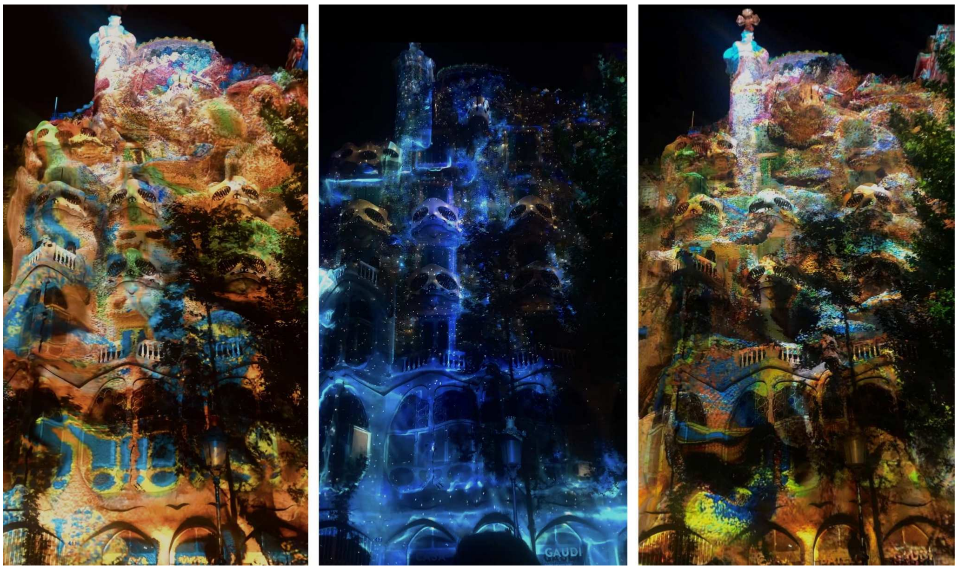

Figure 17: “Living Architecture” by Refik Anadol, Barcelona 5th May, 2023 (Photos by Z. Çolak)

2.2 Generative Design & Open Forms

Computational design harnesses the power of computers and advanced algorithms to transform the design process across various fields, offering a range of benefits and possibilities. Complex Geometry and Forms, optimization, generative design, rapid prototyping and 3D printing, innovation and discovery, and sustainability. With the aid of computational design, architects, and designers can produce extremely intricate and complex forms that would be difficult or impossible to produce by hand. This comprises objects with complex patterns, freeform surfaces, and irregular shapes. Secondly, algorithms in computational design can optimize designs for a variety of factors, including cost, material utilization, structural integrity, and energy efficiency, resulting in more effective and long-lasting solutions. Similarly by lowering resource consumption, minimizing waste, and increasing energy efficiency, computational design techniques can assist in optimizing designs for sustainability. Also, computational design is frequently combined with manufacturing and fabrication technologies such as CNC machining and 3D printers. This makes it possible to quickly produce tangible prototypes and models, which makes testing and evaluation easier. Lastly, based on input parameters and limitations, generative algorithms can automatically generate a variety of design possibilities. This makes it possible to explore design options quickly, which often leads to novel and unusual solutions. Another aspect of it is that it enables experimentation and research, which frequently results in the identification of innovative design ideas and imaginative possibilities. In essence, computational design enables creative minds in a variety of fields, including architecture, engineering, and design, to push the boundaries of what is possible. It provides effectiveness, accuracy, innovation, and sustainability, paving the way for future design solutions that are both functional and aesthetically appealing. We live in a very rare time in history where the merging of several fields including computational designs gives us access to tools we had never before. One of the most important things that came with the advancements in computational design is generative design[24].

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[24] Generative design is a form of artificial intelligence (AI) that takes an engineering challenge that you define and presents a wide range of appropriate solutions to choose from, which you can then refine according to your needs. Instead of trying to keep constraints and parameters in mind while drafting a

Generative design algorithms can analyze and replicate natural forms and processes. Architects can draw inspiration from biological structures, such as tree branches, coral reefs, or seashells, to create organic and biomorphic architectural designs that blend seamlessly with the natural environment. It can optimize material usage by generating complex structures that minimize waste and maximize structural integrity as well. And help design energy-efficient buildings by optimizing factors like orientation, shape, and shading which can align with sustainable architecture principles. In bio-digital architecture, generative design can be coupled with bio-fabrication techniques to create structures made of living materials. These structures can grow and adapt over time, offering unique opportunities for sustainable, regenerative architecture. Generative design can take user preferences and needs into account, enabling architects to create spaces that are tailored to the occupants' comfort, well-being, and productivity. Generative design enables architects to work with complex geometries and parametric models that were previously challenging to design and construct. This allows for intricate, visually stunning architectural forms.

One of the most trending styles for generative approach today is *parametric design* which offers an endless sea full of possibilities for architects who are seeking new forms by using generative algorithms. The biggest opportunity is the designs that seem impossible to draw manually are now becoming possible to construct. Digital technologies have become more than representational tools, they are the keys to finding new forms (Kolarevic, 2004). At the end of the day, end product forms are not designed by architects; architects design the process of the generative form and this process can be designed again and again endlessly. With parametric architecture a fluid and adaptive design methodology is born with basic design principles; folding, twisting, subtracting, intersecting, etc. It gave the opportunity to work with a single continuous surface rather than different parts and assembling. A single surface is taken and differentiated; the idea of having a continuous variation where situations morph and modulate to the other almost seamlessly. We are afraid of monotony but this style that came with digital avant-garde and methodology to achieve new tectonics have so much internal variety and richness nearly like the endless forms of

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product, part, or tool, designers tell the software what the limits and possibilities are for the end-use criteria they’ve identified.

nature where we could have both sense of unity, navigability, and order as well as the variety and differentiation we need. Overall, generative design is a powerful tool that aligns perfectly with the principles of bio-digital architecture. It allows architects to create structures that are not only inspired by nature but also optimized for sustainability, functionality, and aesthetic appeal. As technology continues to advance, the potential of generative design in bio-digital architecture is likely to expand even further, offering new avenues for innovative, eco-friendly architectural solutions.

On the other hand, the concept of *open form*[25] is the outcome of creating encoded designs, in which geometry is parametrically defined and codified in a non-material language rather than being imposed upon materiality, such as drawings or physical models, as is typical of architectural design tradition. Since it is material, a closed form (such as those found in traditional designs) must obviously belong to a metric space and be defined geometrically. Alternatively, an open form (as a parametric or algorithmic design) is defined topologically; as a result, it is not contained in a metric space but, to some extent, inhabits a topological space. Topology is a branch of mathematics that studies the characteristics of objects that are retained after deformations. In addition, it is ultimately not about particular forms but rather about connections and relations within a given geographical context. Therefore while some architects base their spatial study on non-Euclidean geometries[26], while others base it on Topology. The usage of digital modeling software has created new formal exploration areas in architecture where digitally generated forms are not created according to conventional approaches. In reality, new shapes and forms are produced via generative processes based on concepts like topological space, dynamic systems, parametric design, and genetic algorithms, as demonstrated with a case study in the following chapters (Spanish dancer). However, open form in design also implies that the architecture is adaptable and responsive to changing

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[25] A closed form (as found in a conventional design) is defined geometrically and necessarily belongs to a metric space because it is material. On the contrary, an open form (as a parametric or algorithmic design) is defined topologically, it is not contained in a metric space –instead, and to a certain extent, it inhabits a topological space-. Because it is a conceptual design it is not formalized into matter, rather it is a logical construct defined by a code, a non material language. (Marcos, 2011)

[26] Non-Euclidean geometry is the study of geometry on surfaces which are not flat. Because the surface is curved, there are no straight lines in the traditional sense.

needs, both for the occupants and the environment. It often involves designs that can evolve over time or allow for multiple functions within a single space. Open form can be closely related to parametric design principles, which emphasize flexibility and adaptability and often incorporate generative algorithms to create spaces that can respond to various conditions as discussed before.

The concept of architectural complexity is defined as the ratio of design decisions to construction decisions and in today’s terms, the introduction of digital tools, including generative design software, parametric modeling, and open forms as their result allows for *complexity*. Complexity in architecture can manifest both functionally and aesthetically. Functionally, it might involve intricate structural systems, energy-efficient designs, or responsive building elements. Aesthetically, architects may pursue complex, visually striking forms and facades. Although complexity is now more attainable, it should be an effect of site conditions, program complexity, and cultural sophistication, rather than the primary goal. This refers to the discussion in the design world about how some designs are criticized for only looking complex without a function or aim behind it, resulting in *‘arbitrariness’.* However, it should be remembered that there is nothing arbitrary in nature, yet nature already has complexity and it always gets our fascination and curiosity in nature because of it. Because in human perception, the less arbitrary something is, the simpler it is. But in the design world, even the most bold alleged arbitrariness is led by the emotional intelligence of the concept. Therefore the discussion evolves to embrace complexity and just add contradiction if we want to add more depth and fascination to designs.

The discussion of this chapter is how the relationship between generative design, complexity in architecture, and open form in design today is a dynamic and evolving one that reflects the changing landscape of architectural practice. The result is generative design, open form in design, and complexity in architecture are interrelated aspects of contemporary architectural practice. Digital tools and computational approaches have empowered architects to explore and create complex, adaptable, and user-centric designs that respond to evolving needs, sustainability goals, and technological advancements. This relationship continues to shape the future of architecture, enabling architects to push the boundaries of what is possible in terms of form and function.

2.3 Envisioning Future With AI - A New Skin For The City

New technologies don't just help architects with the design process but also it helps them to analyze current situations that are going on all over the world, identify the challenges and trends, and help them to envision how the world is going to turn out in the future and design according to it. This feature became so much easier to access with the emergence of AI. Especially when we are talking about Bio-Digital architects, AI tools are the *philosopher's stone*[27]. Therefore in this chapter, a case project is explained; envisioning the future of the world with AI. The project involves considering the potential impact of artificial intelligence on various aspects of society, technology, economy, and culture. By utilizing AI's ability to develop cutting-edge solutions and address emerging challenges, designers may play a significant part in shaping this future.

The basic challenges that morphed the final result can be split into two categories: environmental-related and people-related. The first category had air, water, and land pollution which will increase as we precipitate based on today's data, the increasing temperature but also C02 and other greenhouse gasses emissions. The second category had people-related problems such as overpopulation of the urban centers, but also psychological problems that are ever-increasing in the society such as burnout, anxiety, depression, and a decrease in socialization needs and skills. Moreover, we imagine that in 2048 technology will be much more immersive and will make people invest even more from their time in front of a screen. Social media will play a more important role in their lives instead of in-person interaction which will lead to higher numbers of self-isolated and agoraphobic people. Besides the challenges, the trends that made our scenario possible include bioreactors with algae, bioluminescence, and *going back to the origins*[28].

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[27] Philosopher's Stone is a mythical substance supposed to change any metal into gold or silver and, according to some, to cure all diseases and prolong life indefinitely. Its discovery was the supreme object of alchemy.

[28] The author refers to the famous quote by Antoni Gaudi: “The creation continues incessantly through the media of man. But man does not create...he discovers. Those who look for the laws of Nature as a support for their new works collaborate with the creator. Copiers do not collaborate. Because of this, originality consists in returning to the origin.” (*Antoni Gaudí Quotes (Author of Gaudi X Gaudi)*, n.d.)

The main proposal for the future of Barcelona is dividing the building structurally and introducing a new skin. Introducing a new skin refers to covering the building's facade with an innovative, biomorphic, and responsive outer layer. This "skin" can serve multiple purposes, including providing thermal insulation, regulating natural light, generating energy, and enhancing the building's aesthetic appeal. The idea was inspired by Gaudi's other quote and the initial idea behind his project Casa Mila.

Figure 18: Model of the curtain wall, *©Fundació Catalunya La Pedrera.*

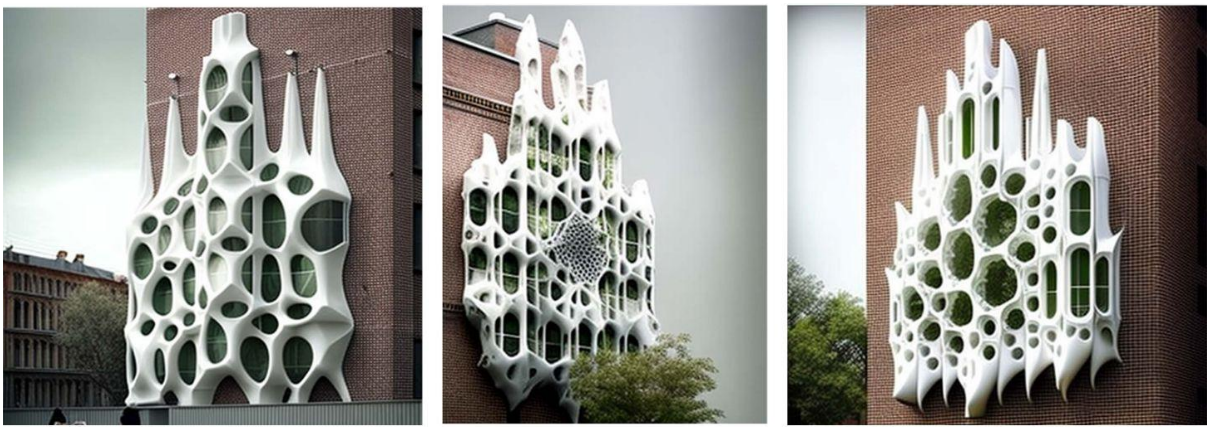

Figure 19: First proposals for the skin, refers to the famous quote by Antoni Gaudi[29] (Çolak, Z. & Curiel, I. & Stamatiadi, M., 2023)

In the further steps of the proposal, the skin evolved to an element which is more biomorphic and something to *grow* and not just attach*.* The iterations generated by AI gave the idea of the skin as a blend of BioDigital architecture as the trend of the future and Art Nouveau (Catalan Modernism) style as the common trend that is seen

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[29] "Buildings need to have a double roof, just like people have a hat and a parasol" (*Architecture Casa Mila* | *Gaudi's Building Barcelona*, 2023)

on the facades of Barcelona buildings today. Therefore the skin idea tries to evolve through the existing elements rather than building from scratch to keep the construction levels in control. Moreover, the new skin for buildings will be covered with algae, in order to purify the air, but also be effective without demolishing the already built environment and in that way revitalize the buildings of the city (fig.20). Our vision is that the buildings are organisms that you live in and must take care of you. So by putting algae on them they can both purify the air we breathe but also gather other valuable micronutrients and give them to the residents. The system is designed for growing photoautotrophic organisms using artificial light sources or solar light to facilitate photosynthesis. PBRs are typically used to cultivate microalgae, cyanobacteria, macroalgae, and some mosses[30].

