COMPUTATIONAL GENERATIVE DESIGN WITH BIOMIMICRY TOWARDS MORPHOGENESIS IN DIGITAL ARCHITECTURE

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COMPUTATIONAL GENERATIVE DESIGN WITH BIOMIMICRY TOWARDS MORPHOGENESIS IN DIGITAL ARCHITECTURE

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

COMPUTATIONAL GENERATIVE DESIGN WITH BIOMIMICRY TOWARDS MORPHOGENESIS IN DIGITAL ARCHITECTURE

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Digital architecture has been undergoing continuous changes through different technological innovations with possibilities far beyond the traditional use of architecture design software. Several design technologies have been introduced, which use algorithms and biological simulation as their core and key morphogenetic strategies. This study examines changes in the architectural design process caused by the introduction of computational-based generative design, thus the development of new algorithmic software which enables the writing of scripts and codes in design process. By computational design techniques, it becomes possible to design free-forms found in nature, then to generate architectural form, referring to biomimicry principles. Biomimicry is an applied science that derives inspiration for solutions to human problems through the study of natural designs, systems and processes. This study is an attempt to link the two emerging sciences; Biomimicry and computational design, by exploring their potential in developing a more ideal architecture: "Morphogenesis." This thesis analyses the experimental studies to understand the complex list of terms and unveils the computational theory behind morphogenetic structures by investigating the principles underlying natural morphogenesis.

Keywords: Computational; Generative Design; Biomimicry; Morphogenetic.

ÖZ

DİJİTAL MİMARİDE MORFOGENETİĞE GETİREN BİYOMİMİKLİ BİLGİSAYARLI GENETİK TASARIM

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Dijital mimari, mimari tasarım yazılımının geleneksel kullanımının ötesine geçen imkânlarla farklı teknolojik yenilikler yoluyla sürekli değişiklikler geçirmektedir. Temel ve önemli morfogenetik stratejiler olarak algoritmaları ve biyolojik simülasyonu kullanan birkaç tasarım teknolojisi tanıtılmıştır. Bu çalışma, hesaplama tabanlı üretken tasarımın getirilmesiyle mimari tasarım sürecinde meydana gelen değişiklikleri incelemekte ve böylece tasarım sürecinde senaryoların ve kodların yazılmasını sağlayan yeni algoritmik yazılımın geliştirilmesini amaçlamaktadır. Hesaplamalı tasarım teknikleriyle doğada bulunan serbest formları tasarlamak, daha sonra biyomimikri ilkelere atıfta bulunarak mimari form oluşturmak mümkündür. Biyomimikri, doğal tasarım, sistem ve süreçlerin incelenmesi yoluyla insan sorunlarına çözüm üretmek için ilham alan uygulamalı bir bilimdir. Bu çalışma, ortaya çıkan iki bilim arasında bir bağlanma girişimidir; Biyomimikri ve hesaplama tasarımlarının potansiyellerini keşfederek daha ideal bir mimariyi "Morfogenez"'i geliştirmedir. Bu tez, doğal morfogenezin temelini oluşturan ilkeleri araştırarak karmaşık terim listesini ve morfogenetik yapıların arkasındaki hesaplama teorisini açıklamak için deneysel çalışmaları incelemektedir.

Anahtar Kelimeler: Hesaplamalı; Üretken Tasarım; Biyomimikri; Morfojenetik.

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CHAPTER 1

INTRODUCTION

> Digital architecture has been defined by aboard range of events and technologies that go beyond the use of architectural software. These include the proliferation and great availability of technologies , the possibility of designing parametrically with the use of many different programs, the use of algorithms and simulation of natural and biological processes as morphogenetic strategies (Kottas, 2013, p. 6).

In the context of digital architecture, Oxman had already described that the importance of digital design lies in the fact that mediated design process is not only the evolution of altogether new and formal content but also a completely new type of architectural ideas. For Oxman these design ideas and their relation with theoretical models, systems and processes, which are nowadays practically implemented in the fields of digital design research as well as digital praxis, are under-consideration for teaching digital design (Oxman, 2008, p. 99). Architecture has undergone a gigantic digital revolution, which is evident from the new architectural projects and specifically from latest architecture forms. According to Kolarevic, : "digital technologies are changing architectural practices in ways that few were able to anticipate"(Kolarevic , 2003, p. 2).

Similarly, Zeynep Mennan argues that using the latest techniques/tools utilized in computation design, gives us the opportunity to collect more and more information on contemporary design procedures and their outcomes. With the help of latest tools and methods, architects more easily manage complicated processes. Therefore, the architectural form is created using complex approaches, which utilize multi-layered concepts (Mennan, 2014, pp. 33-42). Consequently, Pallasmaa describes architecture a “material-based form of art”, which turns non-existent ideas into structural realities using the necessary knowledge (Pallasmaa, 2014).

As far as the role of computing is concerned in today's architectural practice, Marcos Novak pointed out the shift of experts from finite objects to variable objects. The architectural form, today has link with several options in generation resolution, in which, allows to generate several forms that leads to knowledge increases to get ideal solution. It is more relevant to ranges, using which; the form is explored and developed (Novak, 1988, p. 14). Additionally in the context of computation design, Kolarevic mentions that as far as latest architecture designs are concerned, digital tools are allowing architects using formal, conceptual, and tectonic approaches to open new venues, and at the same time, they create a new architectural morphology to which utilizes emerging, as well as adaptive possibilities of form (Kolarevic, 2003, p. 457). Kolarevic further writes:

> The Information Age, like the Industrial Age before it, is not only challenging what we are designing but also how we design Technological architectures are being replaced by computational, digital architectures of topological, and genetic algorithms, are supplanting technological architectures (Kolarevic, 2000, p.251).

As a result, architects tried to use novel approaches and they have undergone different thought processes. Gruber & Jeronimidis pointed out that the architects including Jan Knippers, Achim Menges, and Thomas Speck had made efforts to establish an effective inter-disciplinary connection between relevant fields including architecture, engineering, design, and biology. They believed that both architectural engineering and biological evolution are non-deterministic having many commonalities and convergences but at the same time, they have certain major differences as well. According to them, the differences offered new research areas on latest technologies (Gruber & Jeronimidis, 2012, p. 1).

Biomimetics studies nature models and then takes inspiration from these models to solve human problems. It is one of the highly developing design-engineering fields, has also become an evolving subject of architecture. Benyus argues that during biomimetic processes, architects find solutions through specific methodologies, systematic approaches and rules, which occur naturally (Benyus, 2002). Today, Biomimetic design which integrate nature with architecture has offered a completely new research field. Mazzoleni notes that all this became possible with the very idea of utilizing nature in architectural design for human comfort and other needs. Biomimicry, in other words, is developing nature-inspired architectural solutions, through the interconnection between different scientific fields for solving complicated issues (Mazzoleni, 2013, pp. 4-5). Moreover, linking different fields of study provides certain intellectual solutions. Many of them were found by examines nature to integrate that biological knowledge with architectural design.

This study focuses on significant architectural design developments and its tools including design-process methodologies, computer-aided designs, simulation approaches and evaluation tools. It mainly cross questions the control-level of architects on the design processes and the infinite possibilities of form-finding in computational architectural design. The aim of this thesis, is to discuss and compare current architectural design approaches. In relation with different digital media technologies which are not just used for visualization purposes but also for form-finding and its transformation. Coined as digital architecture, these approaches includes form origination as well as its transformation. This thesis evaluates the effectiveness of digital generative processes, which are linked with concepts like parametric design and algorithms. The emphasis is on "finding of form" by digital generative techniques. The field of "computational Generation design" heavily relies on natural principles, and architecture practices, which have gained wider acceptance in professional field. This is possible when we try to amalgamate Biomimicry and Digital Architecture - the two evolving sciences, helps explore new possibilities, which exist in innovative architecture design solutions.

1.1. The Dialogue Between Conceptualization and practice of Digital Architecture

> Bill Gates has predicted that the present decade will be known as the digital decade. He believes that by the end of the decade, all aspects of our life will be influenced by the digital realm (Leach, 2002, p. 6).

The term “digital”, while used in digital architecture was introduced in the early 20th Century, and was recruited by several theoreticians in several contexts means for Grobman, innovative progress, yearning for latest technological options, and staying a step ahead of “analog” technology, which is now obsolete. As far as the meaning of the term "digital architecture" is concerned, it implies latest and cutting-edge architecture or non-conservative architecture (Grobman, 2008, p. 25). On a similar note, Manovich tried to explain the term "digital" as it is now part of common everyday discourse whenever we talk about technological facilities and advancements. Many household items including Televisions, cameras, ovens and washing machines are now digital despite the fact that they were invented long time before the digital age but the word “digital” was added because of their digital development. In this context, he refers in fact to the importent implications of the term "digital". The conversion from analog to digital (devices now using digital rather than analog signals), a terminology to represent technology and numerical factor (Manovich, 2001).

For Grobman, on the other hand, the term "digital" user more in architecture means: the first and the foremost process of the whole digitalization process is making and presenting the architectural design. Using this process, architects use a computer to create a digital design, which means that computerized or digitalized process is used for the core design rather than just for drafting and demonstrative purposes. Computerized design helps architects to create, shift, copy and manage complex designs. The second process deals with form and architectural-geometry, and the way computer-assisted design helps both. For Grobman this process includes free-form digital architectural work process, curvy, non-linear and complex geometric design processes, which are otherwise difficult-to-make and test. This process is based on formal digital architectural design and it is based on the fact that only computer-aided design can use certain forms (Grobman, 2008, pp. 25-26). Similarly, Kolarevic has argued that using digitalized process is totally challenging the traditional ways, means and methods of architecture design. On the other hand, some traditional designers claim that creating curvilinear designs can create difficulties (Kolarevic, 2003, p. 6).

Kolarevic (2003) pointed out that experts often ignore latest “smooth” architectural designs, which are part of various cultures and design practices. Rounded contours have been there in many cultures during the last ten years but its curves were largely overlooked in the architecture until recently, when they were paid due attention. It is a historic fact that the architecture and construction industries are least adaptive to change and incorporate latest technologies, for example, CATIA (Computer Aided Three-dimensional Interactive Application) stayed in use for twenty years. He also pointed out that the consumer-product makers developed computer-assisted design systems for architects. Some of the softwares used in today's industry including Soft image, Alias, and Maya were genuinely not developed for the purpose of architecture design but for meeting the needs for 3D graphics in Hollywood films; therefore, the architects tried to incorporate products and softwares used in other industries to meet their needs (Kolarevic, 2003, pp. 7-15).

James Steele, in his book "Digital Architecture" enlisted several digital architecture forms and he has discussed the role digital architectural processes which are wreaked with the help of computer-aided design process. He has elaborated diverging approaches for utilizing latest technologies and making them work along with each other technologies. Despite the fact that they are used to process different stages of architecture, combination of all offers higher design flexibility and better options for modification. For makes modification process easier and more convenient than any traditional method. Design softwares allow designers to check the reliability and sustainability of their designs even before initiating the construction process (Steele, 2001).