Figure 20: Diagram and application of skin with algae (Çolak, Z.&Curiel, I.&Stamatiadi, M., 2023)

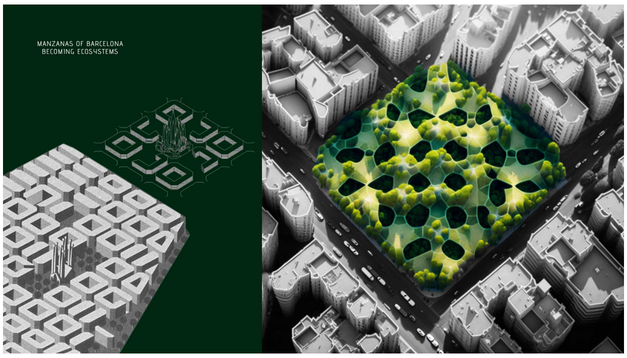

Figure 21: The manzanas after the skin growth

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[30] Panellus Stipticus: Produces light by the action of enzymes called luciferase. They attract insects with the bioluminescence to spread spores and therefore they help species to survive. GFP (Green Fluorescent Protein): Exists in jellyfish Aequorea victoria, a protein called aequorin releases blue light upon binding with calcium. This blue light is then totally absorbed by the GFP, which in turn gives off the green light.

Figure 22: Growth of algae (Çolak, Z. & Curiel, I. & Stamatiadi, M., 2023)

Therefore in our proposal we took that into account and offered to work on how we can enhance the walking experience in Barcelona without changing the building arrangement. The main idea behind this is that everything will cooperate and communicate with the environment that is both inside it and outside it, so the city works like one whole entity. As Aristotle said “The whole is greater than the sum of the parts” (Halimi et al., 2020). And when the skin of the buildings grows, they will cover the manzanas (clusters) of Barcelona and create their own ecosystem like an island (fig.21).

As for the immersive technology the main goal was to make the city interactive enough so it can compete with how interactive personal devices will be by then. Therefore the proposal was a *self-guided city*. To achieve it the bioluminescent proteins that can be found both in some algae and jellyfish species, can be used as guides on the road and the buildings. We imagined daily life that in order to go to the metro residents of the city would follow the green-colored algae, to go to the nearest square the residents would follow the blue-colored algae, and so on. The proposal relies on the method to use fewer phones as a GPS, to force city users to look around and make the city interactive and easier to walk around.

Skin of the buildings grow along the streets to guide pedestrians to social spaces, open views, transportation nodes.

As the skin of the buildings grow, streets start to create a new skin through the city with railroad worm to illuminate the city and guide its residents.

Figure 23: Poster showing the idea ‘self-guiding city’ (Çolak, Z. & Curiel, I. & Stamatiadi, M., 2023)

The result is a city reconnecting the people of Barcelona with their fauna and flora Giving them an ecosystem. A time in the future that nature never goes obsolete. One of the primary motivations for dividing a building structurally and introducing a new skin is to enhance sustainability by improving energy efficiency and reducing the building's environmental footprint and not constructing from zero and saving land. Thus, Dividing the building into modular components makes it more adaptable to changing needs and conditions. It will seamlessly integrate with the natural environment by blending harmoniously with the surroundings, fostering a connection between the building and nature. Introducing the new skins with bio-digital architecture embodies principles of sustainability, adaptability, aesthetics, and functionality.

Figure 24: Barcelona at night, covered with algae (Çolak, Z. & Curiel, I. & Stamatiadi, M., 2023)

III. BIO-DIGITAL ARCHITECTURE

In the rapidly evolving landscape of architecture, the fusion of biology and digital technology has given rise to an innovative and transformative concept known as Bio Digital Architecture. This paradigm shift challenges conventional notions of design, construction, and sustainability by harmonizing the principles of nature with cutting-edge computational tools. With its potential to revolutionize the built environment, Bio Digital Architecture represents a fascinating intersection of organic systems and advanced technology. At its core, Bio Digital Architecture seeks inspiration from biological systems to create structures that mimic the efficiency, adaptability, and resilience found in nature. This approach involves the utilization of computational algorithms to simulate the growth patterns of living organisms, translating them into architectural forms. The result of this synergy between biology and digital precision is a design language that blurs the boundaries between the natural and the artificial, yielding structures that seamlessly integrate with their surroundings, the creation of highly customized, structurally efficient, and aesthetically captivating architectural marvels.

This fusion as the most recent trend in the design world emerged from the intersection point of several fields; science, technology, and design. If we get deeper into it we can see biology, digital technologies, and architecture in it, and if we even go further, math arts and engineering come along. That is to say, Bio-Digital architecture is an interdisciplinary field, born from a collaboration. Even though the fields of architecture and biology have some similarities like both of them dealing with entities operating in context and employing computational models, there are also significant differences in their objectives, epistemologies, knowledge bases, methods, discourse, and institutional structures that make communication and collaboration challenging. What they share in common and both of their strengths in today's circumstances is digital tools and technology and they come together in this new emerging field that will dominate the design world in the future. Despite their contrasts and challenges, a collaboration between biologists and architects is essential to guide design toward ecologically friendly outcomes. Thus, biologists working with architects is not just a one-way benefit, both fields can affect and improve each other in many contexts. Firstly, architectural designers can benefit from a better understanding of biological morphogenesis because they frequently attempt to solve problems that nature has already solved. Secondly, they increasingly seek to incorporate ideas and methods that have equivalents in nature, such as growth or adaptation. Lastly, they share a common language in that they both try to model growth and adaptation. However, in the opposite direction, research in biology can benefit from architecture and engineering because organisms' components grow and specialize in response to environmental factors like static and dynamic loads. Thus, architecture and engineering have developed computational tools for evaluating and simulating complex physical performances; however, such tools are as of yet unusual in biology. Most importantly, computational modeling is becoming an increasingly important tool for studying such influences in both biology and architecture. Therefore, this thesis makes the case that biology can provide instances of growth systems capable of inspiring more adaptable, dynamic, and interconnected organizations of automated and hybrid generative architectural workflows.

The most striking application of BioDigital Architecture is in the realm of sustainability. By emulating the energy-efficient processes of ecosystems, architects and designers can develop buildings that respond intelligently to environmental stimuli like reducing energy consumption, improving air quality, and reducing carbon footprint.

3.1 BIO DIGITAL REALM

3.1.1 Interdisciplinary Design

Interdisciplinary design is a method that incorporates collaboration and the synthesis of knowledge and experience from multiple fields in order to address complex design problems. It acknowledges that many modern issues and possibilities require insights and skills from a variety of professions. As it combines ideas and elements from biology, digital technology, and architecture to produce creative and sustainable solutions, bio-digital architecture is a prime example of interdisciplinary design. However, other collaborations emerge in addition to these in the bio-digital architecture field. That is to say, collaboration among professionals from many disciplines, such as biologists, ecologists, engineers, and digital designers, is common in bio-digital architecture. The design solutions are informed and comprehensive thanks to the collaborative approach, which takes into account both biological and technological factors.

Biodigital architecture merges principles of biology with architectural design. In order to inform the design of structures and spaces, it takes inspiration from natural systems and processes, including biomimicry. This interdisciplinary approach allows architects to create buildings that are more sustainable, efficient, and in harmony with the natural environment. In addition to that, digital technologies and computational design techniques are strongly included in bio-digital architecture. For modeling, simulating, and analyzing biological and ecological concepts, architects use cutting-edge software and algorithms. These digital tools give architects the ability to explore complex geometries, improve building efficiency, and produce generative design solutions. In some cases, biotechnology, such as living materials or bioengineered systems, may be incorporated into the design of bio-digital architecture in specific circumstances. This fusion of living things or biological processes gives a special dimension to architectural design and calls for knowledge from both biology and architecture.

Another key component to bio-digital architecture is environmental sustainability. This is also related to giving value to adaptability and innovation which are both important for sustainability and also concepts that biodigital architecture embraces deeply. Architects can design structures that are energy-efficient, responsive to environmental factors, and equipped with natural ventilation and cooling by incorporating biological concepts into the design process for sustainability. Thus, they can create buildings that adapt to changing environmental circumstances, maximize resource use, and encourage sustainability by taking lessons from natural systems. These interdisciplinary approaches address pressing issues related to climate change and resource conservation and promote experimentation and ongoing learning. While these principles form the main structure of the design trend, bio-digital architecture also successfully integrates aesthetics and functionality. Designers are inspired by the beauty of nature, but they also incorporate practical biological ideas, such as responsive facades. Lastly, the user experience is taken into account in the interdisciplinary design of bio-digital architecture. It tries to design environments that support ecological and biological principles while simultaneously improving human comfort and well-being.

In conclusion, bio-digital architecture is a prime example of the effectiveness and promise of interdisciplinary design. It blends biology, digital technology, and architecture to provide aesthetically pleasing, sustainably built environments. By taking inspiration from the natural world and utilizing the possibilities of digital technology, this strategy offers solutions to important global issues like climate change and resource depletion.

3.1.2 Emergence of Math and Digital Morphogenesis

When we talk about biodigital design we also come across the word *morphogenesis*. In the modern design world, computers simplify the generation of design through versioning and gradual alteration by automating some steps of the design process. These methods of designing have been referred to as "morphogenesis" in current architectural discourse. This thesis predicts that, as a result of the increased use of parametric modeling, digital fabrication technologies, and mass customization, complex, non-uniform structures will become more common in architecture. There are no direct precedents in architecture for the new opportunities and challenges that the design of such structures presents. However, there are examples of this kind of adaptation in nature, where structurally complex living organisms have existed for millions of years. This research compares the formation of cellular structures in biology and architecture to find methods of architectural design that can broaden architects' range of imaginative possibilities.

In the field of architecture, morphogenesis—also known as "digital morphogenesis"—is a collection of techniques that use digital media not as representational tools for visualization but rather as generative tools for the emergence of form and its transformation, frequently with the goal of expressing contextual processes in built form (Roudavski, 2009). According to this broad description, digital morphogenesis in architecture is largely analogous to or metaphorical for the processes of morphogenesis in nature, sharing their reliance on gradual progression but not always adopting or referring to their actual mechanisms of growth or adaptation. Recent discussions on digital morphogenesis in architecture relate it to emergence, self-organization, and form-finding, among other ideas. The potential for structural benefits from redundancy and differentiation as well as the capacity to support many simultaneous functions are among the advantages of biologically inspired forms, according to their advocates.

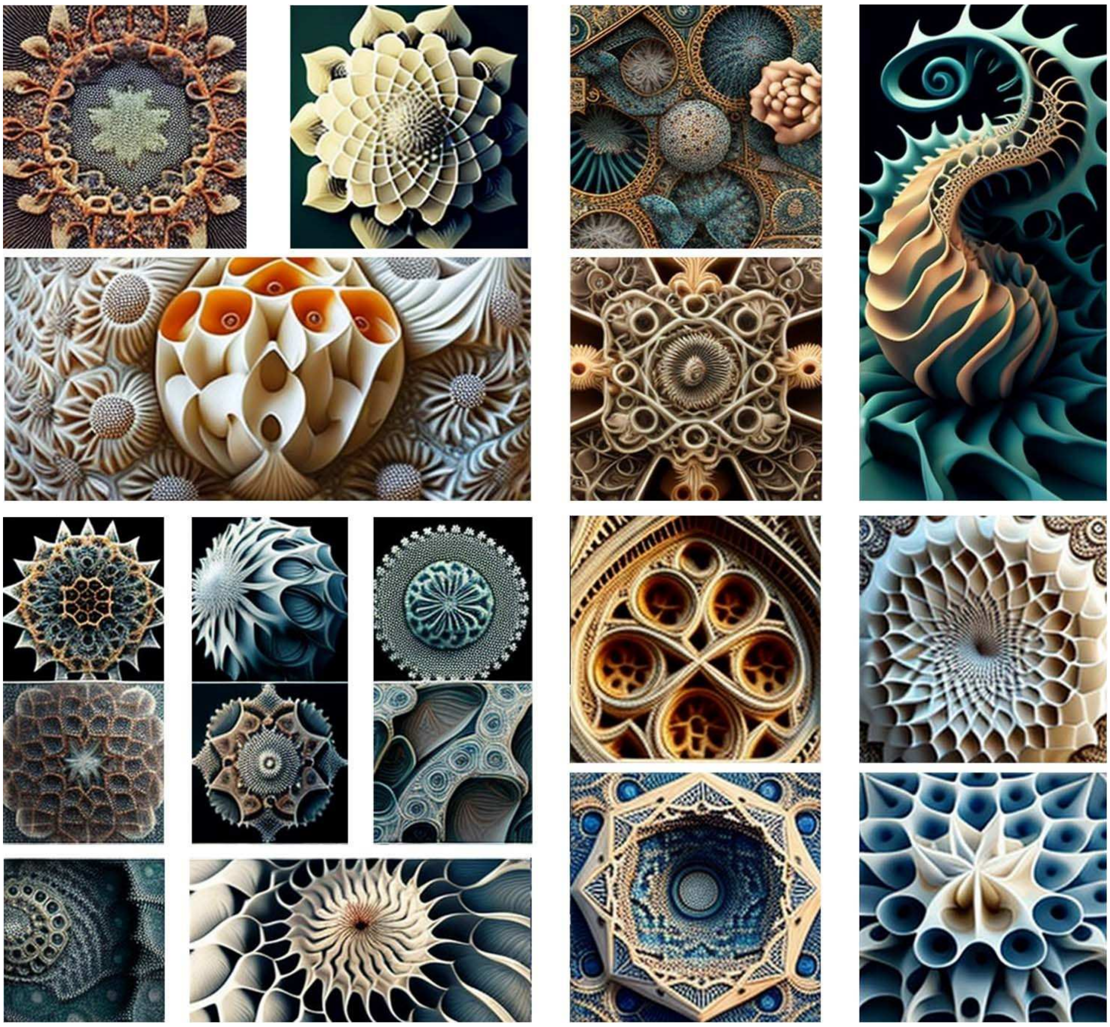

Figure 25: Mathematical patterns in nature reimagined with AI. (by Z. Çolak)

Figure 26: Mutations in cells reimagined with AI to design a pavilion. (by Z. Çolak)

Algorithm definition and subsequent digital reproduction occur in 3D modeling. A variety of software applications can determine an organism's morphogenesis in the digital environment, just as cell DNA (as a form of natural software) does in the natural world. As a result, computational algorithms that are also morphogenetic can be used to create digital designs for architectural projects. Digital morphogenesis is influenced by biology; it follows an optimization-based logic that can be strengthened by computation and it is extracted from nature.