As a result, one can say that the development of digital architecture has one major component: Computer-aided design. Now, it is utilized in large numbers of computer-based professional assistance tools, developed for engineers and architects for carrying out and improving the design processes. Its development, however should be examined more carefully.

According to Oxman, the basic CAD facility was the first transition from paper-based design to on-the-screen design. After that major shift, CAD systems had undergone developments including 2D and 3D graphics, which enabled designers to draw closer-to-life models instead of just sketches. The first generation CAD systems used software only for geometrical modeling. The basic CAD was mainly used for graphic display of digital projects (Oxman, 2006, p. 246). From this mentioned frame Cadazz adds that later in 1980s, CAD industry made phenomenal progress, which mainly took place because of quick advancements in computer hardware. At that time, Parametric Technology Corporation launched software products including 3D solid modeling, Unix 3D, and CAD Pro/Engineer, which made a difference in the architecture design forever (Cadazz, 2017). Additionally, Kalay claims that very little qualitative effect was observed in that era as compared to conventional models. Nowadays, new bonds have emerged between real and digital models because the modeling process has become "dual-directional." Frank Gehry recognized it for the first time, after which, it was given status of a significant design development, and it is even valid nowadays in the conceptual stages of digital design (Kalay, 2004).

As compared to CAD, the BIM modeling creates parametric final products, which provide sufficient information for practical construction processes. An architect or civil engineer can extract this information from BIM model during any stage of development, which is indeed a very helpful characteristic. In the next section, we will present overview of how BIM evolved. Researchers including Eastman, Sacks, Liston and Teicholz claimed in their book called the "BIM Handbook" that the crux of development process of digital architecture lies in building information modeling (BIM). BIM has many advanced characteristics including 3D representation, which can be seen if the information is provided. The new design paradigm of design addressed some issues including non-recognition by CAD systems and interconnection issues while adding different inputs in the mainstream project (Eastman et al., 2008).

Whilst Menges (2012) argued that CAD design is based on object-oriented processes of gaining data and coding it through symbols. At the same time, it does not allow the information to exceed the initially given information.
Menges, therefore, claimed that CAD systems did not make changes in the way architects worked and it merely "computerized" some well-recognized pre-existing geometric systems (Menges, 2012, pp. 1-2).

As also explained by Quirk, the initial real BIM software was Radar CH, but its makers later transformed it into another program called ArchiCAD. It was originally developed in Hungary by Gabor Bojar. Despite the fact that ArchiCAD was the first in the category of BIM softwares, it could not gain much attention or popularity until recently because during its early phases, it had computational limitations and besides, it was facing unfavorable market (Quirk, 2012). In the same context, Eastman et al. reported that Rober Aish was the first researcher to coin the term "Building Modeling," He introduced this concept in 1986 in his research paper. His paper contains a case study, to which, Building Modeling System was practically implemented. For Eastman et al. the term "Building Information Model" which was first mentioned in the research paper "Modeling Multiple Views on Buildings" presented by G.A. van Nederveenand F. Tolman, in 1992 (Eastman et al., 2008). Additionally, as pointed by Quirk in 2002, the Autodesk Inc., developed Revit software and marketed well. Now, Revit included various new features, such as parametric families, construction phase controls, schedules and visual programming environment (Quirk, 2012). BIM which was now an established process. However, created some issues for users. It was unable to handle complicated geometric shapes, design modification, and so. Architects did not find it flexible enough to fulfill their requirements. As also defined by Menges:

> Computational design fundamentally differs from CAD. While in the computerization of analogue design techniques information is only compiled and associated, computation enables the processing of information in such a way that new information is created. […]computational design externalizes the relation between the process of formation, the driving information, the generated form and its resulting performance (Menges, 2012, p. 2).

1.2. Analytical overview of Computational Form Generation with Biomimicry

In this era, many digital design options and production procedures are opening new avenues for conceptual, formal, and tectonic possibilities, introducing a whole new architectural morphology based on adaptive aspects of models. The focus of architects and architectural researchers has now shifted from "making" to "finding" form; therefore, it helped creating various digital generative techniques (Kolarevic, 2003, p. 17). According to Menges:

> Computational form generation is in the process of profoundly changing the way architecture is conceived, designed and produced. Numerous facets of the discipline are being informed and changed by the ramifications of the rapid development of this field. Of particular interest for is the way computational design has begun to open up novel possibilities for a biomimetic approach to architecture (Menges, 2012, p. 1).

Kostas Terzidis believes that computation is different as compared to computerization because both of them have very different paradigms and formal conceptualization of solutions rather than any pre-determined logic (Terzidis, 2008, p. 65-73). Nowadays, Aghaei Meibodi refers that design computation utilizes parametric-associative processes and algorithms that help turning various constraints into segments of the exploration model. Consequently, new forms of inter-model interdependence and constraints emerge, which are explorable in different final designs. But the main concern was how computational tools can help designers to unleash their creativity. This concern became a reason for important innovations and findings (Aghaei Meibodi, 2016,p. 17).

Kizilcan offers that some software-operated and those software programs are designed using complex algorithms for finding the solutions. These algorithms are written in the form of codes and almost every code needs to be accurate for making the whole program and the machine function properly. The codes are linked with each other and every code has its own specified purpose, and the program executes commands with the help of codes (kizilcan, 2015, p. 60). Mennan (2014) notes that:

"Calculation leaves an incomplete space that cannot be saturated with information alone and waits to be filled with meaning and interpretation" (Mennan, 2014, p. 40). Here, Mennan wants to say that the interpretation of an obtained number or figure is very important because it helps understanding as to why the calculation was conducted in the first place.

Additionally in the context of computation design, Cucakovic, Jovic and Komnenov mentions that computation process takes place through algorithm-like patterns, which are based on geomatric shapes. Modeling and using latest computer softwares has helped understanding complicated biological structures. Understanding biological structure laid the foundation of for biomimetic design processes (Cucakovic, Jovic & Komnenov, 2016).

Biomimetic designs are carried out using a technique computational design, which is a reliable and innovative solution. It offers great potential in architecture. During their recent research on biomimetics, Badarnah & Kadri claimed that even now, using Biomimetics or implementing Biomimetic designs is challenging for architects and construction engineers. Experts have found that the information pertaining to natural adaptation strategies is voluminous and requires a huge data for calculations pertaining to natural design. The most significant features, which must be studied and taken from nature to architecture, are form and morphology. It is a reality that despite all research, very few natural design concepts can be termed as successful mainly because there are limitations to emulate natural design concepts for meeting needs of residential and commercial building occupants (Badarnah & Kadri, 2015, p. 1). Steadman points out that biology of all sciences, which first confronted the central problem of teleology of design in nature; and it is very natural that of all sciences that the designers take special interest in it (Steadman, 2008, p. 4).

Thus, this study explain the possibilities that computational form generation offers for enabling Biomimietic form generation processes in architecture. These processes should be clear, innovative, and explorative right according to the needs of architecture. The development and innovations in architecture design and computer-based digital tools have opened up greater possibilities; therefore, this study, aims to analyze changes, which have taken place as an outcome of computational design and Biomimicry. Also study the concepts and factors, which affect both of them, and try to find the link between them. The aim is to solutions for the research question: How Biomimicry and computational generative design can help exploring possibilities for better and close-to-ideal architecture.

The nature has a potential to teach today's architects to find appropriate solutions for architectural products. In this study, the main aim is creating detail-oriented and more comprehensive understanding of the developments and possibilities in computational form generation, Biomimicry, and the digital architecture. Another aim of this study is searching for further possibilities by utilizing biological principles in collaboration with today's sophisticated computational form generation for finding improved architectural design solutions. A clear research methodology is conveyed throughout the research for assuring achievement of research purposes. First, overview of published literature review, on important concepts including computational form generation, digital architecture, and Biomimicry. Later, rephrased the relationship between computational design and Biomimicry. The discussion with studying effects of Biomimicry on digital architecture. Next, Morphogenetic computational design analyses of computational design of Biomimicry, and its effect on today's architecture design. At last, each a step is analysed through several architectural examples in order to understanding the relation of these principles and to evaluate the advantages and disadvantages of such a design approach.

Although, the scope of thesis is to study computational generative design theory, its scope extends to the analysis of Biomimicry in architure, which is nowadays emerging as an important tool for developing sophisticated computational form generation solutions. It applies and focuses on specific biomimetic principles, which are utilized for generating morphogenetic computational design processes; therefore, the relationship between biomimicry and morphogenesis of generative design. Also highlight the futuristic potential of the innovative design.

1.3. Structure of the Thesis and Introduction of the Chapters

This thesis comprises of five chapters each one of them discusses different aspects. Introduction (chapter 1);Computational generative design (chapter 2); influence of Biomimicry on digital architecture (chapters 3); Computational Morphogenesis (chapter 4); Finally, in the last chapter we present the conclusion of the thesis (chapter 5). Brief description of chapters is as follows:

Chapter 2: Computational generative design

This chapter discusses many important computational and generative design developments. It consists of a short historical overview of computer-aided design, use of technology in architecture, computational form-generation, and development of architectural form. It also sleds light on significant fundamentals including design algorithms, integral computation applications, and different materialization possibilities. It also highlights significant approaches to generative design and computational design theories.

Chapter 3: Biomimicry (Influence Of Biomimicry In Architecture Design)

The whole chapter deals with the definition of biomimicry which its influence on computational form generation. It sleds light on the processes, through which, an organism is selected, its structure is observed, its complex geometrical shape and features are noted, and its shape is imitated in the architecture projects after careful evaluations. It shows two distinct approaches to biomimicry having clearly separate information flows. The former approach is called as "design looking towards biology," and the later approach is "biology influencing design," which proves that the biological factors affect artificial (humanly constructed) designs. It also discusses certain biomimetic principles used to implement computational design strategies using available knowledge and technology.

Chapter 4: Computational Morphogenesis

This chapter explains the concept of computational morphogenesis, it's possible benefits, its future, and its importance for architecture design. It also explains some relevant general concepts and principles, which help understanding the computational morphogenesis. It also discusses approaches to morphogenesis as both a biological concept and a significant architectural design source. The chapter compares computational modelling of botanical morphogenesis with architecture design techniques. The main theme of this chapter is design integration through computational generation, biomimicry, and morphogenesis with practical examples of some inspirational projects constructed so far and their underlying biological and construction principles along with benefits of such projects and approaches.

Chapter 5— Conclusion

This chapter ends the discussion by bringing out major conclusions, which have been drawn for the interest of the readers. It also gives direction to the researchers for future research on the subject.