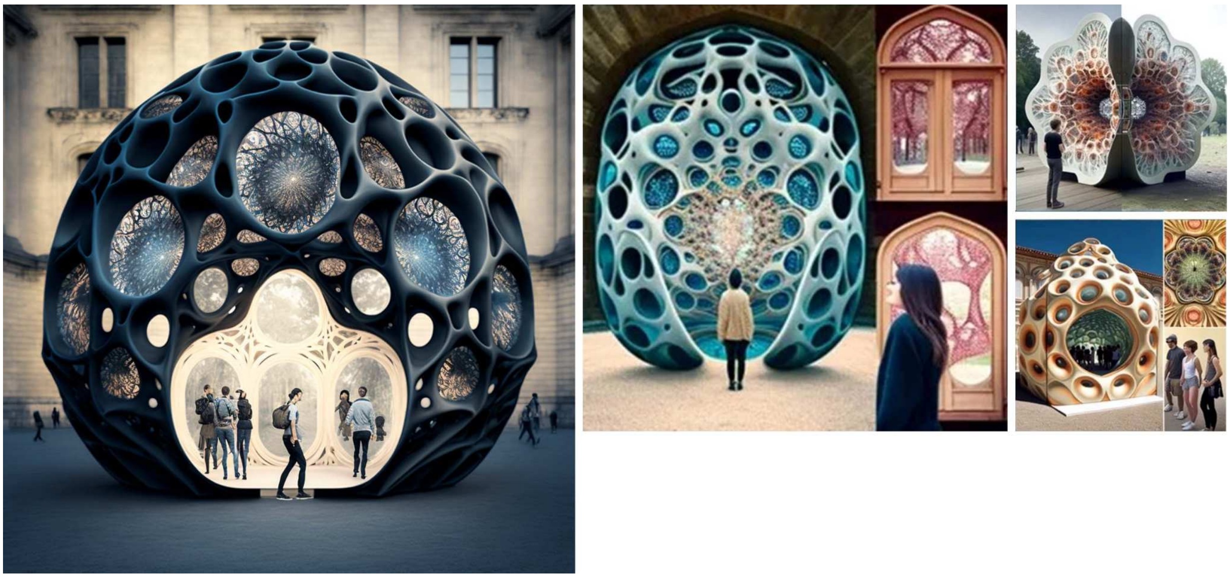

Figure 27: Mutations in cells inspire the design of a pavilion. (by Z. Çolak)

3.1.3 Craftsmanship Meets Digital Fabrication

Architecture is another field that demonstrates the harmonious coexistence of craftsmanship and digital fabrication. Modern architectural marvels frequently have complex facades and ornamentation, effortlessly blending traditional aesthetics with cutting-edge techniques. This fusion is best demonstrated by Antoni Gaudi's Sagrada Familia in Barcelona. A combination of artisanal craftsmanship and digital modeling was used to bring Gaudi's imaginative designs to life, making it possible to realize complex geometries and organic forms that would have been challenging to accomplish entirely by hand. As a result of this convergence, we are witnessing an innovation renaissance where the blending of human touch and cutting-edge technology prepares the way for a really exceptional period of superior design. While the construction of Sagrada Familia had been started before computational design and digital fabrication tools, Gaudí had already designed it at the intersection point of art, design, and math. Therefore, someone who looks at Sagrada Familia today will see the handcrafted, exquisite details and sculptures and computationally designed, digitally fabricated elements at the same time. After all, both Gaudí proponents of parametricism emphasize the integration of art and architecture, blurring the boundaries between the two disciplines. What makes Gaudi’s works so impeccable is the fact that he had a multidisciplinary design perspective, he could think like a sculpture artist and create those intricate details and making them look pleasing to the eye and telling a story with stone, concrete, and ceramics while he also thought like an architect by creating sensory spaces and he thought like an engineer by calculating the precise structural components and finding the most suitable solutions for construction. Therefore his works are one of a kind and so timeless because In order to become a fine architect, one should first become a painter and a sculpture artist first to learn the aesthetic principles of them and then become an architect (Çolak, 2021). Because thinking like a sculpture artist and like an architect and painter means mastering the *‘plastic language’* (see more in chapter 1.2). Plastic language is a way of communication and a method for action and all fields of arts share it, as well as *nature* itself.

Gaudí's designs often feature intricate, handcrafted details, while parametricism's digital tools allow for the precise customization of ornamentation. Biodigital Architecture can be crafted too, in fact, in a unique and technologically advanced manner. Craftsmanship can collaborate and integrate with digital fabrication in bio-digital architecture in several significant ways, allowing for the creation of innovative and highly detailed structures that combine the precision of digital technology with the human touch of skilled craftsmanship. As a result of the place we stand today where crafting can be so much more valuable with the lessons of the past generations and novel design tools. The main reason for that is, that even with the most advanced tools we have, there is still a value that crafting adds and it can't be replicated or put in the same place. As an architect and an artisan who specialized in sculpture, it is accurate to say, that craftsmanship brings an exquisite touch by emphasizing the importance of creating objects or spaces that resonate with people on a sensory and emotional level, moreover enhancing user experience and well-being which are some main aims of biodigital architecture.

Figure 28: A handmade object with clay, with texture applied (by Z. Çolak)

Craftsmen (artisans[31]) can collaborate with architects and digital designers from the early stages of a project. Since they are experts and very knowledgeable in traditional techniques and various materials, including wood, stone, metal, and ceramics, they can inform the design process, ensuring that digital models and plans align with the possibilities and limitations of craftsmanship. Thus, they can collaborate with digital fabricators to select the most appropriate materials for different parts of the building, taking into account factors like durability, sustainability, and aesthetic qualities. In bio-digital architecture, artisans and architects collaborate to choose materials that align with sustainable and bio-responsive principles that can include organic substances, recycled components, and innovative biomaterials.

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[31] Artisan is a person skilled in a utilitarian art, trade, or craft, especially one requiring manual skill. However, a great architect is both an artist and craftsman. Because while art is subjective, craftsmanship is not; therefore an artist's calling is to express, evoke and innovate.

Moreover, artisans can contribute to sustainability by promoting traditional and eco-friendly construction techniques. By combining their knowledge of sustainable practices with digital tools, they can achieve resource-efficient and environmentally responsible outcomes. Artisans also excel at creating intricate details and customized elements that can be challenging to achieve with digital fabrication alone. They can apply their expertise to customize various architectural elements like intricate joinery, sculptural elements on facades, or other decorative features. Whether it's hand-carving intricate designs, creating bespoke structural components, or crafting unique finishes, customization allows for a unique and artisanal touch in bio-digital architecture. As it is mentioned before, bio-digital architecture often integrates complex and organic forms inspired by nature, and artisans are able to bring these forms to life by also adding depth and character to the design.

Figure 29: Kaleidoscope Parasite (Çolak, Z. & Stamatiadi M. & Dharmadikari P., 2023)

The project ‘*parasite kaleidoscope*’, (fig.29) shows how craftsmanship and digital fabrication can merge. By manipulating the 3D printing process (fig.30), we achieved organic legs that seemed to be growing from their roots with the local material (the pebbles inside the pot, where the project is located to cover up the watering device). In order to do that, while the 3D printer was printing with the code we created for the legs, we started to add pebbles that were collected before from where the project would be located. Therefore while the printing process was still going on, we manipulated the process by adding materials manually by hand (fig.30). The result was mostly a success in that it functioned and looked organic and added a characteristic that a printer couldn’t do even if it was coded to do so.

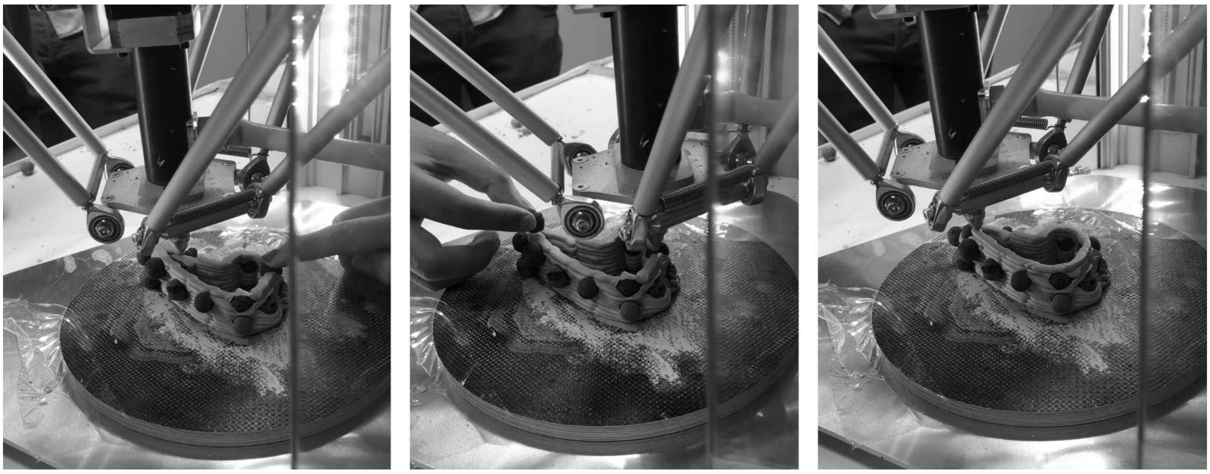

Figure 30: Manipulating the 3D printing (Çolak, Z. & Stamatiadi M. & Dharmadikari P., 2023)

In the ever-evolving landscape of design and production, the convergence of craftsmanship and digital fabrication represents a remarkable union between tradition and innovation. This innovative collaboration breaks through the limitations of both time and technique to produce ground-breaking improvements in creativity, effectiveness, and aesthetics. A new era of boundless possibilities marked by the seamless synthesis of human skill and machine precision emerges as artisans embrace digital tools and technologies. Craftsmanship, which is rooted in centuries of tradition and expertise, has long been admired for its precise attention to detail and the distinctive character it provides to each creation. Because craftsmanship is tactile, it enhances the quality and authenticity of items by bringing a human touch to them. On the other hand, digital fabrication promises unmatched precision, speed, and the ability to turn complex designs into physical reality. These two forces work together to create a revolutionary synergy that transforms design in a variety of fields. In essence, craftsmanship in bio-digital architecture involves a holistic approach that combines the best of both traditional artisanal skills and cutting-edge digital technologies. This integration not only results in visually stunning and functional structures but also pays homage to cultural heritage and promotes sustainable, bio-responsive design principles.

3.2 BIO-DIGITAL SKYSCRAPER

The Spanish Dancer project is a fusion of nature learning and machine learning, carrying the aspects of art aesthetics, structural support of mathematical precision, and system functionality of organisms. It is composed of computational design and digital fabrication and explores the possibilities of a new avant-garde architecture while answering the environmental challenges we are facing today.

As the last decades passed, the Earth started to face climate change which comes for all of us. As designers, our duty is to take humanity to a new era of a built environment not causing global warming but fighting with it, and the way to achieve that comes from changing our design perspectives and paradigms. We've been hearing the words “A house is a machine to live in” for decades but these words came out in the industrial era therefore today we need a new inspiration. Men went through so much starting from simply surviving by gathering fruits, learning from hunting and harvesting to fast fabricating , living in nests, temples, and skyscrapers, and riding from horses, cars, and planes. Eventually, we lost the balance and surrendered to the industrial age therefore in order to create the balance again we need to remember where we came from, the basics, nature and the living. After all, a genius Catalan architect once said “Originality means going back to the origin” and he was right. Nature has always been the ultimate teacher for mankind, everything we learned we learned by looking at the depths of nature so our houses can't be machines to live in but *a house can be an organism to live in*.

3.2.1 Bio-Learning & Employing AI in Form Finding

The project's development incorporates computer-supported design methods currently under active discussion in architecture while also implementing a cellular structure that resembles those found in biology, which can help to illustrate the comparison between interpretations of morphogenesis in biology and architecture. Spanish Dancer is a project that is deeply rooted in nature and bio learning[32] and machine learning in order to process, analyze, and create a solution to the current design problems. As the first step of every design problem, site conditions must be analyzed and a system should be designed to answer the challenges in Barceloneta Beach where the project is located. The first thing to consider was the fact that the coastal location means that the skyscraper will be subject to strong winds, saltwater exposure, and occasional storms therefore building materials and design should be chosen to withstand these conditions. In addition, Barcelona places a strong emphasis on sustainability, so incorporating green building practices, energy-efficient design, and renewable energy sources into the skyscraper's design to align with the city's sustainability goals was crucial. Thus, given the coastal location and the potential for rising sea levels and climate change impacts, the skyscraper had to be designed to be resilient against flooding and other environmental challenges. Considering these conditions, I turned to nature and looked for inspirations from systems of living organisms and forms (fig.31). Main inspirations were skeletons, in particular exoskeletons for resilience and elasticity for adaptability and translucency for functionality like openness and ventilation. The final inspirations that were chosen were *glass sponges, spanish dancer*[33]*,* and *jellyfish.*

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[32] Nature learning refers to the process of studying and gaining insights from the natural world as a whole. This includes observing natural systems, patterns, processes, and phenomena in the environment. It encompasses a broad range of aspects, such as the study of natural forms, ecosystems, climate, geological processes, and biodiversity. Bio-learning, on the other hand, narrows its focus specifically to the study of living organisms and their biological processes. It emphasizes the examination of living systems, organisms, and their adaptability. Bio learning often involves the study of biology, genetics, and biotechnology to gain insights into how biological processes can be harnessed in design (more on chapter 1.3)

[33] “The Spanish dancer acquired its exotic name from its startling appearance and graceful movement.” (Downer 2002:12)

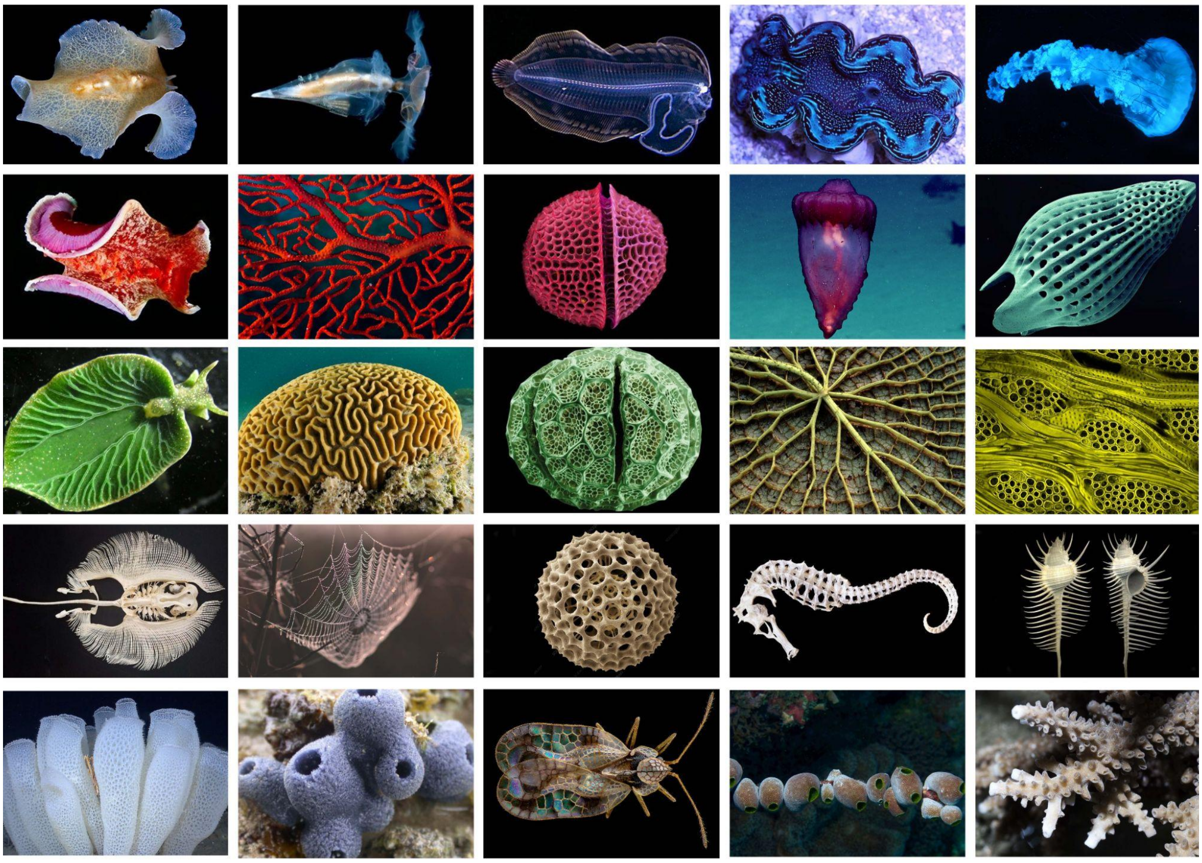

Figure 31: 25 Images from nature that inspired the Biodigital Skyscraper.

Glass sponges which are also referred to as “the Venus' flower basket” are permanently fixed to the bottom of a deep ocean. Their cylindrical skeletons are composed of silica, Silica, the same substance used to produce glass. The silica is organized as spicules, which are concentric layers, and the spicules are organized into a square lattice that resembles a tube. The main frame is made up of two distinct but overlapping lattices, and because these lattices can still move in relation to one another, the skeleton can be flexible as it develops. Struts that run vertically, horizontally, and diagonally support the lattice's squares. The lattices are further supported by these struts, which are formed of bundles of spicules and resist bending, sliding, and twisting stresses. Being produced with layered internal structures that make them naturally tough but flexible which is not very commonly assumed about skeletons. Glass sponge with its strong yet flexible characteristic inspires building construction with a highly effective and strong skeleton for the building with less energy and optimum material. Spanish Dancer on the other hand, is a kind of flatworm and it has a hydrostatic exoskeleton which is composed of layers of muscles. Similar to the condition of a glass sponge, which is composed of multiple layers of skeleton. However, because it lacks bones, it can move in a very flexible manner. It does this by twisting its body and creating propulsion through the wave-like movement of its wing-like mantle. It also propels itself forward with its flat, flexible foot by repeatedly contracting its muscles. This flexible movement is inspiring to be used in the skyscraper as it varies its elasticity yet having an exoskeleton, it can create a good condition for ventilation in Barcelona’s humid and hot weather. Lastly, jellyfish have bells that contain fluid and circular muscles rather than a skeleton made up of bones. Specifically, deep sea jellyfish are bioluminescent like most of the deep sea creatures. Using bioluminescence helps them to achieve both defensive and offensive strategies. So why can’t our buildings do the same chemical reactions and take care of the organisms inside, in other words, its residents?

What is seen commonly in these three creatures is the fact that none of them contains bones yet they have their own skeleton works in distinct functions. While some of them work to give strength like the skeletons do as we are familiar with, they also give elasticity and flexibility. This is similar to what we see in construction sites today, it is established that a building must contain a steel skeleton, concrete cover, and glass to give translucency because it's the only way for it to be strong enough. Considering these the first initial ideas in sketches are shown in fig.32. And the concepts inspired by the ideas are exoskeletons composed of layers, elasticity, and translucency.

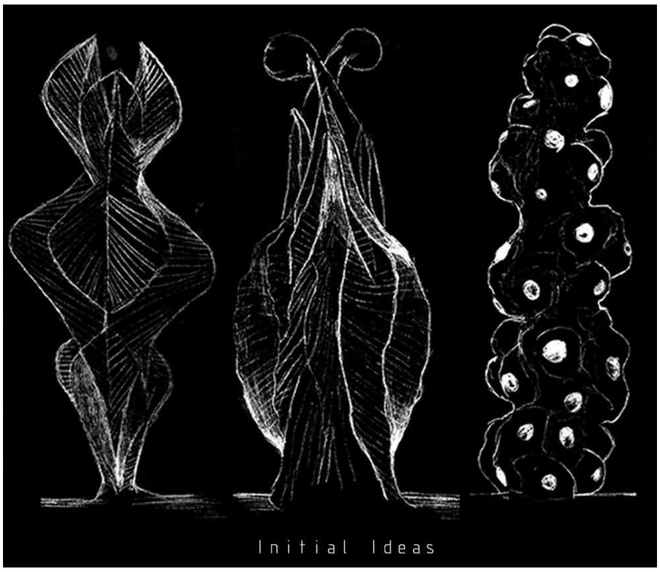

Figure 32: Initial ideas as sketch, inspired by 25 images in nature (by Z. Çolak)

Figure 33: Proposals of a bio-digital skyscraper, prompted to generate a design according to initial sketches. Translucency and jellyfish concepts are highlighted. (fig.32) (by Z. Çolak)

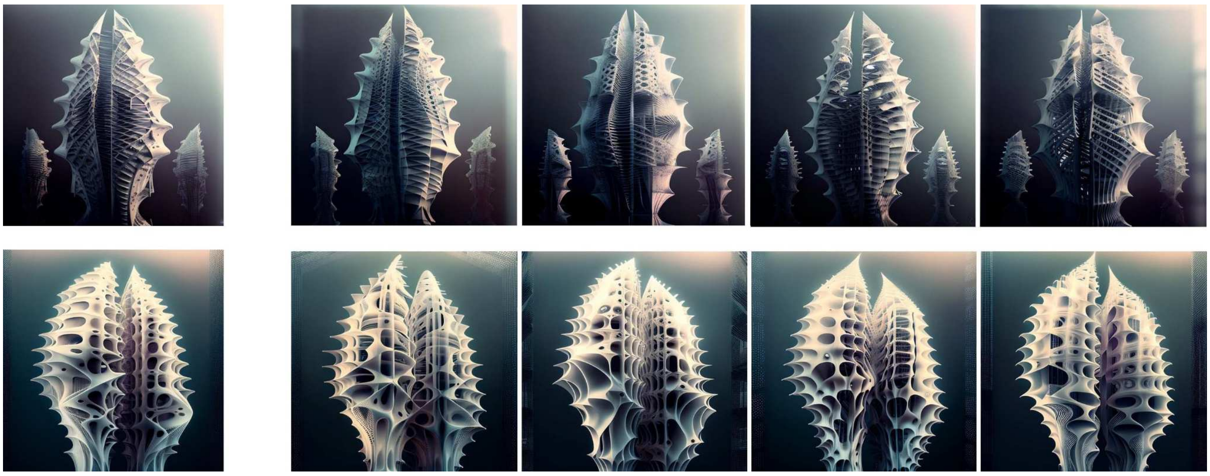

Figure 34: Proposals of a bio-digital skyscraper, prompted to generate a design according to initial sketches (fig.32). Exoskeletons and translucency concepts highlighted, inspired by animal skeletons. (by Z. Çolak)

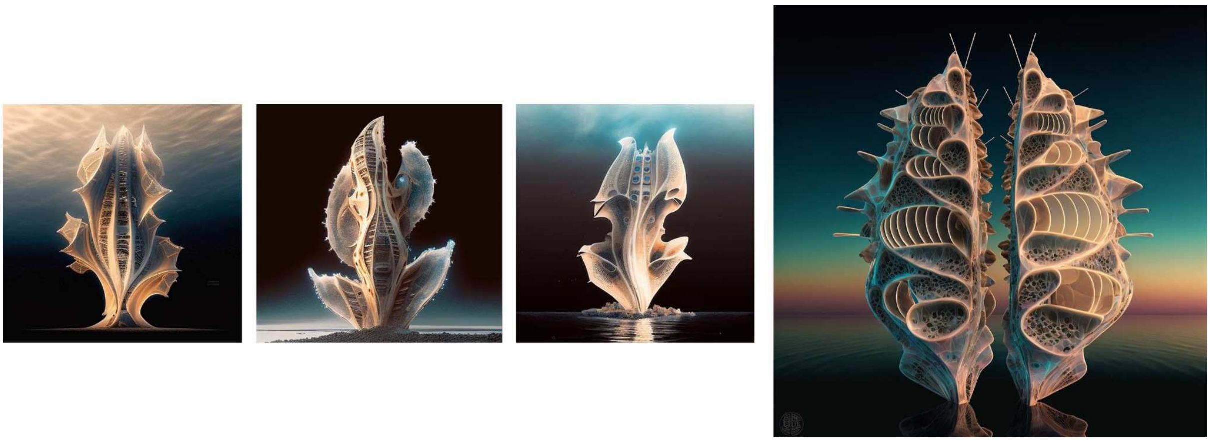

Figure 35: Proposals of a bio-digital skyscraper, prompted to generate a design according to initial sketches (fig.32). Exoskeletons and translucency concepts are highlighted. (by Z. Çolak)

3.2.2 Gyroids And Reaction Diffusion

Spanish Dancer also explores the relationship between biological systems and the precise mathematical language in which the entire universe was written. Therefore the project occurs from a gyroid which is described as a minimal surface in math to form the layers of exoskeleton which results in forming the spaces of a residential skyscraper.

A gyroid is a triply periodic minimal surface, which means it's a surface that smoothly divides space into two separate regions without any excess material. It's a type of mathematical surface that repeats itself infinitely in three dimensions. The gyroid has a unique structure characterized by interconnected, labyrinthine networks of channels and voids that create a continuous, self-repeating pattern. A minimal surface is a surface with the least possible area for a given boundary. In the case of the gyroid, it's considered minimal because it has a relatively small surface area compared to other surfaces that would enclose the same volume. It achieves this efficiency by forming a complex, interconnected structure with minimal surface curvature. They have significant potential in computational design for several reasons: Gyroid structures are known for their high strength-to-weight ratio, making them suitable for *lightweight* and strong architectural and engineering applications. Therefore in the case of “Spanish Dancer”, the intricate network of channels in gyroids function to facilitate efficient *heat and mass transfer*, which is useful in Barcelona, where the project is located. Thus, the repetitive and visually intricate nature of gyroids has always attracted designers and architects, as they can be used to create *aesthetically* pleasing and structurally efficient designs. These kinds of minimal surfaces have similarities to structures found in nature, making them suitable for *biomimetic design* where natural principles are applied to engineering and architecture.

The most important aspect is that a gyroid has a specific equation and it functions by filling the spaces (fig.36). Therefore the skyscraper and all the spaces in it are formed by one surface. Gyroids are fascinating geometric structures with minimal surface properties that have found applications in computational design due to their efficiency, strength, and aesthetic appeal. They also share structural similarities with certain living organisms, making them an intriguing subject for biomimicry and further exploration in various fields, from materials science to architecture and beyond.

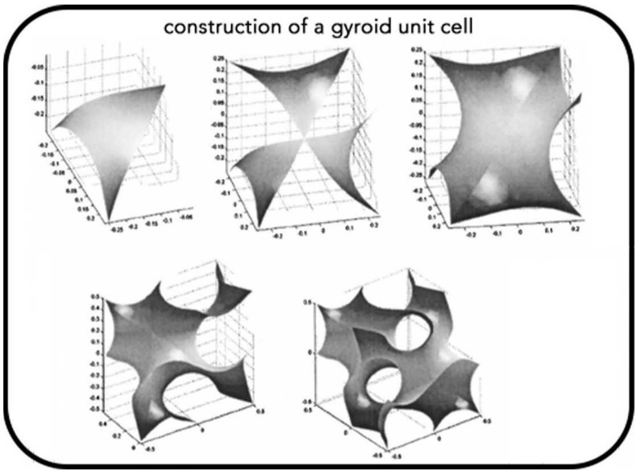

Figure 36: Construction of a gyroid unit cell

In addition to that, gyroid structures can be found in some of the certain biological systems like butterfly wings, bone structures in some animals, and marine sponges. To explore this more deeply; some butterfly wings feature gyroid-like structures in their scales, which contribute to iridescent colors through the manipulation of light. The trabecular bone structure in some animals, including birds and some mammals, exhibits gyroid-like patterns, which provide both strength and lightweight properties. Lastly, some marine sponges have a skeleton structure with gyroid-like configurations, helping them maintain structural integrity in water currents.