CHAPTER 2

COMPUTATIONAL GENERATIVE DESIGN

In the context of computational generative design (CGD), Aghaei Meibodi writes that “Computation” implies information processing but still, it does not always generate outcomes; so, “generative” implies the property of a design that automatically generates output. Professionals use computational processes for design exploration (Aghaei Meibodi, 2016, p. 52).

In architecture, generative design is a very significant issue. In the current century, technology has become single most important factor that drives the present and future of architecture. Computer technologies are developing in the architects as well. nearly a decade age are making use of software, which were originally created for very different purposes including aviation and movie animation. Now, the computer-based software are fully capable of automatic design generation. It is now possible to generate architecture ideas by following generative rules that transmute thoughts into designs through software with the help of "Scripting Language." Some softwares also help architects creat new possibilities of design in their minds, augment their ideas, execute complicated calculations, and compare available alternatives. The purpose of this chapter is clarity of significant developments in the field of generative architecture design.

According to Frazer, Tang, Liu & Janssen, architectural concepts need expression in generative order for increasing the speed of their execution and exploration using computer-based technologies. Some concepts are expressed in the form of a coded script. Computer-based models simulate prototypical forms, which can be later evaluated for performance in any simulated environment. This makes possible to generate voluminous evolutionary steps within limited time and even unexpected forms emerge (Frazer et al., 2002, p. 2).

Frazer et al. believe that in the current era, it has become quite possible to utilize generative design strategies to resolve complex environmental issues and to overcome design drawbacks. To make it possible, it is important to understand how to use codes for creating a structural form through algorithms and how complex and apparently poor design elements can be described; so, computer technology is both a generative technology as well as an evolutionary accelerator (Frazer et al., 2002, p. 3).

Discussing generative design, Stavric and Marina have pointed out that using architecture design codes created issues throughout history of architecture. They showed that after the widespread use of computer technology in architecture, codes became a set of instructions for assuring certain attributes in the final project. Computerization of the design process has opened new avenues and provided much better and previously unavailable generative algorithms (Stavric & Marina, 2011, p.9). However, they added that the digital design development was not over just with simple parametric modeling. It was enhanced through generative algorithms. Many computer programs allow graphic editing of algorithms, which even do not require programming/scripting knowledge; still, they help designers generate a variety of non-standard design possibilities, which can be interactively altered. Experts call it parametric approach to architecture, which helps generating novel forms (Stavric & Marina, 2011, p. 9). Lorenzo-Eiroa, & Sprecher pointed that codes' relevance can be obviously promoted through computational form generation. A code is "formal digital substrate of form generation," which is a unit let refers to the geometric condition of form. In addition, it is quite expressive and goes beyond the pre-programmed graphical user interfaces; however, its only limitation is programming language and lack of geometrical options (Lorenzo-Eiroa, & Sprecher, 2013). Consequently, Terzidis ’s defines Code, or algorithm as :

> […] is a computational procedure for addressing a problem in a finite number of steps. It involves deduction, induction, abstraction, generalization and structured logic. It is the systematic extraction of logical principles and the development of a generic solution plan (Terzidis, 2008, p. 65).

Continuing with the mentioned frame of computational generative design, Stavric and Marina supported that generative programming is a form of computer programming but it utilizes automatic code making mechanisms. Generative programming, consists of two principles of generative algorithms. The former is associated modeling, which is based on systematical performance of objects and their interdependence. The latter is generative principle, which gives option to the architect to select a 3D configured solution out of various 3D configurations (Stavric & Marina, 2011, p. 12). The transition has taken place from basic computerized design to computational design, which is now very popular among architects. For Menges, the way computation has positively affected other professions, it has great impact on almost every aspect of design and construction. For completely understanding the possibilities emerged because of computational design, it is significant understand the difference between computational design and computer-aided design (Menges, 2012, p. 1).

2.1. Generative design exploration

Researchers including Frazer et al. mentioned that generative design makes use of the virtual space available in the computer software, and besides, this process helps resolving basic design issues including yacht design. Architectural issues need higher computing power than what is available in the market; therefore, current options are just tip of the iceberg (Frazer et al., 2002, p. 2).

Researchers like Aghaei Meibodi (2016); and Abrishami, Goulding, Rahimian and Ganah (2014) endorsed this idea while Abrishami et al. wrote an overview of generative design possibilities, which implies a specific design practice, in which, a designer takes help of a computer program for resolving a design issue and stays autonomous at the same time. One the other hand, eminent researcher Aghaei Meibodi believes that the design exploration is a process that explores new possibilities in the architecture design and at the same time, it offers alternatives during the design process (Abrishami et al., 2014, p. 352; Aghaei Meibodi, 2016. P. 16).

Abrishami et al also believe that despite the fact that the existing generative systems can assist designers for resolving issues and creating models, they are unable to meet significant designer needs; so, evolutionary algorithm still provides design alternatives. This helps improving the computing capabilities by helping to create complicated forms with multi-faceted details and complex layouts, which is otherwise impossible (brishami et al., 2014, p. 352). Aghaei Meibodi further writes that the design exploration model helps establishing constraints for several design implications. Generative design approach consists of a limited number of rules, which help producing many different construction forms (Aghaei Meibodi, 2016, p. 16).

According to Merriam-Webster Dictionary, word "generation" has two possible meanings: the former means the next process or bringing something into existence while the second means the development process that the former type undergoes. Discussing the second aspect, Kalay claimed that the term generation has "interrelated" meanings in the realm of architecture design; therefore, any generative process that is focused on improvement can also be a part of another process. A model is normally taken through process modification for making it effective and right according to the screening criteria (Kalay, 2004, pp. 283- 285).

Utilizing computer software and hardware have unleashed their potential to do form-generation tasks. Expressing their views on form-generation through computers, Grobman, Yezioro & Capeluto wrote that form evaluation process takes place in “after-the-fact” method because computers create form using the new information. We can assume that form-generation is implemented right in the initial phases after commencement of design work while later processes involve optimization, which needs careful evaluations (Grobman, Yezioro, & Capeluto, 2009, p. 537). They further wrote that the given information is valid for simple structures without any secondary spaces. As far as final building designs are concerned, many form-generation levels take place before creating the structures. Some steps are given:

1st step: Initial envelope/form generation

2nd step: Secondary space generation

3rd step: Building elements generation (for example, facades, windows, doors, etc)
4th step: Building details (Grobman, Yezioro, & Capeluto, 2009, p. 537). Still, these four steps do not cover all the input range, which can be utilized for architectural form-generation. Designers provide yet another type of information: For Kalay, link between function and form shold be articulated in close connecting. According to famous quotation by Sullivan, “Form follows function.” He also claimed that the “appropriate design solution” exists in the possibilities offered by context, function and form. For Kalay, form is a significant factor, which specifies the spaces and defines how those spaces will exist together. Clearly defined function shows the predicted performance expectation while the context sleds light on the relation between the environment and the urban fabric (Kalay, 2004).

Kolarevic pointed out that new digital trend has initiated a very thought-provoking debate pertaining to the opportunities and the difficulties, that might emerge because of digital form-generation. Now the focus has shifted from "making" to "finding" form, which is possible through digital generative techniques (Kolarevic, 2003, p. 457). In the same way, Aghaei Meibodi also raised the argument that generative design possibilities require specific design-intent. It includes resolving design issues, exploring untapped potentials, and overcoming design-process limitations using most appropriate and sophisticated computational methods. These methods help handling both real and digital data (Aghaei Meibodi, 2016, p.16).

For Aghaei Meibodi, as the design process is no longer limited just to human creativity and ideation now there is a man-machine collaboration to explore suitable alternatives available for design. This collaboration has given some inconceivable outcomes and the design options, which were unavailable before (Aghaei Meibodi, 2016, p. 16).

Computation-based design process is a substantial breakthrough for creating geometrical designs and controlling them as well in the best interest of building users; however, its practical application has largely remained a challenge as any error could affect the effectiveness and objectivity of a project. Still, the technology and training has provided great progress since the time the whole idea was conceived and presented to architecture designers. Aghaei Meibodi, during a discussion on computation, has claimed that most of the algorithms and design techniques can be added to the exploration model. Consequently, inter-model interdependence has emerged, which has implications for dealing with limitations and they can appear as final design outcomes. The main concern is as to how designers can utilize computational tools for augmenting their creative potential and find innovative solutions and outcomes (Aghaei Meibodi, 2016, p. 17).

Novak suggests paradigm shift to computational composition using latest technology and methods for high quality architecture that will be much better than the traditionally designed architecture (Novak,1988). Practically, Abrishami, et al. questioned as to why BIM and CAD technologies were failing to create a wholesome and fully-integrated design process. These softwares are still unable to assist designers and do much when they took decisions pertaining to material, structure and shape (Abrishami, et al., 2014, p. 351).

It is a fact that the architects, who solely rely on sketch-drafting and commonly available software It is a fact that the architects, who solely rely on sketch-drafting and commonly available software laces to provide any substantial option for complete form elaboration during the design process. provide any substantial option for use during the design process. In addition, both the currently constructed 2D drawings as well as 3D modeling are hectic tasks to accomplish as they take lot of attention, time and focus. Moreover, BIM and CAD have capability to handle complex data to a certain limit and then it becomes challenging task for architects to continue their tasks with convenience. Projects, which contain complicated processes and data, cannot be accomplished with the help of traditional softwares and sketches because they are unable to troubleshoot project issues. Aghaei Meibodi assumed that the design process and the overall architecture are not meant just to create a specific design solution or optimize an existing solution but it is largely meant to model the innovative designs (Aghaei Meibodi, 2016, p. 17). Therein, it is possible to stated that computational software, specially on form generation, gives to appropriate methods to create more innovation and novel solutions for existing design issues.

2.2. Design Automation of computational generative design (practice & tools)

Bentley stated that automated designs largely rely on softwares, using which, designers design, save, amend, and retrieve their designs. With the help of softwares, designers have been improving their designs when they use analyzing softwares, which provide learning chances to them. In the process of designing and analyzing, designers learn how to create alternative solutions to the existing issues. Designers' knowledge helps generating innovative solutions, which are the products of very different ideas. This method has the potential to introduce altogether novel designs and finding new methods to use an existing technology (Bentley, 1999, p. 2). While studying computational design, Kostas Terzidis (2008) noted: Engineers, architects and project managers felt the need for computational methods to resolve, address and understand complex design requirements. As a result, logical solutions emerge, based on appropriate, systematic, and traceable solutions to the design issues (Terzidis, 2008, p. 86).

In the context of computational design in architecture, Menges had already described that in computational design, forms are not only determined out of series of modelling steps, but also used scripted links with generative procedures. In contrast to Traditional design, computational design made the relationship clear between form and information (Menges, 2010, p. 4). Similarly, Shea, Aish & Gourtovaia wrote that the design softwares and tools have gone farther than just a means of producing drawings. They now utilize a whole new integrated design approach, new modeling approach, and performance monitoring tools. Today, computer systems have become design partners because it is now possible to generate new designs, which were earlier inconceivable before (Shea, Aish & Gourtovaia, 2005, p. 253).