Considering these, Spanish Dancer uses the potential of minimal surfaces in residential architecture and design. While exploring the parameters of gyroids in the first steps, several iterations have been formed. Figure 37 shows the iterations that have been worked on to explore how spaces are formed and decide on the optimal gyroids to form spaces in which people can reside in. In order to achieve the optimum spaces for people to reside in. After creating several iterations of the gyroid with different parameters, the optimum model is carried out by merging two variations of the gyroid formed with the same equation but with different parameters. The end result is called as *'dual gyroid[34]' (also double-gyroid).*

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[34] The double gyroid (DG) structure is a three-dimensionally periodic bicontinuous structure with $Ia\bar{3}d$ symmetry that consists of two interpenetrating networks of the minority component and a matrix of the majority component (Williams, 2019)

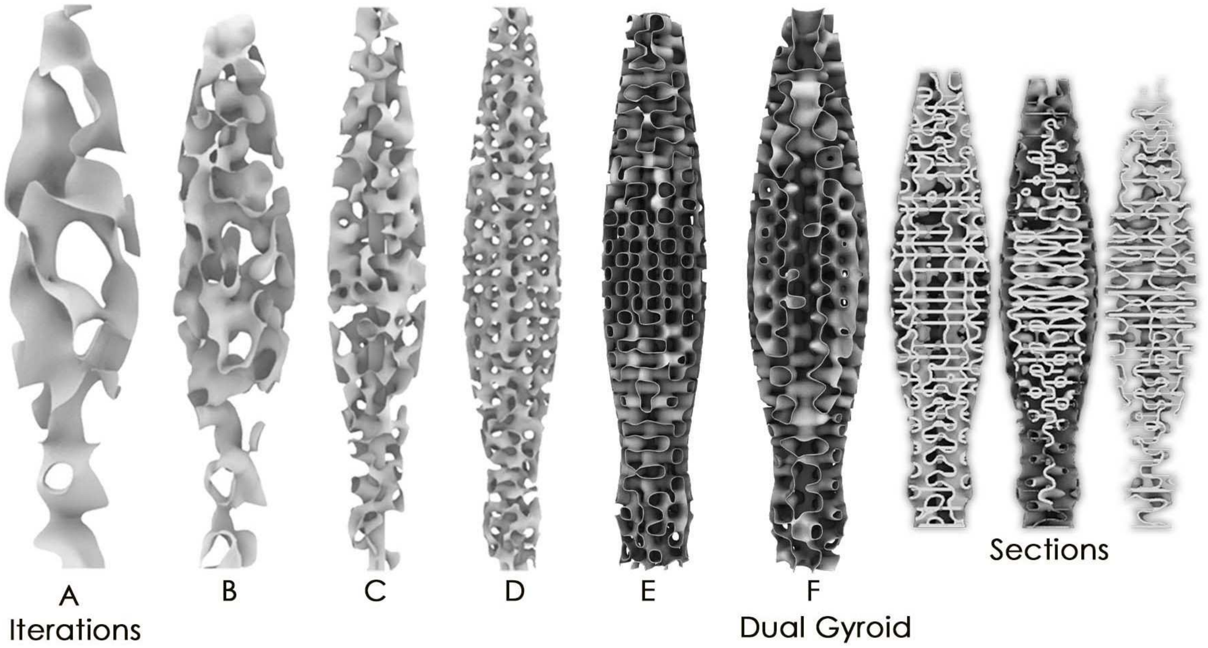

Figure 37: Image A to E showing iterations of the towers created with gyroids. Image F shows the dual gyroid (created as a merge of two gyroid equations with different parameters in order to achieve the most suitable living spaces inside and create an optimum building skeleton)

The result is a residential skyscraper with so many variations of space differing in functions such as to reside in, to socialize, entertain, or common use. This allowed for an exquisite structure similar to a sculpture rather than a traditional residential architecture project. That is to say, since humans started to industrialize everything, we also started to mass produce for 'efficiency' and 'easiness'. However, in the nature of sculpture, there is no such thing, a sculpture must be experienced differently from several perspectives to grasp the whole thing. Figure 35 shows the variations of spaces formed in the section. Therefore this is concrete proof to change our perspectives and start rethinking the spaces we live in. Humans are attracted to nature and its organic, continuous forms because they have the ability to calm us, to give us inner peace, and to relax. If we start rethinking the spaces we spend so much time in by working, eating, relaxing, or sleeping we will get to the result that most of us are not happy or at peace. Because we basically live in boxes with corners, however, there is no such thing as a 90° in nature, in fact, everything is well connected and continuous. This situation arose on the surface with the emergence of Covid in every part of the world which left people desperately in need of bigger spaces, open spaces, and brighter spaces. Spanish Dancer, in this case, shows the "*growth of living spaces*", morphing into another.

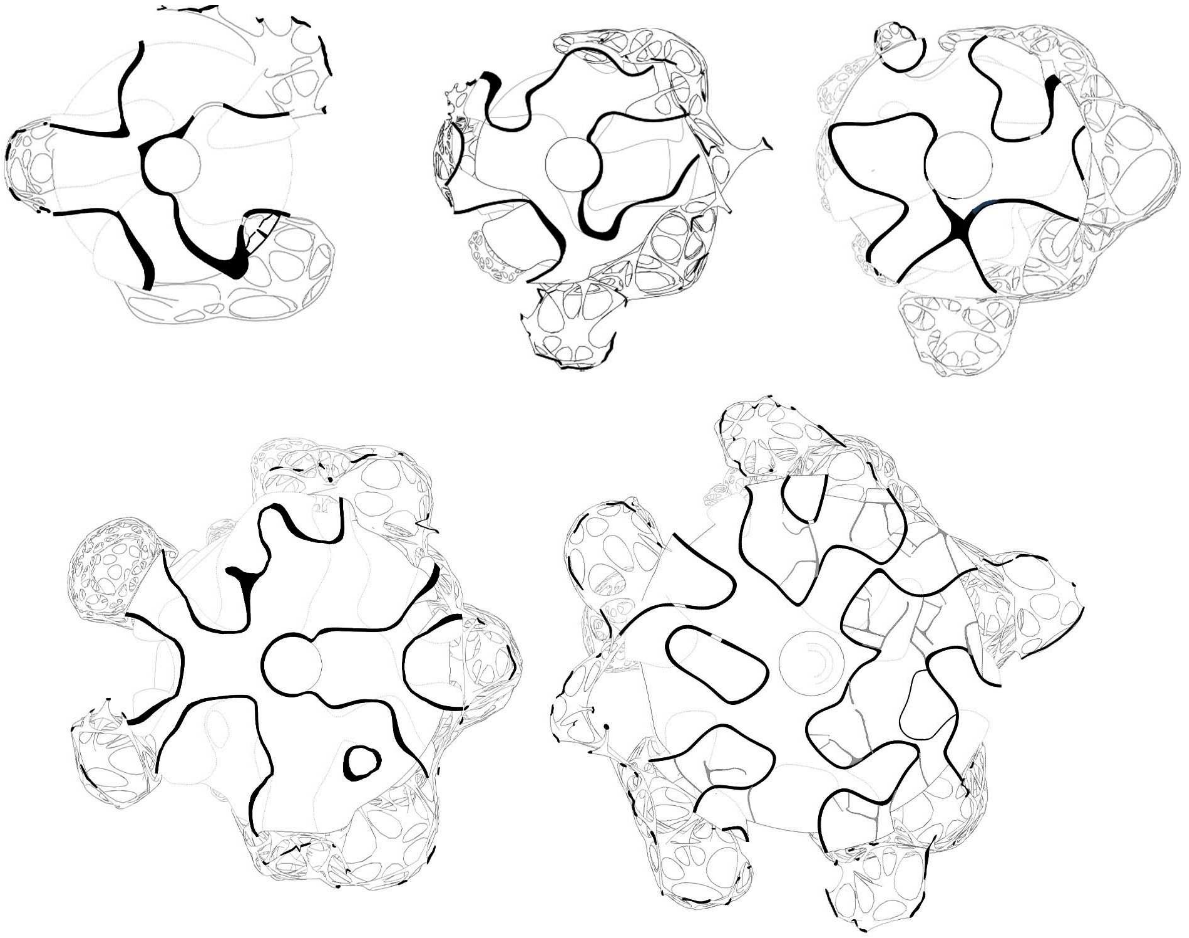

Figure 38: Top sections of Spanish Dancer Skyscraper Project from different levels, undetailed (by Z. Çolak)

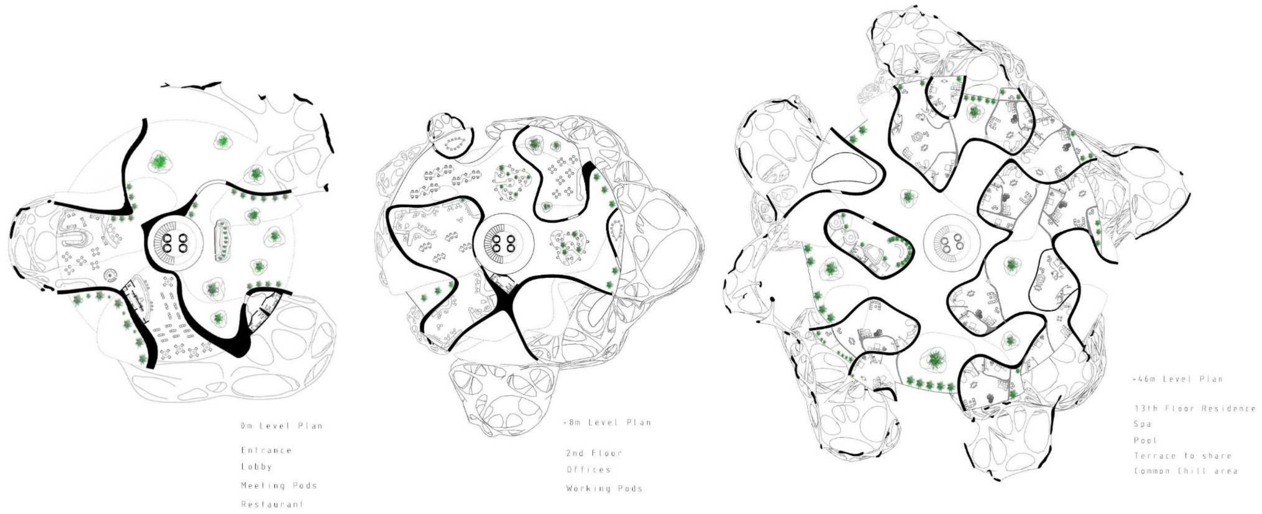

Figure 39: Detailed plans of Spanish Dancer Skyscraper Project from different levels (by Z. Çolak)

After getting the spaces and the main skeleton of gyroid for the skyscraper, there was still a need for another layer of skeleton to cover up the openings and make it a livable place. In order to achieve that, there was a need for a solution that is organic and continuous, a solution that would work with gyroids as if it is growing out of gyroids. The solution came with the caps that covered the gyroids and completed them as a closed shape as seen in the figure 40. The result was getting a shell with gyroids and as if a skyscraper form was carved out of that shell (fig.37, form F) and left the outer shell as caps of gyroid (fig.40 shape 3). After this step, *reaction diffusion*[35] is applied to the caps and creates the outer shell resembling the veins of an organism (fig.40) which after covered with translucent material in needed parts in order to form openings of a building.

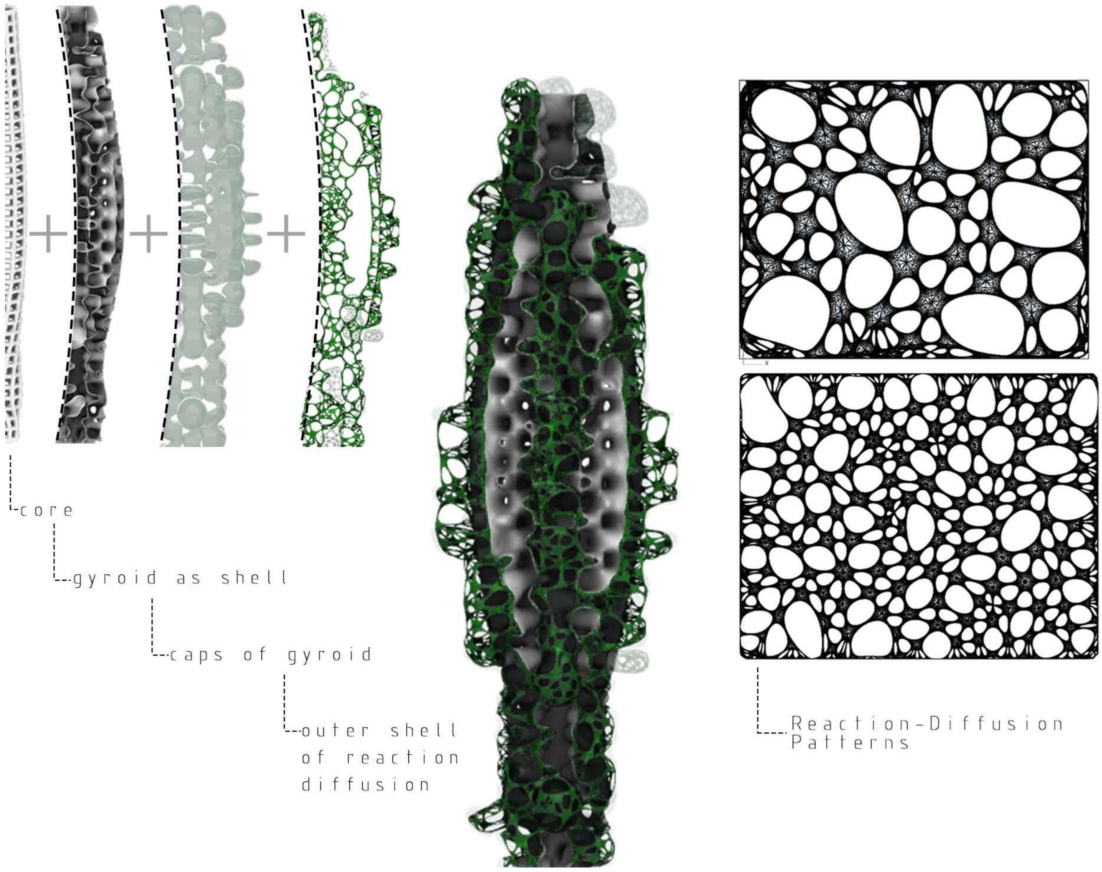

Figure 40: Skeleton Layers (by Z. Çolak)

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[35] Reaction-diffusion systems are a particular class of continuous field models. They can show strikingly rich, complex spatio-temporal dynamics. The reaction-diffusion model describes the emergence of periodic patterns such as spots, stripes, and maze on the surface of animal coat through chemical interaction among cells. In the reaction-diffusion model, two hypothetical chemicals, called morphogens (activator and inhibitor) are considered.

What's more, is that they can also work as actual veins of the building since they cover the whole building and are interconnected to each other, therefore they can be covered with algae and function as bioluminescent at night or transport water through the building. The end result of the project is 4 layers of skeleton differing in functions yet connected to each other. The first layer creates the core of the skyscraper and carries the elevators and stairs while the second layer, which is the gyroid layer, grows from this core skeleton and covers spaces, and forms the main skeleton of the building. The third layer is composed of the caps of gyroids to form openings and enclosures which are made of translucent material like glass and the fourth layer is the skeleton generated with reaction-diffusion to cover the third layer and carry them by strengthening it.

However, gyroid and reaction-diffusion are not the only concepts seen in the project. Spanish Dancer skyscraper is located on its island and it is reached by the bridge connecting the island of the building and the beach. To provide continuity and protect the organic structure overall, the island and bridge are covered with branches of paths coming from the core of the skyscraper (fig.41). *Branching* is one of the main bio-digital concepts and in this case, it is achieved by *shortest path*[36] algorithm in Grasshopper. Besides its appearance like the growing roots of a tree or the veins in an organ functioning to transport necessities, these pathways are becoming a part of the experience by becoming a part of the skyscraper. They reach to every corner of the island and form promenades that go on the bridge, curving on the sea and helping the visitors to experience Spanish Dancer from various angles.