Discussion computational design, Menges point out that the tools for finding correlation, which deals with algorithmic data, helps generating designs despite material constraints and limitations. Computational design helps understanding important aspects of building design including design, structure, form, material, and fabrication as well as link each of them with the other. It helps unleashing multiple possibilities in design. The computer-based analysis and design help generating new solutions and explore new possibilities in materials (Menges, 2008). In another study, Menges (2010) also pointed out the computational designs have a direct feedback mechanism within form generation process. Using computational design has many other features. According to Agkathidis, some digital design tools are generally "seductive" for building designers. One the other hand, they increase the design speed, which makes them pay less attention to important aspects like materials and gravity. Orthodox physical modeling makes learners understand their importance and their critical nature in the architectural production (Agkathidis, 2015, p. 53). Now computational design not only speeds up design processes but also helps giving creative option and acts as an auxiliary tool to help taking important decisions pertaining to building design. In addition, computational design helps providing creative solutions to the design issues and some viable alternatives for direct usage. Despite all the options it provides, designers need more tools for increasing their professional efficiency. This urged design and software producers to improve their packages by giving the designers more options that are viable.

The first option is Parametric Design. Goulette & Marques believe that a parametric design is a principle-based and dynamic approach, which is managed through parameters and variations. They were basically developed for aeronautical engineers and car manufacturers; so, parametric modeling creates visual dimensions of graphic concepts (Goulette & Marques, 2014, p. 2). Additionally, Abrishami et al pointed out that the computational design has been created after fully understanding the designers' needs in later design stages, which has helped them finding viable solution to their design issues through design alternatives. Fundamental design options were created years ago and the currently available parametric options helped designers improve their design output (Abrishami et al., 2014, p. 352).

Asl (2014) believes that parametric design includes introducing defined factors and allowing designers to make changes in them according to different situation. Parametric form can be easily changed and a designer discovers various modes using the parameters. Moreover, parametric design is a futuristic design option because it is multidimensional (Asl, 2014, p. 184). Goulette, & Marques (2014) notes that :

> The term “parameters” relates to numerical and graphical data, which determine a series of variations.[...] The updating of shapes is based on the new values and a set of descriptors (algorithm) of geometric elements and relationships. In a parametric design environment, the model has no fixed form or content, but may be modified and explored from its variables(p. 2).

Further, in term of parametric design, Oxman suggests that traditional techniques within a parametric design environment create professional environment, which helps designers use user-defined generic properties. Contemporary parametric design options are based on non-standard and non-traditional geometric rules, which designers can use for creating a dynamic change (Oxman, 2006, p. 233).

According to Goulette & Marques , parametric design has possibility of multiple instances while on the other hand; Asl opines that the parametric tools help decreasing issues pertaining to form. Building modeling software helps understanding the building response against environmental situations and helps it make more environment-compatible because even before designing a building, a designer understands the direction of sun and wind, and facts like natural heating, cooling or moisture (Goulette & Marques, 2014, p. 2; Asl, 2014, p. 184). Goulette & Marques opine that parametric design/morphogenesis focuses on two kinds of objects: 1. Algorithm in a programming language and its graphic interface, which shows geometric and topological dynamics. 2. Parameters that interpret and show specific instances (Goulette & Marques, 2014, p. 2).

According to the opinion by Abrishami et al, parametric design application is successful in several BIM applications, which act as change agents and its management engines. Parametric design systems developed gradually and now they are very effective for design but even now, architects do not consider them as comprehensive architecture design softwares (Abrishami et al., 2014, p. 352).

Asl (2014) further writes that parametric design helps creating aesthetic form for the visual comfort even when an investor does not want to spend a lot of money on a building. It also helps improving environmental efficiency of a building and its space utilization (Asl, 2014, p. 190). Therefore, Goulette, and Marques (2014) finally wrote that when an algorithm is fully defined, a kind of dialogue initiates between the graphic software and the designer, which makes him or her modify parameters for more optimized design and look for better design options (Goulette, & Marques, 2014, p. 2).

According to Kizilcan (2015), an algorithm has finite set of instructions for problem solving pertaining to data processing, computation, and reasoning automation. It also helps define basics or milestones of problem solving. Now it is quite probable to write algorithms in many representatives in different forms such as flowcharts, pseudo codes, spoken languages or programming languages (kizilcan, 2015, p. 60).

Kolarevic (2003) believes that common characteristics have appeared in many designs, which have been designed earlier. This has happened repeatedly in 2000s. Guggenheim Museum Bilbao, which was designed by Frank Gehry, is a good example of incorporating new design concepts (Kolarevic, 2003, p. 2). Additionally in the context of computational design, Zaha Hadid was one of the successful architects. Her architectural designs from smooth curvilinear lines were inspired from fluid lines and movements of a body. Consequently, the new computational design tools had an important and increasing influence on the works of successful architects.

Figure 2.1: Gallery of Heydar Aliyev Centre by Zaha Hadid (Source: www.zaha-hadid.com/architecture/heydar-aliyev-centre)

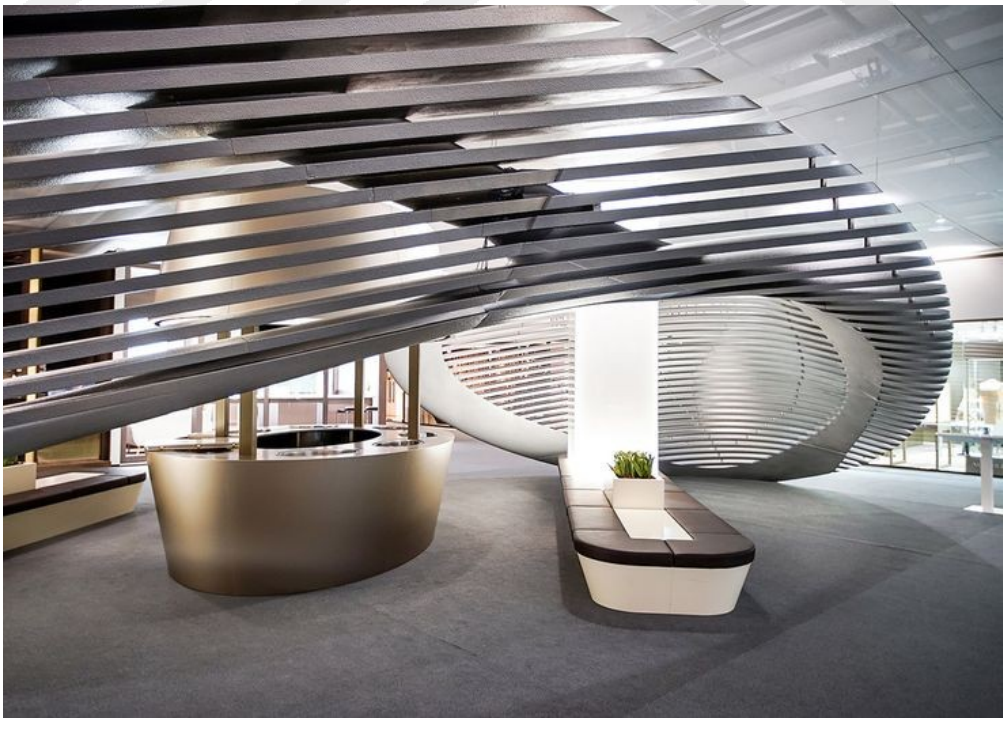


Figure2.2: Baselworld 2015 Design by Zaha Hadid (Source www.dezeen.com/zaha-hadid-sterling-silver-jewellery-georg-jensen)

For effective usage of computational design, a designer should initially convert his concepts into programmable shape using a "Scripting Language." According to Adriaenssens et al. (2014), scripting means code development. Scripts are actually small codes, which work with important supporting software. Scripting was introduced in 1960s for handling repetitions and long tasks. They extend and customize programming possibilities to meet the specific needs of commercial users, for example, CAD applications work with very simple scripts (Adriaenssens et al., 2014, p. 237). Biloria, et al. (2006) define scripting:

> Scripting refer to the process of writing a simple program in a utility language to orchestrate behavior. It consists of a set of coded instructions that enables the computer, to perform a desired sequence of operations (p. 78).

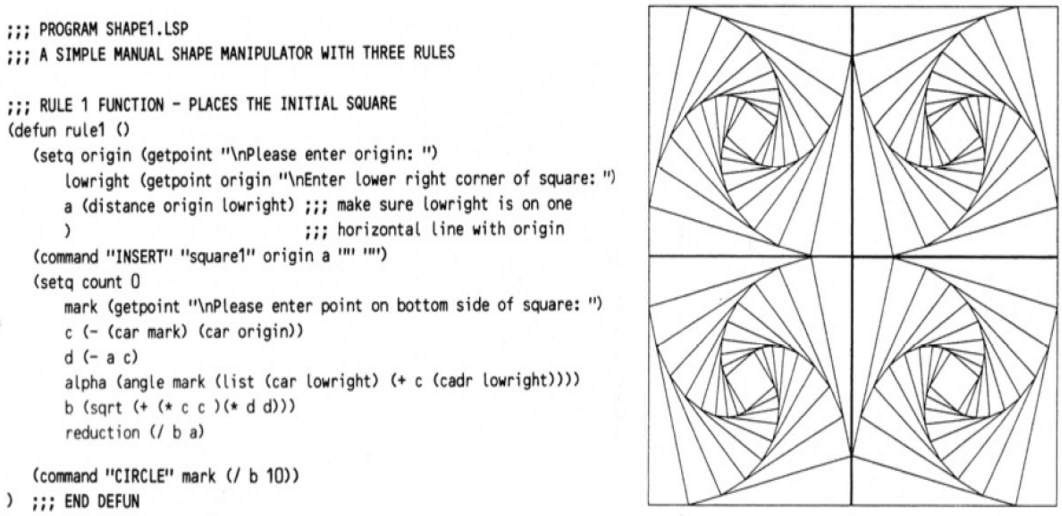
During a discussion on scripting, Oxman mentioned that the scripting process work with non-deterministic purposes and form generative initiatives and not with explicit representation of specific form either on CAD or on paper. The non-deterministic design has emerged as a new reality in the building design, which offers additional possibilities in the digital design (Oxman, 2006, p. 250). Aghaei Meibod believes that synergies are created by the interaction of algorithm and computer (algorithm-based 3D programs), and it also helps generate new designs and give automation to the design process (Aghaei Meibodi, 2016, p.65). According to Kizilcan (2015), formal systems can solve only decidable issues, so, coding was introduced to resolve both formal and quantifiable issues. Assumptions like "closest distance" and "farthest point" are quantifiable geometrical assumptions and they help resolving the issues using computational methodologies (Kizilcan, 2015, p. 56).

Scripting languages differ with respect to syntaxes and structures, and with respect to their outcomes as well. The available scripting language softwares include AutoLISP, Rhinoscript, and Grasshopper. Following is the description of popular scripting softwares:

First scripting tools is AutoLISP. In fact AutoLISP is a high-level programming language used for AutoCAD. It was introduced in mid-1980s for assisting AutoCAD Release 2.1 programming.

AutoLISP users can operate and control all the options provided by AutoCAD because it offers a useful variety of tools. It helps creating tools for improving AutoCAD output. Moreover, it helps exploring complicated geometry that traditional CAD packages do not offer (Autodesk, 2015).

As illustrated, AutoLISP is useful AutoCAD usage facility because it helps enhancing and extending the options offered by AutoCAD and executing functions more effectively; however, designers do not use it frequently because it needs programming knowhow for successful and effective operation. Besides, it takes massive effort to exploit this programming language's full potential.



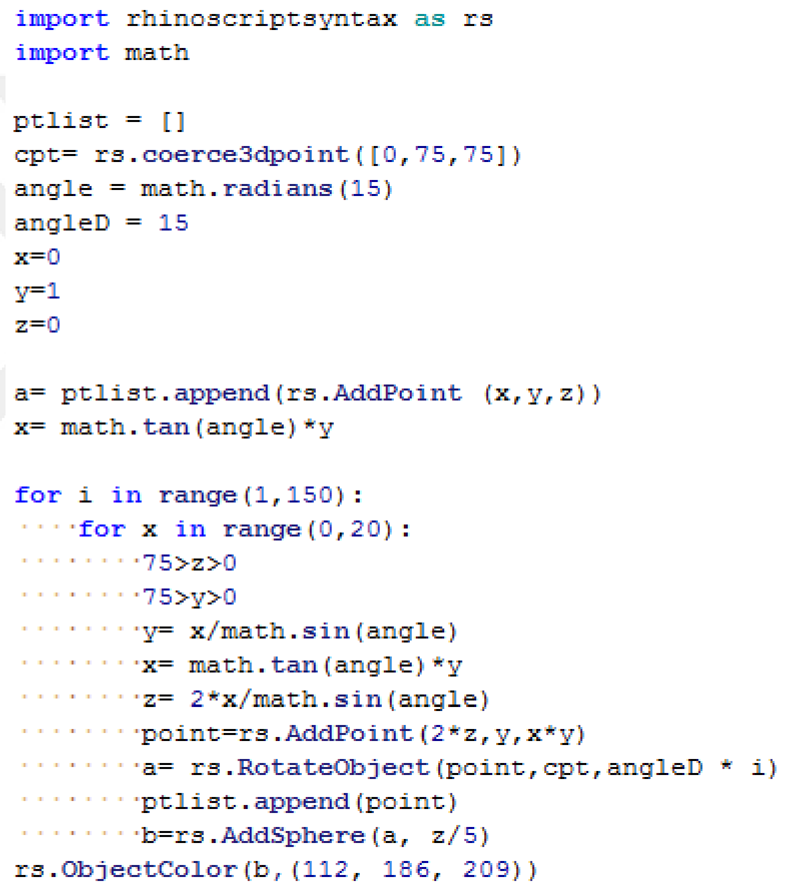
```
;;; PROGRAM SHAPE1.LSP
;;; A SIMPLE MANUAL SHAPE MANIPULATOR WITH THREE RULES

;;; RULE 1 FUNCTION - PLACES THE INITIAL SQUARE
(defun rule1 ()
   (setq origin (getpoint "\nPlease enter origin: ")
      lowright (getpoint origin "\nEnter lower right corner of square: ")
      a (distance origin lowright) ;;; make sure lowright is on one
      )                            ;;; horizontal line with origin
   (command "INSERT" "square1" origin a "" "")
   (setq count 0
      mark (getpoint "\nPlease enter point on bottom side of square: ")
      c (- (car mark) (car origin))
      d (- a c)
      alpha (angle mark (list (car lowright) (+ c (cadr lowright))))
      b (sqrt (+ (* c c )(* d d)))
      reduction (/ b a)

   (command "CIRCLE" mark (/ b 10))
)  ;;; END DEFUN
```

Figure2.3: Autolisp scripting example (source: Celani, 2008, P.11)

Rhinoceros is next on the list of script languages. Rutten mentioned that Rhinoceros 3D has a command line interface that works with the help of keyboard command. Macros is the easiest option available for Rhinoceros 3D programming. In this program, users can develop new commands and record a command sequence whenever needed. Macro takes a single command to execute the whole sequence of commands. This is a flexible feature but its limitation is the need to write commands many a times. This shortcoming created a need for a scripting language to act with qualities of macros, programs, and plug-ins at the same time. Rhinoscript is very popular because of its amazing and useful features (Rutten, 2007). And added that the performance of Rhinoscript scripting because it provides a user with access to Rhino's geometric library, processes, contents and graphic interface using VB (Visual Basic) language, which is the easiest programming language. Rhinoceros 3D library is the main reason why Rhinoscript is a very popular scripting language because it helps designers create complicated shapes. Therefore, most of the users use it for modeling geometrically complicated shapes (Rutten, 2007).



```
import rhinoscriptsyntax as rs
import math

ptlist = []
cpt= rs.coerce3dpoint([0,75,75])
angle = math.radians(15)
angleD = 15
x=0
y=1
z=0

a= ptlist.append(rs.AddPoint (x,y,z))
x= math.tan(angle)*y

for i in range(1,150):
    for x in range(0,20):
        75>z>0
        75>y>0
        y= x/math.sin(angle)
        x= math.tan(angle)*y
        z= 2*x/math.sin(angle)
        point=rs.AddPoint(2*z,y,x*y)
        a= rs.RotateObject(point,cpt,angleD * i)
        ptlist.append(point)
        b=rs.AddSphere(a, z/5)
rs.ObjectColor(b,(112, 186, 209))
```

Figure 2.4: Screenshot of Sample Python Code in Rhinoscript (Produced by the author)

Rhinoscript users requires programming knowledge and many designers are unable to use it; however, lack of programming knowledge can be overcome through visual programming. We will throw light on visual programming in the next segment.

Grasshopper is third and another popular scripting package. Akos & Parsons mentioned that Grasshopper facilitates users with the help of visual programming language, which architects had developed as a plug-in for Rhinoceros 3D. Grasshopper was originated when the clicking option "Record History" was provided in the 4th version of Rhinoceros 3D, which automated modeling. Later, David Rutten raised a concern: "What if we try to gain explicit control over the modeling procedure history." After his question in 2008, Explicit History, the previous version of Grasshopper, was created (Akos & Parsons, 2014). Asl (2014) writes that Grasshopper had a plug-in of Rhino, which was a new addition and it helped curve creation and new form exploration. It is parametric, based on geometry, and helps creating complex diagrams and Norbez lines. Asl also pointed out that Grasshopper design generator helps discovering geometrical shapes and exploring new possibilities (Asl, 2014, p. 186). But Akos & Parsons argued that Grasshopper was basically developed as a graphic editor, and it was later integrated in Rhinoceros 3D. For operating it, designers do not need programming skills because it helps users use components for drawing a form or a parameter. The introduced components help creating a dataflow. Its results appear in Rhinoceros 3D as well (Akos & Parsons, 2014).

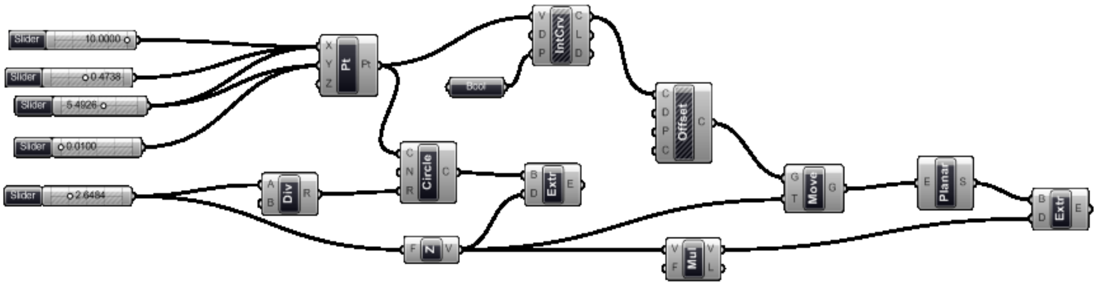


Figure 2.5: Grasshopper and logic element connection (Produced by the author)

According to Stavric & Marina, Grasshopper is perhaps the most important generative design editor so far. The form of modeling that is linked and helps generating designs, is termed as generative algorithm modeling. They generate shapes and objects with the help of algorithms and also finalize or amend them with the help of algorithms (Stavric & Marina, 2011, p. 12).

Grasshopper has been so popular for a major reason, which was its graphical interface, and it makes it easy-to-learn. Grasshopper had taken the market like a revolution and even now it is one of the most popular tools available. This tool is very helpful during the initial phases of a project as it does not give very good options for later design phases. Leach supported Grasshopper by saying that it exploited the true potential of digital design and created new opportunities. It helped optimizing design processes through pseudocomputational logic, which is a very important part of the contemporary design (Leach, 2002, p. 36).

Ultimately, a fact should be acknowledge that designers' software operational skills are not like software engineers. Their operational capacity and adapting capacity is very different; therefore, they need easy-to-learn operations.

2.3. Generative design and computational theories

Latest architectural methodologies and digital technologies changed many theories and beliefs about computational generative design. Here, it is important to investigate various computational generative design theories. Some of them were designed after taking inspiration from biological analogies (see the next chapter). Generative designs are focused on locative design to make use of a computer’s processing potential to deal with data processing limitations. According to Oxman, generative design has evolved in a different way and it took place while producing design categories. The impact of generative design created the need to rethink the ongoing practices and theories pertaining to generative design for explaining and thinking about the futuristic research and development (Oxman, 2006, p. 229). Agkathidis (2015) defines generative design in following words:

> It can be described as a design method where generation of form is based on rules or algorithms, often deriving from computational tools, such as Processing, Rhinoceros, Grasshopper and other scripting platforms (p.48).

Frazer (1995) believed that architectural designs are made using specific generative rules and in the process, they might be digitally encoded. Generative instructions create many prototypical forms for performance evaluation within a simulated situation (Frazer, 1995, p. 9). For Kolarevic, on the other way, algorithms can be considered a form of evolutionary and adaptive search processes. The "string-like structure" seems like naturally existing chromosomes with genetic makeup and biological laws such as reproduction and genetic mutation, as if a string-like structure in a generative process (Kolarevic, 2003, p. 37). In addition to it, Frew states that less universal approaches accrue benefits to computational generative design, which helps designers create building plans, mostly constructed on empirical grounds (Frew, 1980). Bentley claimed that computerized generation of form is just limited to "cramped" segments of the design including geometrical or other creation-linked issues (Bentley, 1999).