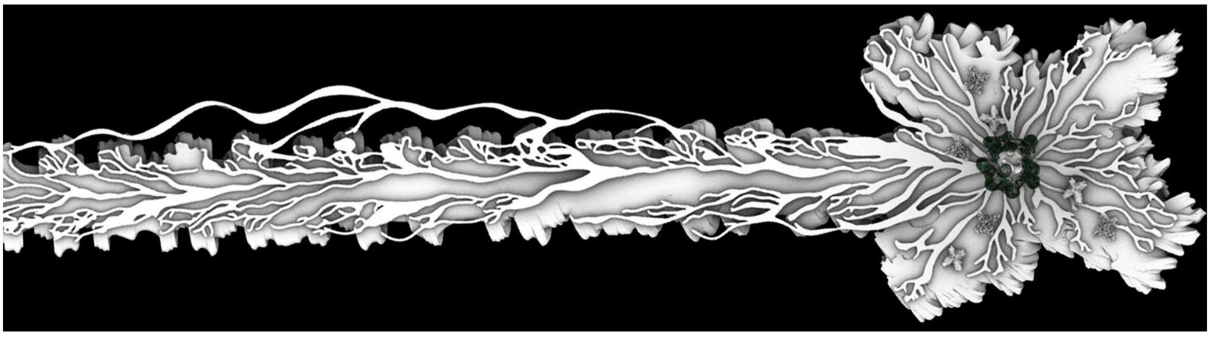

Figure 41: Branching pathways top view in Spanish Dancer project, generated with shortest path algorithm. (By Z. Colak)

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[36] Shortest Path Algorithm, also Dijkstra's algorithm is an algorithm for finding the shortest paths between nodes in a weighted graph, which may represent, for example, road networks.

Besides the skyscraper itself and the pathways of the project, everything located on the island, including the island and the bridge itself is part of the continuous, organic project. In other words, everything included in the project, *each part is responding to another and creating the whole, and the whole is reflected in those parts*. As seen in the figure 42, the benches located on the island share the same *DNA* with the island and the skyscraper. What it means is, that they are generated with the same algorithms in different parameters. After forming the first prototype of the bench in an organic form resembling jellyfish with an umbrella on top of it to cover from the sun of Barcelona, the patterns and structures are applied by using reaction-diffusion. This way, the bench is created like a pergola, protecting from the sun yet it has enough openings to ventilate the visitors who are chilling and relaxing in the sunset lounge zone.

With this in mind, it can be said that all of the components in the Spanish Dancer project have *grown from the same roots*. They are parts of a whole differing in functions, yet they respond to each other and share the same info and as a result, they create an *experience* for their visitors by serving them and taking their needs into account.

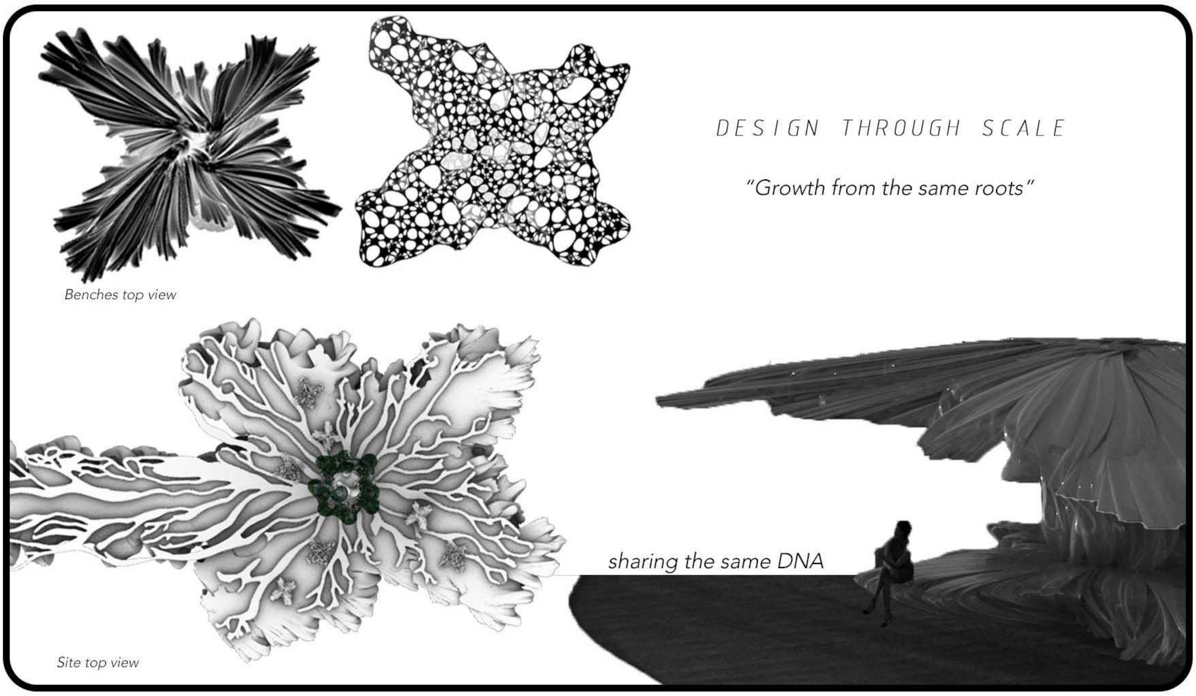

Figure 42: Top view of benches and island, showing the idea Design Through Scale (By Z. Colak)

3.2.3 Digital Fabrication

Digital fabrication plays a crucial role in bio-digital architecture by enabling the realization of complex and sustainable designs that blend biological and digital elements. Digital fabrication significantly affects and helps bio-digital architecture in the context of achieving precision, complexity, rapid prototyping, scalability, and cost efficiency as applied in the case of “Spanish Dancer”.

However, while using the digital fabrication technologies and tools in order to achieve the precision some trial and error are inescapable. Thus, bio-digital architects often explore innovative and experimental designs. Therefore, digital fabrication enables rapid prototyping, allowing designers to quickly test and refine their concepts before full-scale construction. This iterative process can lead to more efficient and effective designs. In the case of “Spanish Dancer”, many iterations were tested before the end product.

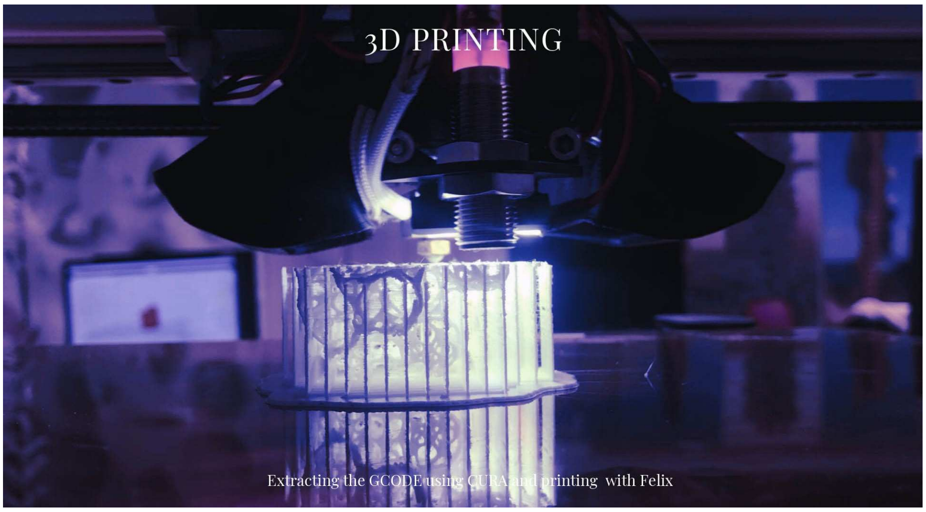

Figure 43: 3D Printing with Felix (Photo by Z. Çolak)

In terms of scalability, digital fabrication techniques can be scaled up or down to accommodate different project sizes, from small installations to large-scale buildings as in the bio-digital skyscraper case. This scalability is vital for applying bio-digital concepts across various contexts. This also affects the cost efficiency of projects. That is to say, while digital fabrication technologies may require an initial investment, they can ultimately lead to cost efficiencies through reduced material waste, faster construction times, and the ability to create complex structures with fewer resources.

In order to achieve the high level of precision and complexity of the project, digital fabrication technologies, such as 3D printing, CNC milling, and laser cutting machines were used in the Spanish Dancer project, since they offer a high level of precision and the ability to create intricate and complex structures. This is essential for realizing the intricate geometries and patterns often found in bio-digital architecture. Figure 44 shows the digital fabrication products of the Spanish Dancer compared to their digitally generated models. The skyscraper models itself and the benches are printed with Felix 3D printer, while the island model was done by CNC milling machines.

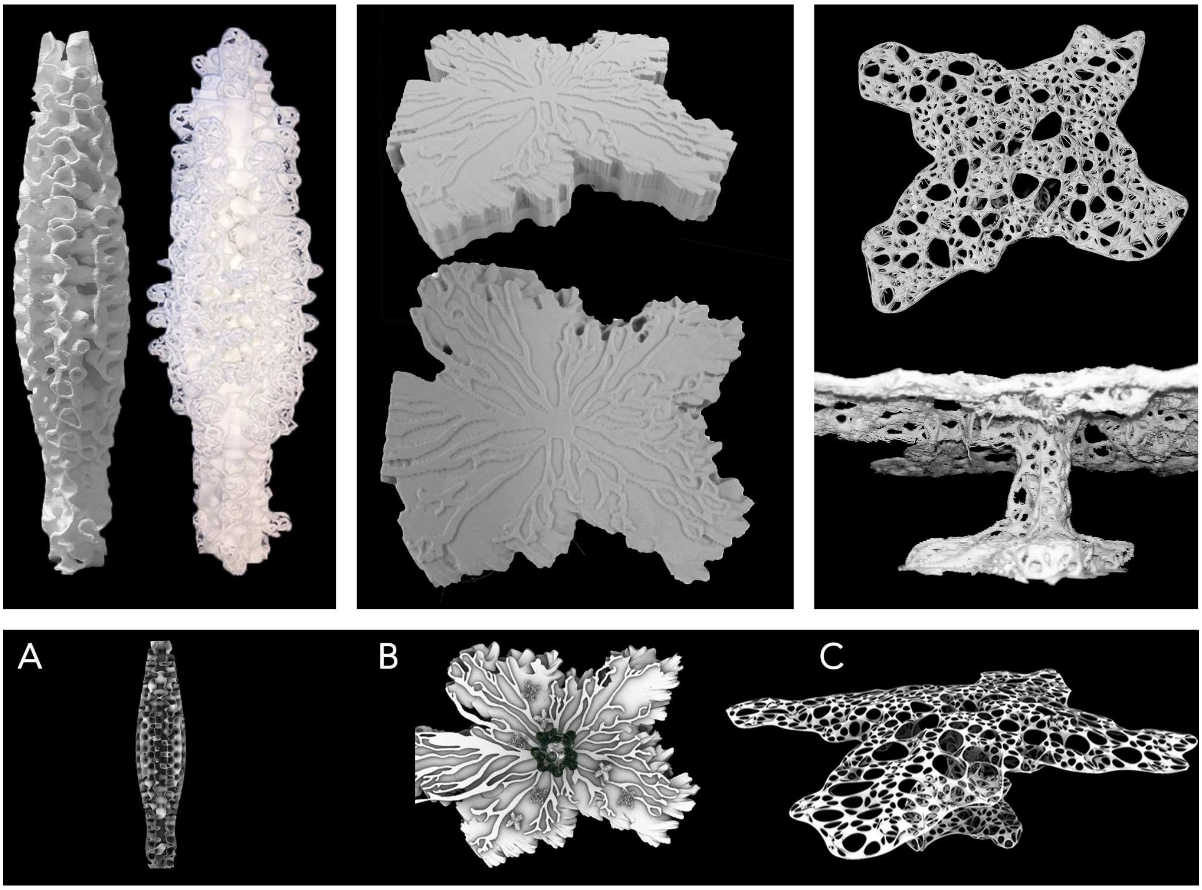

Figure 44: Digital Fabrication products of the Spanish Dancer Project with their generated 3D models. Image A shows the fabricated model of a gyroid skyscraper (above) and the generated model (below). Image B shows the fabricated model of the island (above) and the generated model (below) Image C shows the fabricated model of the bench (above) and the generated model (below). (By Z. Çolak)

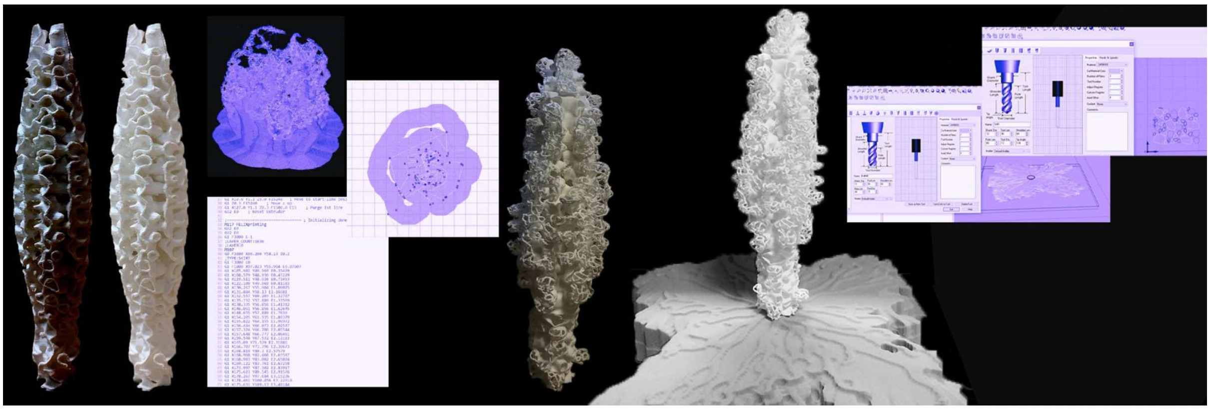

Figure 45: Skycraper and island models, its gcode and adjustments of CNC milling file

Besides these aspects, digital fabrication enables for material integration which seamlessly integrates biological materials, such as living organisms or bioengineered materials into the design which allows for the creation of living walls, façades, or structures that incorporate organic elements. Moreover, it helps to achieve efficiency and sustainability by minimizing material waste since it allows for a precise cutting and shaping of materials that results in reducing resource consumption and environmental impact. In addition, it allows for an interdisciplinary collaboration between architects, biologists, engineers, and digital designers. Digital fabrication provides a common platform where experts from different fields can work together seamlessly to bring bio-digital concepts to life. Also, it contributes to the development of new materials and composites that are well-suited for bio-digital architectural applications. These materials can have unique properties, such as self-healing capabilities or bioactivity. Lastly, digital fabrication can be integrated with data-driven design and simulation tools. This means architects can use real-time data on environmental conditions, user behavior, or structural performance to inform the fabrication process, creating responsive and adaptive architectural solutions.