Discussing the same topic, Oxman mentioned that the evolutionary design is the outcome of evolutionary process. Orthodox techniques were part of research, which analyzed computational form-generation mechanisms. For form-generation, internal genetic coding has replaced traditional methods. Important theories on complex systems are linked with evolutionary models (Oxman, 2006, p. 256). Abrishami et al. discussed evolutionary design methods as well as software including genetic algorithm, cellular automata, L-systems, swarm intelligence and shape grammars, as tools which helped designers to improve their design capability the initial years of computerized design (Abrishami et al., 2014, p. 352). These tools can be described as follows:

- Cellular Automata

According to Grobman et al., Cellular Automata were most probably the evolutionary generative systems. They were inspired by biological concepts and they were part of a self-production model presented by John Von Neuwann in 1940s (Grobman et al., 2009, p. 540). Later, Rocker argued that 2D technology became the evolution of simulating algorithms and design softwares. A package called Conway’s Game of Life was made in 1970s that helped designers draw 2D patterns using fundamental rules (Rocker, 2006). Although, Wolfram believed that cellular automaton is based on simple mathematical and analytical methods for generating wide range of complex diagrams. They were holistic models, which encompassed systems pertaining to physics, chemistry, biology, and other sciences. Varying rules having varying degrees of complications generate complex patterns, which are generally not predictable enough [Fig2.6] (Wolfram, 1984).

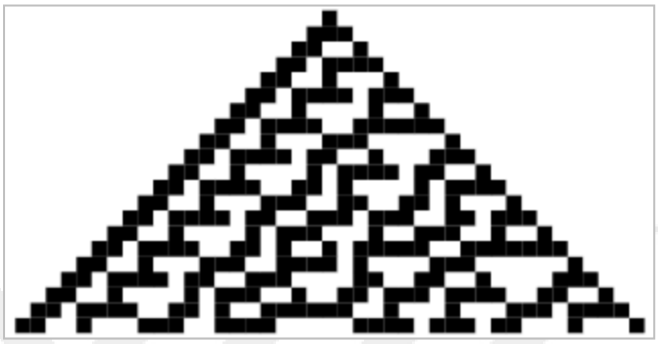


Figure 2.6: Cellular Automata (Source: http://mathworld.wolfram.com/ElementaryCellularAutomaton.html)

- L-systems

Rocker pointed out that from the very beginning, architects were inspired by nature, and geometrical forms existing in it. They tried to incorporate nature's geometry in their work, for example, L-system was inspired from the nature. Famous biologist and botanist Aristid Lindenmayer developed a system for learning from plant growth. He observed rules, constants and modification parameters using varying starting points (Rocker, 2006). Similarly, Prusinkiewicz, Hanan, Hammel and Mech argued that formalism was linked with abstract automata as well as formal languages, which was significant and interesting for theoretical computer scientists. Mathematical L-systems was inspired by plant modeling. L-systems and its relevant systems became popular after 1984 because at that time, Smith presented graphics for visualization of structures and specs of models. Then experts studied plants, their leaves and branches to learn from them. The L-system had a set of symbols and it was rule-based, which helped finding new forms with different attributes. Natural processes including plant development include "shedding" or removal of specific parts from the structures (Prusinkiewicz et al., 1996, p. 7).

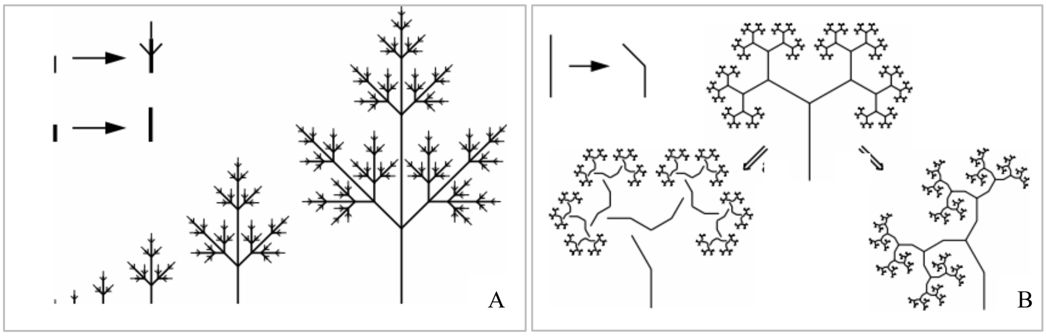


Figure 2.7:Plant development as a rewriting process (a) Developmental model of a compound leaf; (b) comparison of the construction (Prusinkiewicz et al., 1996, p. 2)

Kolarevic (2003) writes in his book "Architecture in the Digital Age" that the L-systems are based on rules and a branching system, through which, designers can create complex structures and replace the objects, which were created before. Karl Chu is famous for his work on digital morphogenesis and specifically for "proto-bionic" architecture created on generative logics present in the L-System. It was used for plant growth simulation (Kolarevic, 2003, 38). Moreover, Smith introduced the idea of "database amplification," which means that compact data can be used for creating complicated structures, and it proved as a cornerstone of L-system functions for synthesizing images (as cited in Prusinkiewicz et al., 1996, p. 1). Theoretical biological principles helped creating an effective generative computing system, which was later used as a part of many design generation and computational tools.

- Voronoi Diagrams

Nowak had discussed Voronoi Diagrams in his research. The title of his research paper was: "Application of Voronoi Diagrams in Contemporary Architecture and Town Planning." Voronoi diagram comprises of a graph that contains ovule cells, corners and nodes. It is made up of parts with half lines (Nowak, 2015, p. 30). According to Fasoulaki, Voronoi studies have been manifested centuries ago. He quoted example of René Descartes (1644) but the final version of the diagram appeared when George Fedoseevich Voronoi presented it in 1907. It is a series of spaces and polygons containing generation points (Fasoulaki, 2008). Additionally in the same context, Nowak writes that the current version of Voronoi diagrams is a significant inspiration for those architects, who create structural forms. Latest design processes depend on nature and self-organizing principles of biological structures with the help of mathematical modeling (Nowak, 2015, p. 30).

Figure 2.8: Voronoi diagram found in nature in dragonfly wing (a); sea urchin shell (b); Voronoi as dual graph (c) (Nowak, 2015, pp. 30-31)

- Shape grammar

Stiny and Gips defined shape grammar as "design-oriented" generative systems. They were discovered and presented by George Stiny and James Grip in 1970s (Stiny & Gips, 1971). Grobman et al believe that a shape grammar has rules, which apply to initial shape. For that, the form is acknowledged and its replacement is considered. Phase structure grammars utilize alphabetic symbols for generating single-dimension symbol strings. Shape grammar has orientation towards their initial design stages (Grobman et al., 2009, p. 541). Shape grammar uses a computer's processing speed and execution power for generating intricate forms in the normal design processes. Rules and principles make their geometric shapes and distributions easy-to-understand, which helps design and construction management and modification. Grobman et al. summarized that the forms are structured as per formal rules, and their effect is limited to creativity and inspiration. They believe that while differentiating between the forms, this approach is not a stand-alone approach, so it cannot resolve any issue (Grobman et al., 2009, p. 542).

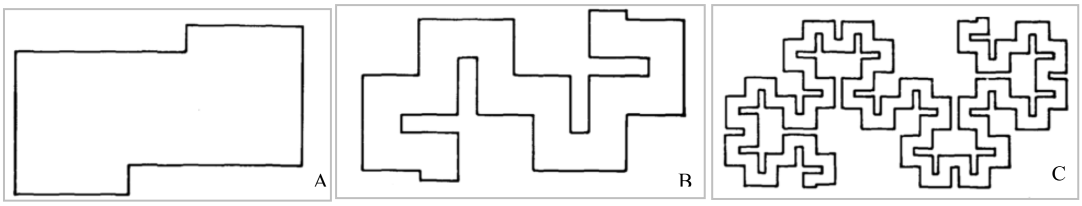


Figure 2.9: Shape grammar generated of the repeated use (a,b,c) (Stiny & Gips, 1971, p.132)

- Genetic Algorithms

Goldberg & Holland wrote that even simple "genetic programs" are quite complicated as compared to complex human designs (Goldberg & Holland, 1988). Fasoulaki explains genetic algorithm as a computational procedure, inspired by natural evolutionary, which was first introduced in the 1970s by Holland. This system has been used as a method of solving optimization problems of biological evolution. The first population is termed as genotype, which is governed by genetic principles and specs (Fasoulaki, 2008). Refering to Fasoulaki 's discussion, one can state that genetic algorithms consist of four roles including population creation, selection, crossovers, and mutations. These terms are used in architecture for handling complicated nature of projects. It helps solving fully defined construction issues including structural or performance issues [Fig.2.10] (Fasoulaki, 2007).

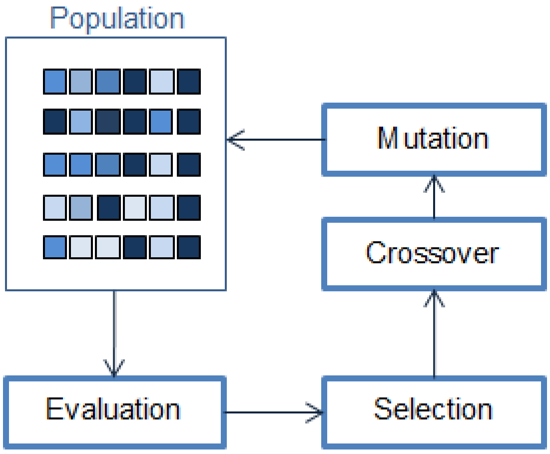


Figure 2.10: Genetic Algorithms (Source:https://www.fontenay-ronan.fr/unrelated-parallel-machine-scheduling-problem-heuristic-genetic-algorithm/)

Grobman et al stated that Genetic Algorithm Designer is the name of software, which Bentley (1999) designed and it helps separating "genotypes" and "phenotypes". Genes are coded and they exist in their basic shape called as parameters. Genetic algorithms analyze the outcomes and it is created to reach the best possible solution (Grobman et al., 2009, p. 543). Generative designs are widespread ways and poignant to the design process. It allows many options, alternatives and possibilities, which other tools do not offer. Current generative design techniques have great potential but still, it is not possible to leave everything to them because still the architect's knowhow, creativity and understanding plays a major role in the design process. Even now, some hardware and software limitations limit the process of design and its possibilities, for example, the learning curve used for programming and handling large-scale issues.

In this segment, described how information that computer usage has enhanced the possibilities in computational generative design; therefore, integrating computational processes in the design phase helps designers handle data complications. Digital design development does not stop with basic parametric modeling but it can be enhanced through generative algorithms. Generative design cannot eliminate the role of designer but with its help, better design work and sophisticated execution become possible. We, therefore, draw a conclusion that generative designs result in effective outcomes when highly pragmatic collaboration emerges among designers and programmers. Until now in this chapter, generative design approaches and theories having biological backgrounds are examined. In the next chapter, will be analyzed and evaluated biologically inspired designs from nature.

CHAPTER 3

BIOMIMICRY (INFLUENCE OF BIOMIMICRY ON ARCHITECTURE DESIGN)

> Consciously emulating Nature’s genius means viewing and valuing the natural world differently. In biomimicry, we look at Nature as model, mentor, and measure. J.M. Benyus

Biomimicry was introduced as a terminology for the first time in 1982, but it became a popular concept when Jaine Benyus wrote a book "Biomimicry: Innovation Inspired by Nature" in 1997. According to the author, biomimicry is a science, which is about natural models and their imitations. Such imitations are part of nature-inspired concepts aimed at resolving human problems. Benyus describe nature in following words: "Model, Measure, and Mentor" (Benyus, 1998).

Biology, for Mazzoleni, is conceptually abundant field of education, which extends beyond the scope of other sciences. Besides, it has a tendency to blend in other sciences and go beyond its limits to apparently irrelevant subjects, including architecture."Biomimetics" is a popular scientific terminology, which Otto H. Schmitt introduced in 1960s. He considered it as “biology + technology” but this equation was applicable just to engineering. Biomimicry has been a significant part of regular scientific research and development since 2000, when it was first applied to design (Mazzoleni, 2013, p. xix). Furthermore, as Badarnah & Kadri deemed biomimetics appeared as an emerging and developing discipline of computational design. Biomimetics, for term, is the utilization of natural mechanisms, materials, and methods for finding architectural solutions. Experts introduced several biomimetic design methodologies. Between 2005-2015, however, biomimetics has been a significant acter for architectural studies for only the last two decades (Badarnah & Kadri, 2015, p. 1).

Steadman mentioned Biomimicry and its use in computational architecture design in his book: The Evolution of Designs. This book sleds light on the link between Biomimicry and computational design, with a prospect towards their past and their probable future. He mentioned that for understanding natural forms, the designers should dig deeper to understand biological systems for making appropriate models and developing innovation methodologies (Steadman, 2008, p. xv). Similarly, Mazzoleni claims that biomimicry creates a link between complexity, biodiversity and coexistence. When a designer mimics nature, the amalgamation of nature and the designed product results in great and sustainable benefits (Mazzoleni, 2013, p. 39). According to Badarnah and Kadri, however, it is hard to select appropriate strategies from the huge and voluminous database and transferable from nature,including both form and morphology (Badarnah,& Kadri, 2015, p. 1).

Although, there is less utilization that is completely new of biologically inspired strategies in architecture and theory of design, when scientists observed behaviors of different species and applied those principles to design. Biomimietics which learning and applying principles learnt from behaviors of species, is just the same as the old "biotechnique," or "biotechnics" of 20s and 30s, for Steadman. On the other hand, Badarnah & Kadri claimed that successful biomimetic designs are limited, but it is very much possible to perform beyond the current limitations and to implement the natural strategies to meet the users' needs. Architects and designers, often meet the following challenges and issues during the implementation of biomimetics: 1) Finding useful techniques to use nature's database and incorporate its designs; 2) Overcoming issues and obstacles; 3) Addressing conflicting aspects of nature-inspired designs (Steadman, 2008, p. 153; Badarnah & Kadri, 2015, p. 1).

Steadman has pointed out that the process of Biomimetics is gradually gaining momentum mainly out of environmental issues, public focus towards clean, green and improved environment. Due to growing popularity of the very idea, the nature-inspired designs create better and healthier atmospheres. In this context, computers have made it possible by facilitating architects, designers and engineers (Steadman, 2008, p. xv). Since the evolution of modern science and research, architects have been looking towards biological details for getting inspiration and information to create cutting-edge designs. They are no more interested in creating animal and plant imitations and now, they are interested in mimicking nature through imitating natural evolution and growth. Eminent architects including Le Corbusier and Frank Lloyd Wright have emphasized nature-centric designs in their writings and discussions. Le Corbusier believed that biology is a "great new word" for architecture.

3.1. Evolutionary design of Biomimicry

> From my designer's perspective, I ask: Why can't I design a building like a tree? A building that makes oxygen, fixes nitrogen, sequesters carbon, distils water [...] changes colors with the seasons and self replicates. This is using nature as a model and a mentor, not as an inconvenience. It's a delightful prospect (McDonough & Braungart, 1998).

John Frazer, in his popular book "Evolutionary Architecture" claims that biological and evolutionary forms help creating designs, which makes better use of computation and now, the same is applicable to the architectural forms. In the same way, Mazzoleni mentioned that the biomimietic design process is going to transform building methods forever and the designs will be linked with the natural world. He observed a trend towards "RE" and those REs include REpair, REthink, REuse REduce, REcycle and RE-imagine human methods of living on this planet. Technology emerged when the majority had a mindset of "conquering" nature in favor of humans but now, architects want people to live in harmony with the nature to meet their needs; therefore, the design work is transitioning from simple nature imitation to performance-driven and natural computational designs (Fraze, 1995, pp. 10-11); Mazzoleni, 2013, p. 5).

Menges mentioned that Biomimetic architectural possibilities are numerous and they are taking place through computational design. Latest Biomimetic products adjust well within definitive Biomimetic building processes. Bar-Cohen states that nature has always been source of inspiration for those, who have been willing to upgrade their lives. It also helps humans understand different principles to innovate useful devices and upgrade their performance. It is a general observation that the nature caters to the needs of cells because every cell is a biological creature; therefore, biology has answers to the issues and needs of people. Biomimetics has to be learning-based because only then it will be successful (Menges, 2012, p. 9; Bar-Cohen, 2005, pp. 2-4).

Mazzoleni pointed out a fact that for creating useful nature-inspired designs, teams of experts belonging to various professions and disciplines are needed, which include biologists, ecologists, programmers, botanists, engineers and investors. Steadman have created a list of those centers, which emerged as study places for Biomimetics. Most of them are research departments of universities and other research centers including the Centre for Biologically Inspired Designs at Georgia Tech, Atlanta, Biologically Inspired Systems Lab in Sweden, and the Centre for Biologically Inspired Materials and Material Systems at Duke University in North Carolina. A specific and dedicated journal on Bioinspiration and Biomimetics initiated publishing in 2007. In the UK, research places are established in Reading University and Bath University to conduct biomimetics researches. George Jeronomidis started the Reading group while Julian Vincent contributed to initiate The New Science of Strong Materials, Centre for Biomimetics, which was actually name of his teacher Jim Gordon's book. In that centre, researchers explored the properties of organic materials and conducted experiments on biological building blocks like bones, collagen, chitin (used to monitor insects), spider silk and cellulose (Mazzoleni, 2013, p. 5; Steadman, 2008, p. 260).

Mazzoleni emphasizes in his literature that biomimicry links different systems for resolving complicated issues. It integrates various subjects and needs expertise of various professionals. Researchers are working on finding an environment-friendly solution to pollution and energy problems in the buildings. Those solutions are termed as smart solutions, which have obvious scope of harmonizing human habitable spaces with the nature rather than creating negative effects on it (Mazzoleni, 2013, p. 5).

Mazzoleni further writes that the time has come when experts have to find new and more useful ideas for designing building, which have better use in terms of functionality, culture, and technology. This will help setting futuristic living standards. Current parametric designs help architects and designers use algorithms to draw parameters in a digital way that helps generating complicated geometric shapes and forms to design structures and facades (Mazzoleni, 2013, p. 5).

Additionally in the context of Biomimicry, Steadman mentioned that the new architects and researchers are experimenting with computers to create designs and looking for ways to improve them. A major breakthrough they achieved was Lindenmayer L-system and it was named as such to honor botanist Aristid Lindenmayer. L- system uses a system based on rules and it creates branch-like structures using symbols. L-system not only describes plant-like forms but provide impetus for creating surfaces as well as structures in the nearby areas of projected buildings as well. Architect Dennis Dollens has demonstrated software, which designs construction elements using complicated curved forms like organic forms inspired by organism morphology (Steadman, 2008, p. 257).

Steadman reports that natural surface design tools, which were designed to create natural forms, were developed by Una-May O‘Reilly, Martin Hemberg and Achim Menges, who served at the Emergent Design Group, MIT, USA, and also at the Architectural Association, London. Genrallows 3D digital surfaces was developed based on L-systems and it helps designing buildings right according to the environment, which takes into account weather conditions, gravity and sunlight (Steadman, 2008, p. 257). On a similar note Mazzoleni pointed out that amalgamation of biological concepts and building design has led to further discoveries, innovations, and creation of friendlier relation with our environment. Now there is a need for paradigm shift to connect building design with the nature in practical and more definitive ways (Mazzoleni, 2013, p. 48). Steadman writes that now architects are capable of generating organic doubly curved surfaces using softwares but they have no biological basis, which evolutionary algorithm and L-systems have. Experts concentrate on morphogenesis and sometimes, biological concepts as well but practically, nature-based designs are limited only to appearance. Architects may also be following the fact that nature has non-rectangular shapes (Steadman, 2008, p.258).

This thesis is based on biological or nature-inspired designs and computational design, so its large part is based on writings of Michael Hensel, Achim Menges and Michael Weinstock, who worked at Emergent Technologies and Design Group, Architectural Association in London. Their findings show focus on interdisciplinary design and studied it in the context of technological and innovative design. They conducted researches on novel design strategies inspired by evolutionary living systems, use of materials, and primitive adaptive responses to environmental variations.

3.2. Approaches of Biomimicry

Zari claims that Biomimicry approaches are based on two possible actions: First is "design looking to biology", which is an approach that searches nature for solving a human need of design problem. Second, on the other hand, is "biology influencing design", which is an approach that searches for behaviors, characteristics or functions existing within ecosystems as well as organisms, and design solutions to human problems (Zari, 2007, P. 2).

According to Zari, "Design Looking to Biology" is the initial approach, for which, designers observe animals, plants, their families, ecosystems and behaviors. Architects report human living problems to biologists and this way, they find some living creature that has resolved the same kind of issue. Designers can use this approach for identifying the fundamental design requirements (Zari, 2007, p. 2).

Discussing the above-mentioned approach, Badarnah and Kadri mentioned that the architects and designers should begin with defining a problem, explore and investigate it for some time, and find a naturally existing model or shape to find a solution. Zari states that part of the ecosystems and organisms is left unexamined, which creates problems while suggesting or designing the nature-inspired designs even when the biological analogues are matched with humanly identified design problems therefore, human problems might remain unaddressed in the generated designs. Similarly, Helms, Swaroop, and Goel mentioned that problem-solving approach needs steps to follow but in this case later steps affect the former ones, which provides chances to get feedback and perform design-refinement (Badarnah & Kadri, 2015, p. 2; Zari, 2007, p. 2; Helms et al., 2009, p . 6).