In conclusion, the idea of bio-digital architecture cannot be realized without digital fabrication. It enables architects to create designs that push the limits of traditional construction methods and are biologically integrated. This technology-driven approach addresses today's urgent environmental and ecological challenges while encouraging innovation, customization, and precision.

3.2.4 A House Is An Organism To Live In

Biodigital architecture rejects traditional ideas and notions that got stronger in the last century with the emergence of industrialization. It harnesses the idea of a *"living architecture[37]"*, in other words, bio-digital architecture embraces living organisms rather than machines, and growth rather than assembly. In this way, we deconstruct the existing design perspective which supports the motto imposed on us for a century "A house is a machine to live in[38]". In addition to these aspects, the idea of "living architecture" extensively challenges traditional notions about static, fixed structures and makes a huge contribution to the resilience and sustainability of our built environment. Although Living Architecture and Biodigital Architecture are distinct concepts within the field of architecture and design they are still very intricately interrelated. That is to say, living architecture feeds the bio-digital architecture's motive by inspiring, and biodigital architecture offers living architecture a chance to come "*alive*" with its advanced methods and tools. Living Architecture focuses on the integration of living organisms, primarily plants, into architectural design to enhance ecological sustainability.

Biodigital Architecture, on the other hand, encompasses a broader range of concepts and technologies, including the integration of natural and digital elements, biomimetic design, and the use of computational tools to create innovative and sustainable architectural solutions. While both approaches aim to promote sustainability, Biodigital Architecture leverages digital technologies and computational design to a greater extent yet one wouldn't exist without the other.

We are used to the traditional buildings having fixed designs that remain relatively unchanged over time, even as the needs of residents or environmental conditions evolve. Living architecture is intended to be adaptable and responsive. It has the capacity to evolve over time in response to shifting resident needs and environmental conditions. A growing wall, for instance, can vary and expand with the

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[37] Living Architecture is defined as the integration of living systems on or within a building envelope. This includes green roofs, living walls (interior and exterior), and green facades.

[38] The author refers to the Le Corbusier's famous quote "Une maison est une machine-à-habiter" ("A house is a machine for living in") (More on chapter 1)

seasons, adding to the notion that a house is an organism that adapts to fit its environment.

Another aspect is that traditional design often relies on active, mechanical systems for heating, cooling, and ventilation which require energy and maintenance. Living architecture promotes passive systems inspired by nature like green facades of Spanish Dancer to provide natural insulation and cooling. This approach aligns with the idea of a house as an organism that interacts with its surroundings in sustainable ways. A contribution to the sustainability aspect of this is; that the "machine" approach does not always put sustainability first or take into account how the construction will affect the environment over time. But, since living architecture frequently uses renewable resources and passive, energy-efficient technology, it is inherently sustainable. Living elements like plants also contribute to ecological regeneration by increasing biodiversity and strengthening the quality of the air and water. The idea of a house as an organism that actively contributes to its ecosystem is in line with this.

On the other hand, the "machine to live in" perspective frequently places more emphasis on functional effectiveness than on occupants' overall well-being. The psychological and emotional needs of the inhabitants are not always taken into account. As opposed to this approach, and biophilic design ideas, which emphasize the connection between humans and nature, are embraced by living architecture. It aims to include natural elements, promote tranquility, and improve air quality to create places that improve the well-being of residents. This fits with the notion of a house as an organism that looks out for the physical and mental well-being of its inhabitants.

Bio-digital Architecture, as a result, is not just about what is happening on the exterior of buildings but it is also a good opportunity to rethink the spaces we live in. Spanish Dancer rises to the Barcelona skies by bringing a new atmosphere to the city. It gives them not just a building constructed with concrete walls and steel skeletons, but it takes their residents back to their roots, nature. When someone is experiencing Spanish Dancer, they will be surrounded by a sensory experience, between organically formed, continuous spaces. On the outside, as soon as visitors take a step on the bridge they perceive a *building like a sculpture (fig.46).*

Figure 46: Sunset lounge zone with benches (By Z. Colak)

Every sculpture artist knows that a sculpture must be experienced from different angles in order to be appreciated appropriately, and I defend that great architecture comes with the design of a building like a sculpture.

Figure 47: Pathway on the sea showing the transition between land and water on different levels. (By Z. Colak)

The aspects we can consider in the traditional design notion and in living architecture are the relationship with the environment, passive and active systems, user experience, responsiveness and adaptation, and sustainability. The idea of a house as a "machine to live in" typically treats the house as an independent object cut off from its natural environment. Efficiency, functionality, and control over the environment are given priority. However, as seen in the case of “Spanish Dancer”, living architecture blurs the lines between a building and its environment by encouraging a more symbiotic relationship between the structure and the natural world. Therefore instead of controlling the environment, Spanish Dancer, a living architecture, adapts to its environment, and it harnesses natural processes to benefit both the building and its inhabitants.

In essence, living architecture rejects the mechanistic understanding of structures by embracing a new perspective where a house is an organism to live in and one that actively takes care of its residents. It redefines the relationship between architecture and nature, creating spaces that promote well-being, sustainability, and adaptability while fostering a sense of harmony with the natural world. And this thesis makes the case that biology can provide instances of growth systems capable of inspiring more adaptable, dynamic, and interconnected organizations of automated and hybrid generative architectural workflows.

Figure 48: Spanish Dancer at night with bioluminescent algae (by Z. Çolak)

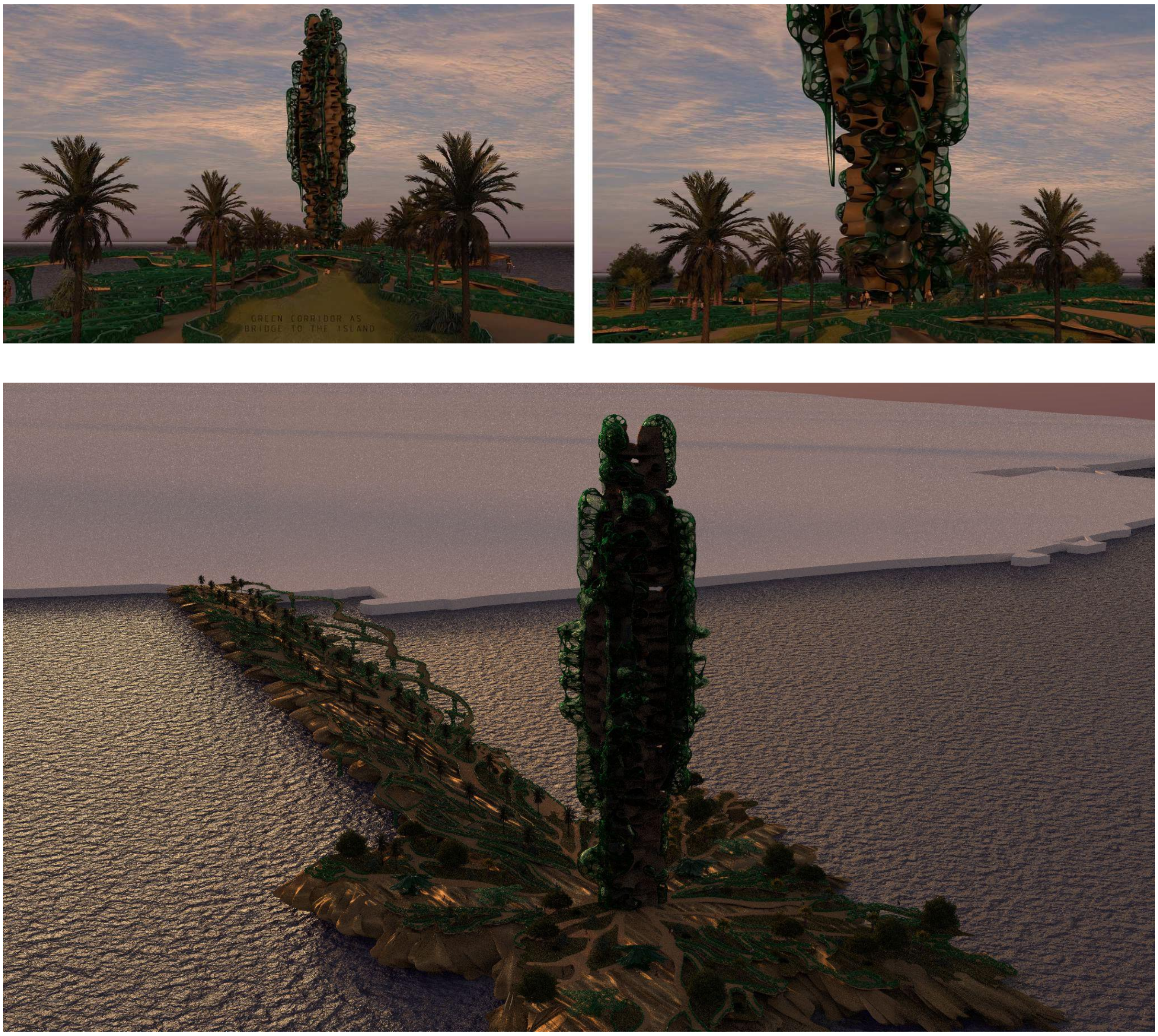

Figure 49: Spanish Dancer from different perspectives (by Z. Çolak)

3.3 Growth, Behavior, and Material Computation

Contemporary design practices progressively incorporate the concepts of growth, behavior, and materiality to produce innovative and sustainable solutions in a world that is changing quickly. In order to understand how designers are utilizing biological and computational insights to shape the future of our built environment, this study explores the intersections of these issues, notably within the field of bio-digital architecture. The invention of human artifacts of any kind always consists of three elements; the geometry, the process, and the material constitute artifacts. It's very clear that new materials engender new forms and architectural design benefits from applying new materials in an informed way (Iwamoto, 2009). Today, contemporary artists explore bio-fabrication techniques, such as growing sculptures from living organisms, to create living artworks or implanting algae on architectural elements or designed objects (fig.51). These works blur the boundaries between art, biology, and architecture[39]. This thesis went back to the roots of design and construction where nature took over the design concepts and it showed, primitive designs showed the most efficient biomorphic forms and materials that even grew. Even though we have been distracted by the industrialization era, bio-digital architecture today, offers a *new path to go back*, and even further than we've never been before in the design field.

The idea of growth in today's design doesn't go further than using biomimicry methods and organic forms while bio-digital architecture perceives the idea of growth and reflects it as living design. Natural growth patterns and forms are increasingly being used as inspiration by contemporary designers. By using such a biomimetic approach, structures are created that mimic the effectiveness and aesthetics of organic growth. The way, Antoni Gaudi's Sagrada Familia features biomorphic designs drawn from the growing patterns of nature. On the other side, bio-digital architecture takes growth to the next level by integrating living organisms into the design process. This includes the use of biological materials, such as mycelium or algae, to create living facades and walls that can grow and adapt to environmental conditions. Figure 50 shows the first analyses of a bio-receptive tile a bio-receptive column and bio-receptive panel designs with the implementation of algae. To design them, we had to compose a new medium for the algae strains. The start point is algae strains in tap water as the medium (45ml). Five freshwater green algae strains (Mougeotia sp, Oedogonium foveolate, Zygnema sp., Microspora sp., Spirogyra sp., and Pyrocystis fusiformis (bioluminescent dinoflagellate.))The next step was choosing the new medium for the algae farming (Diatom Medium Composition) therefore, we used for the new 100mL medium (boiling the water twice first)After the boiled water and added to the solution, we added our algae strains to the cup and

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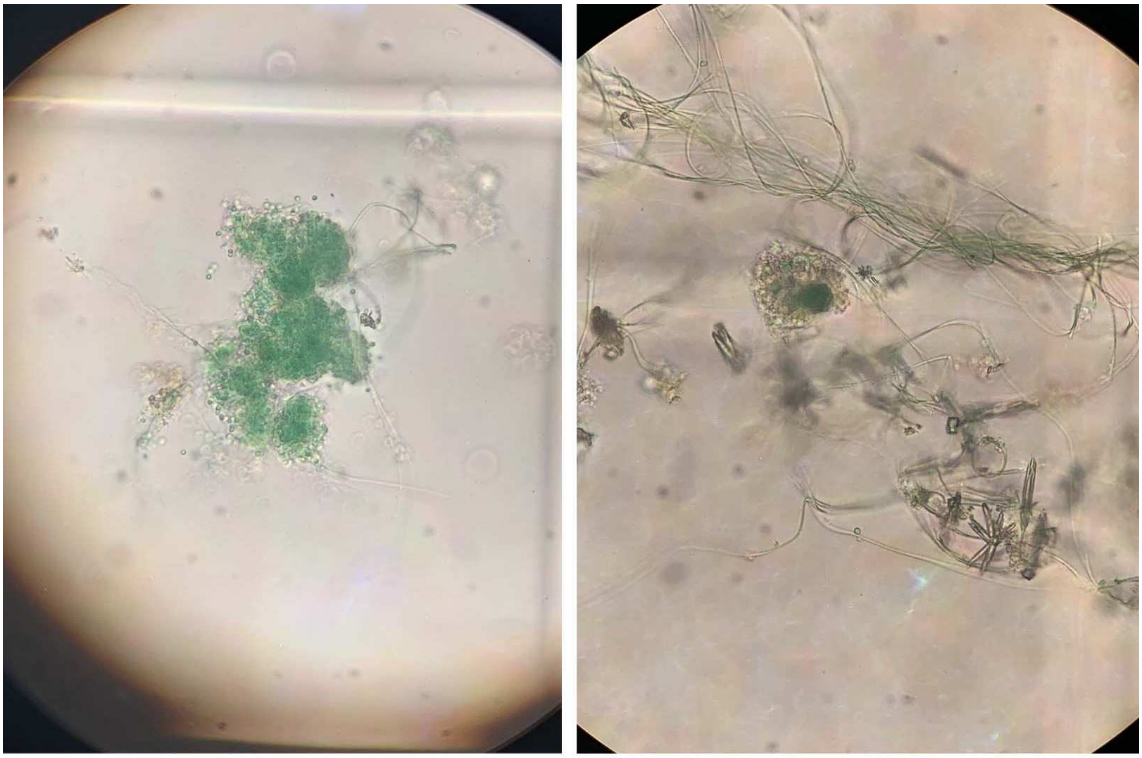
[39] (Myers, 2015) *Bio Art: Altered Realities*.

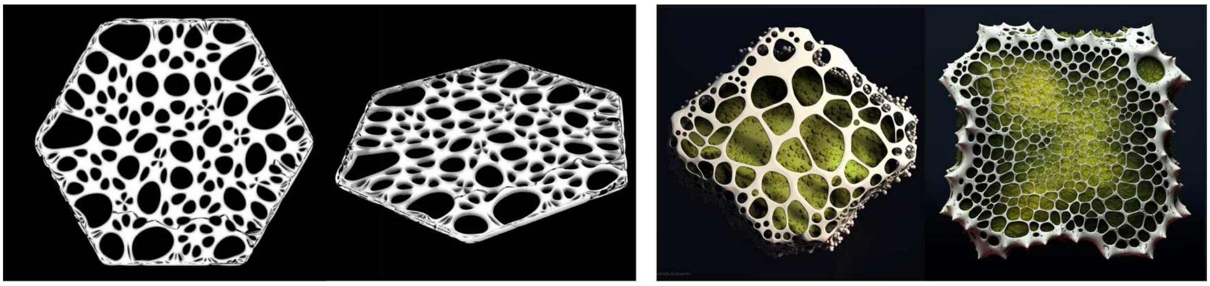
left it in a close cup to avoid contaminating the sample. The figure shows the successful algae starting to grow and can be implemented when the tile is printed with 3D printer. The final recipe to get this medium is; $Ca(NO2)2 + 4H2O$ (calcium nitrate 20 mg), 0.002gr; $KH2PO4$ (monopotacium phospate 12.4 mg), 0.00124gr; $MgSO4 + 7H2O$ (magnesium sulftate 25mg), 0.0025gr; $NaHCO3$ (Bicarbonate of soda 15.9 mg), 0.00159gr.



ALGAE		SCIENTIFIC CLASSIFICATION	SHAPE DESCRIPTION	CELL SIZE	REFERENCES
Mougeotia sp		Class: Zygnematophyceae Order: Zygnematales Family: Zygnemataceae	Filamentous algae without branching; a single plate-like chloroplast in each cell.	Cell body µm long, 18 µm wide.	http://protist.i.hosei.ac.jp/PDB/Images/Chlorophyta/Mougeotia/group_2/sp_7.html
Oedogonium foveolate		Class: Chlorophyceae Order: Oedogoniales Family: Oedogoniaceae	Filamentous algae; cell division occurs near septum and adds "apical cap". cell body cylindrical, laterally straight or wavy or swell at one end of the cell body.	Vegetative cells 50-75 µm long, 11 µm diam.	http://protist.i.hosei.ac.jp/PDB/Images/Chlorophyta/Oedogonium/sp_5.html
Zygnema sp		Class: Zygnematophyceae Order: Zygnematales Family: Zygnemataceae	Filament without branching; cell body cylindrical; two chloroplasts star-shaped; tubes formed at conjugation; zygospore spherical or broad ellipsoidal formed within female gametangium.	Cell body 30-73 µm long, 16-20µm wide.ygospores spherical or nearly spherical, 36-46 µm in diam., 34-45 µm long; medial spore wall yellowish brown, with small pores 3-4 µm in diam. arranging at 2.5-4 µm intervals at maturity.	http://protist.i.hosei.ac.jp/PDB/Images/Chlorophyta/Zygnema/sp_1f8b.html
Microspora sp		Class: Chlorophyceae Order: Sphaeropleales Family: Microsporaceae	Filamentous algae without branching; cell body mostly cylindrical. Cellwall shows H shape in transverse section; chloroplasts reticulatedwithout pyrenoids.	Cell body µm long, µm wide, L/W=	http://protist.i.hosei.ac.jp/PDB/Images/Chlorophyta/Microspora/sp_36.html
Spirogyra sp		Class: Zygnematophyceae Order: Zygnematales Family: Zygnemataceae	Filamentous algae without branching; cell body cylindrical; chloroplastband-, plate- or star-shaped. Cell body cylindrical; spirally arranged within the cell, pyrenoids present; septum with or without folded structure.	1 turns x 155 µm	http://protist.i.hosei.ac.jp/PDB/Images/Chlorophyta/Spirogyra/group A/index.html
Pyrocystis fusiformis		Phylum: Dynoflagellata Order: Gonyaulacales Family: Pyrocystaceae	Oval-shaped, elongated cell, of a relatively large size for micro-organisms of the same type.	A single cell can measure up to 1 mm	https://www.researchgate.net/publication/352806724_Designing_Direct_Interactions_with_Bioluminescent_Algae

Figure 50: New medium for algae strains observed with an electron microscope and the analyses of the medium (by Z. Çolak, I. Curiel, 2023)

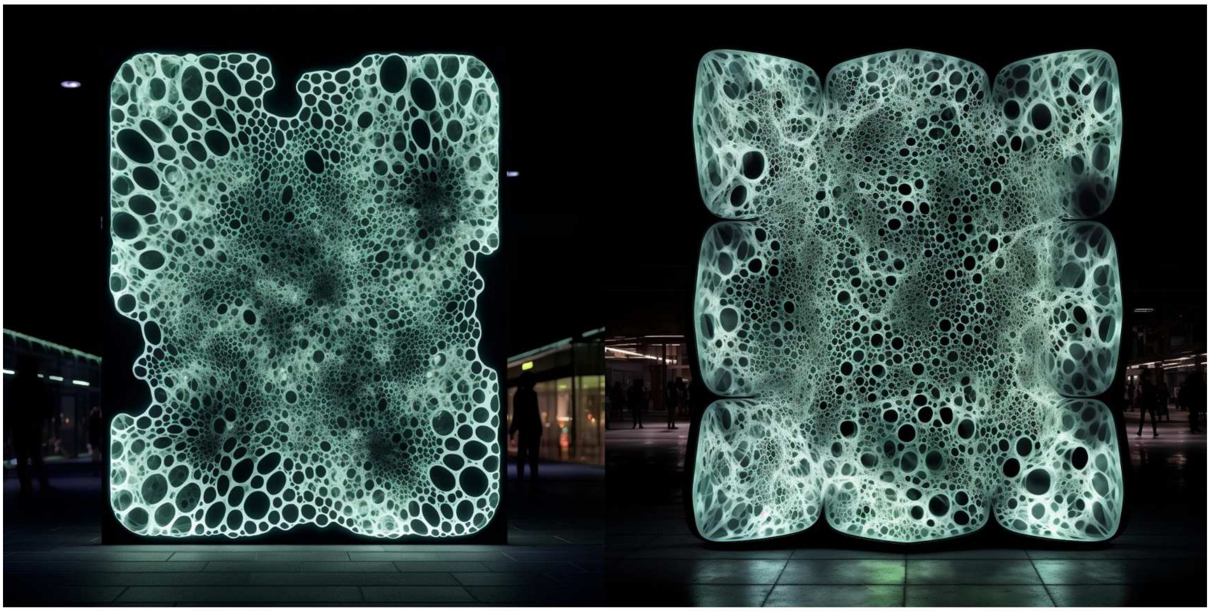
The reason why we chose diatoms, also called single-celled algae, are the only organisms on Earth with translucent, opaline silica as part of their cell walls. Diatom cell walls are ornamented with complex and beautiful silica patterns. Therefore their patterns within frustules also inspired us for a 3D structure with *reaction diffusion.*



A) Digital model of bio-receptive tile with reaciton diffusion

B) AI designed bio-receptive tile with algae

C) AI designed bio-receptive panels on different stages (without algae, on growth stage and grown)



D) AI designed bio-receptive panels with diatom, bioluminiscent at night

Figure 51: Bio-receptive tile models and bio-receptive panels (by Z. Çolak)

Figure 51 shows how the new medium of diatom algae can be implemented and grow on the bio-receptive tile, its digitally designed model, and the images of the tile and panels created with AI. In current bio-digital architecture, the concept of growth is often explored through biomimicry and parametric design. Designers draw inspiration from natural growth patterns to create structures that adapt and evolve. However, in the future, advancements in materials science and nanotechnology may enable architects to design structures that genuinely grow and self-repair with new materials or create light and a new ecosystem like the algae does. Buildings could use self-healing and growing materials to fix minor damages or adapt themselves based on occupancy needs.

On the other hand, when we talk about behavior in design, it usually covers a user-centered design, but bio-digital architecture takes it to another level by creating responsive environments. To create spaces that enhance functionality and well-being, designers are placing more and more emphasis on comprehending and anticipating user behavior. Layout, lighting, and furniture choices are always influenced by behavioral insights. Biodigital architecture makes use of AI to build responsive spaces that adapt to the response of user behavior and environmental conditions. Buildings, for instance, can adjust lighting, temperature, and ventilation based on user preferences and occupancy. Even though current bio-digital architecture incorporates behavior through smart systems and sensors. The future holds the potential for more advanced behaviors. Buildings may exhibit biological-like responses such as learning from their environment as the Spanish Dancer does.

Lastly, for materiality in design, sustainable and environmental materials have been getting more popular in the last years however, materiality in bio-digital architecture is strengthened by bio-fabrication, In the architecture field today, materials that are recycled, repurposed, and low-impact are becoming prioritized like furniture and building materials are made from recycled plastic. In contrast, investigating the utilization of biologically modified materials is called "biodigital architecture." This includes products made from living organisms, such as mycelium, which can take the place of conventional building supplies like concrete. These bio-fabricated materials can have special qualities and are lightweight and environmentally friendly. Material computation involves using computational algorithms to design and fabricate materials with specific properties. Architects currently employ this concept to create lightweight, high-strength materials suitable for innovative structural designs. But, with the advancement of 3D printing and nanotechnology, architects may have access to materials that can adapt to various conditions or even self-repair. These materials could be integrated into the structure itself, leading to buildings that continuously optimize their performance and longevity. It is already known that the computer can create the design and produce what we call living materials and designs. Although computer-aided design offers new possibilities that have appeared on the horizon lately, living materials were already explored by our ancestors who were observing nature. For instance, the lime mortar which is a cement material that made up the Giza Pyramids was self-healing. When a crack develops the material can heal itself without any kind of human interaction. Therefore today, bio-digital architecture can take it over. During this thesis, it is already covered there are certain aspects that are special for living organisms; growth, self-healing, differentiation, aging, and cell division. The case studies in different contexts showed the potential of these aspects with the advancements in bio-digital architecture and now, it shows the promises of bio-digital architecture in the new emerging horizons.

In conclusion, bio-digital architecture is at the forefront of the convergence of the fundamental design concepts of growth, behavior, and material computation. The potential of these in bio-digital architecture is closely tied to technological advancements. As technology evolves, architects will have more tools at their disposal to create structures that not only respond to their environment but also actively contribute to sustainability and efficiency. Additionally, the interdisciplinary nature of bio-digital architecture, involving biology, materials science, and computation, will foster innovation in the field, pushing the boundaries of what is possible in architectural design and construction.This developing discipline pushes the limits of architectural creativity and ecological responsibility while embracing the responsive, sustainable, and dynamic aspects of living systems.

CONCLUSION

In conclusion, bio-digital architecture represents a groundbreaking paradigm shift in the field of architectural design. It seamlessly blends the wisdom of nature with the power of digital tools to usher in a new era of architectural innovation and sustainability. This thesis has delved into the profound synergy between nature learning and digital design, highlighting the transformative potential of this approach. The study has shown that bio-digital architecture learns invaluable lessons from nature. It recognizes the brilliance of natural forms, processes, and systems, deciphering the intricate codes that have evolved over millions of years. Through biomorphism, natural morphogenesis, and an understanding of the mathematical language of the universe, architects have gained inspiration to craft structures that harmonize with their surroundings, respond to environmental stimuli, and enhance the well-being of their occupants.

Moreover, the integration of digital tools, computational design, and machine learning has opened up new horizons. It has enabled architects to transcend the limits of conventional design, generating complex and adaptive structures that were once inconceivable. When digital architecture achieved a new architectural paradigm in the meantime, both conceptions and new production standards served as the foundation for this paradigm, and they still do today. Complexity has become commonplace in digital architecture as a characteristic of computerized systems. For the experimental usage of materials created using digital fabrication processes, a new idea of materiality and materials has been developed. Consistency in architecture will continue to rely on tectonic and constructive principles, as it always has, but they will be explored in novel ways according to the synergies brought about by computer-aided architectural design and manufacture. Generative algorithms, digital fabrication techniques, and parametric design have become the cornerstones of this architectural revolution. Architects are no longer just designing static structures; they are crafting dynamic processes that evolve over time. Yet, this thesis showed that conventional methods like craftmanship haveq1 still so much to teach and cooperate with digital tools and fabrication processes

Also, material computation will bring forth materials that are not merely static components but active participants in the architectural ecosystem. These materials will grow, self-repair, self-regulate, and contribute to the sustainability of the built environment. In the face of pressing global challenges like climate change and resource scarcity, bio-digital architecture offers a ray of hope. It embodies the ethos of sustainable, adaptive, and regenerative design. Looking ahead, the promises of bio-digital architecture are immense. The concepts of growth, behavior, and material computation are at the forefront of this transformative journey. The future holds the potential for buildings that truly grow and adapt, mirroring the resilience and efficiency of biological systems. Smart behaviors will make structures responsive, learning, and self-improving, creating spaces that optimize user experiences and resource consumption.

In conclusion, bio-digital architecture is more than a style; it is a philosophy that embraces nature's wisdom and marries it with the possibilities of the digital age. It is a testament to the boundless creativity and innovation of architects and designers who seek to create a built environment that is not just sustainable but regenerative, not just static but dynamic, and not just functional but inspiring. As we stand on the precipice of a new architectural era, bio-digital architecture beckons us to imagine, design, and construct a future that is in harmony with nature and brimming with potential for growth, behavior, and material computation. Bio Digital Architecture stands as a remarkable leap forward in the world of design and construction. By drawing inspiration from the elegance of nature and harnessing the power of digital technology, this approach holds the potential to redefine the aesthetics, functionality, and sustainability of our built environment. As society continues to grapple with pressing ecological concerns, Bio Digital Architecture offers a beacon of hope, demonstrating that harmonious coexistence between the natural and the digital is not only possible but also essential for a more resilient and beautiful future. As we know it today; the concepts of innovation and futurism are the base points of the 21st century and the challenge of it comes with skillful minds with multidisciplinary perspectives. This perspective includes the new merge of architecture, art, and science and computational design is the key point to the new emergence. A good designer must perceive the connection between architecture and other fields that it is fed with; a pure combination of aesthetics, structural principles, and mathematical precision.

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