Bionic Car can be considered, as an illustration for this approach Daimler Chrysler designed a Bionic Car based on natural principles [Fig 3.1]. Chrysler used car design, which was inspired by box fish (biological name: ostracion meleagris), which is a wonderful aerodynamic fish type having a box-like body. The whole car structure is biomimetic, and computer-aided design technology was used to create its model. The outcome obtained was like a skeleton, in which, materials were added to specific parts only (Vincent, Bogatyrev, Bowyer & Pahl, 2006).

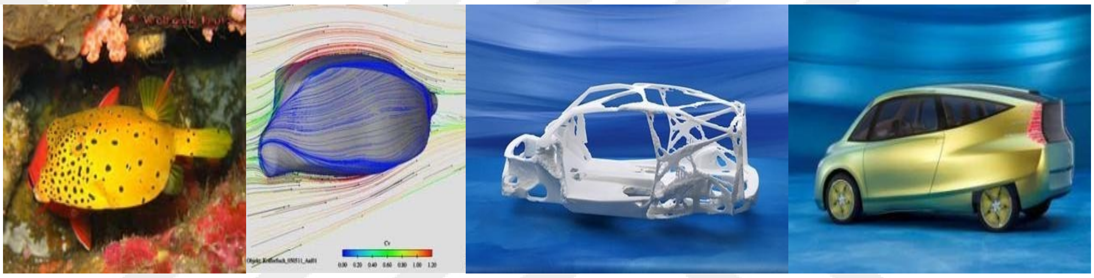


Figure 3.1: DaimlerCrysler bionic car inspired by the box (Source: Zari, M. 2007, p. 2)

Bionic Car is totally fuel-efficient because of its aerodynamic body designed like a box fish. Moreover, it needs fewer materials because its structure is based on tree growth, which requires minimum material quantities. Since the car is not a new traveling concept, only the shape was designed using biomimetics. As also mentioned by Helms et al., using analogies help resolving engineering issues through using biological systems as an inspiration (Helms et al, 2009. p. 1).

In the same way, Zari urges the designers to conduct researches and find biomimetic solutions to the existing design and construction problems; however, using limited understanding keeps both the obtained biological knowledge and its implementation in the design limited and less effective. Mimicking biological forms is easy but biological processes like photosynthesis are difficult-to-do using either chemical or mechanical processes. Despite the flipsides, this approach is beginning of a transition phase, which might change our lifestyles from unsustainable to sustainable and environment-friendly. Moreover, top thinkers of generative design including William Reed and Ray Cole believe that it is possible to regenerate the ecosystems' capacity to restore local environments but it cannot be done through gradual improvements. It will need rethinking on approaches towards architectural design (Zari, 2007, p. 3).

Several researches were conducted in Biomimicry Institute and Georgia Institute of Technology by Michael Helms, Swaroop S. Vattam and Ashok K. Goel, at the Design Intelligence Lab (2006), recommended six definitive steps for overall progress: 1. Problem definition; 2. Reframe the problem; 3. Search for biological solution; 4. Define the biological solution; 5. Principle extraction; 6. Principle application (Helms, Vattam, and Goel, 2009, p. 7). According to this framework, biologists continuously look for organisms, which have solved those problems that humans are facing. Designers, on the other hand, do the rest of the job because they identify issues, convert them into goals, and identify needs to resolve them.

The second approach, Zari mentioned, was called as "Biology Influencing Design." It means that the biological information affects humanly constructed design; therefore, collaborative design needs collaborative biological and ecological research instead of humanly determined design issues (Zari, 2007, p. 3).

Vincent at el. (2005) studied this approach and found that the knowledge of biology can make designers to think out-of-the-box and beyond predetermined issues. It results in discovering new technologies, which can resolve some design issues. This means that still there is great potential to change the way humans do the design work or think about it and that kind of design is biomimetic design. On the other hand, Zari pointed out that the mentioned approach has a disadvantage for the designers because it makes biological research compulsory and requires it to be relevant. It needs proper recognition of such a research for creating appropriate results. For example, how lotus stays clean despite growing up in muddy or dirty waters [Fig.3.2]. That idea led to an amazing invention of paints, which allow building to do self-cleaning (Zari, 2007, p. 3).

Figure 3.2:Lotus Inspired Lotusan Paint (Source: Pedersen Zari, 2007, p. 3)

Helms, Vattam and Goel conducted a research at the Design Intelligence Lab, Georgia Institute of Technology, in 2006, which converted the given approach in 7 definitive steps: 1. Identification of biological solution: For this stage, the designers should have a specific biological solution in their minds; 2: Defining biological solution conceived in the first step; 3: Principle extraction; 4: Reframing the solution: It urges designers to think how people will respond to the achieved biological solution; 5: Searching problem: Finding new, emerging, contemporary or forgotten issues Step 6: Defining a problem; 7: principle application (Helms, Vattam, and Goel, 2009, p. 16). According to this framework, designers should have a specific biological solution in their mind from the very beginning. Then, in close relation with the biologists, designers, and interpret the biological solution in architectural content.

4.3. Generation of biomimietic design principles

As also supposed by Frazer et al., it is difficult yet possible to generate nature-based architectural form. It takes place through profligate prototyping, which taps the creative potential existing in evolution, and it is very much possible to generate, which have the capability to adjust to the environmental changes. Architecture, which has been seen as purely artificial, works with natural principles including morphogenesis, selection and genetic coding (Frazer et al, 2002, p. 2).

Nature has a lot to offer in terms of architecture and it is inexhaustible in terms of ideas/solutions, which makes biomimetics an important tool. Understanding the significance of natural solutions and nature-inspired ideas is needed because they will ultimately lead our world to a much better living standards and realizable solutions. Designs created with the amalgamation of engineering and nature is a source of consistent interaction between the created buildings and the environment.

Adriaenssens, Gramazio, Kohler, Menges and Pauly mentioned that transition of biological rules into technical applications has been a valuable tradition in mechanical engineering; however, contemporary digital design developments have provided the designers with endless opportunities to improve their designs. This takes place through fabrication as well as generation of complicated geometrical shapes, which are critical design elements (Adriaenssens et al., 2016, p. 156). Badarnah & Kadri, while discussing the scope of biomimetics, mentioned that biomimetics is recognized as a promising area of study, which will bring major developments in future. During the last decade, several biomimetic strategies were developed but even now, the applying biomimetic principles to architecture still poses a challenge (Badarnah & Kadri, 2015, p.1). Benyus (2002) mentioned that biomimetics has great creative as well as, innovative potential, this will facilitate humanity in the near future.

Discussing biomimicry, Mazzoleni pointed out that until now biomimicry was just about imitating the morphological aspects of natural arena; its functional potential was ignored. Now architects are finding ways to incorporate the functional biomimetic aspects to give generative designs (Mazzoleni, 2013, p. xix). In the same way, Badarnah & Kadri mentioned that for developing biomimetic designs, designers must undergo a list of phases to meet the required challenges, observe animal and plant world, and find the systems, which can help the design process. They also emphasized the need to generate introductory concepts, analyze them and acknowledge them as legitimate solutions, this can be achievued through searial analytical stages; including challenge identification, exploration of target species, and analysis of strategies, rules, classification and implementation of concerned data and materials. After that, it is necessary to validate and analyze the overall solution, which must be followed by further exploration for gaining more knowledge (Badarnah & Kadri, 2015, p. 5).

Discussing challenges pertaining to biomimetics, Gruber and Imhof (2017) wrote that a major impediment in biomimetic design is the absence of appropriate role models, which could be observed for learning. The species are numerous and habitats aplenty. This shows that in fact natural principles are limited but nature has implemented them in so many species and organism families, that makes it difficult to select any specie as a final role model. That is why, finding specific patterns in various species is a laborious task, which requires, abstraction is useful for successful allocation (Gruber, & Imhof, 2017, p. 5).

Also mentioned by Badarnah and Kadri, several researchers conducted various observations to explore methods for enhancing biomimetic developments. It is a fact that exploring natural options help disclosing unique and sometimes very helpful aspects. Even now, conducting biomimetic research is still a challenge because of natural abundance of forms. Another issue is the non-existence of a design system to find out "successful" as well as sustainable natural systems like structures of organisms, animal and plant behaviors, and ecosystems. A successful design needs finding the right system out of such a great number of systems and sub-systems for reference (Badarnah & Kadri, 2015, p. 1).

Hensel and Menges claimed that creating biomimetic generative processes need material-environment interaction, and for that, researchers must study behavior patterns and the environment. It needs modulations including luminous, thermodynamic, sonic or other modulations with similar properties. Biomimetics includes some additional elements, which belongs to the physical state, including temperature, moisture content, internal forces, and frequencies. (Hensel, & Menges, 2009, p. 92). In additional to the physical state, aforementioned exploration of target species, and to analysis of the strategies and its behaviors make the issue more and more complex. Several biomimetic principles, therefore have been enforced for gaining the desired outcomes out of complex biomimetics:

The first principle is Adaptation. Adaptation is in fact a process that makes specie or a group of organisms well suited to their living place/natural habitat. It is a fundamental biological phenomenon. Mazzoleni has discussed the topic in detail in his book "Architecture Follows Nature-Biomimetic Principles for Innovative Design." He wrote that adaptation is not a traditionally central to architecture but in order to improve the "ecological footprint," designers and builders must give it due significance. Reduce the speed of constructing new buildings and adjusting architecture according to the environment will definitely help reducing the negative effects of human population on our planet. In the same way, Badarnah and Kadri mentioned that nature has provided so many options and for using them, we need enormous database to apply to the architecture design. Discussing the same topic, Mazzoleni stated that natural designs could be adapted through "synthetic" understanding of how species survive in the environment keeping in view its relations with other members of its ecosystem. This approach has the capacity to make the designs highly functional. The outcomes do not point towards a specific organism but towards its functions, and their helpfulness for design (Mazzoleni, 2013,pp. 32-47; Badarnah & Kadri, 2015, p. 1).

Second principle is Material as Systems. Panchuk (2006) believes that species and their ecosystems have many interlinked elements and substances, which form their micro and macro structures. At micro levels, cells act as basic agents and they fulfill needs of the system and the specie (Panchuk, 2006, p. 26). Moreover, Hensel, Menges and Weinstock claim that natural forms have hierarchies, in which, some elements and building blocks are subservient to others and some materials change their responses under changed scenarios. Biological systems are intertwined and interdependent as they are made up of fragile materials, which are filled in strong and dynamic structures. The properties of natural materials are very different as compared to material properties of artificially manufactured materials (Hensel et al., 2010, p. 15). Kelly (1994) thinks that ecosystems utilize energies as well as materials, which optimize the overall system and not individual species. Similarly, Panchuk (2006) declares that cells act according to the needs of their hierarchy. On micro level, they transport water from root hairs to leaves but additionally, they provide strength to a tree while being light components and at the same time, they provide flexibility as well (Panchuk, 2006, p. 26).

Third principle is Evolution. Hensel, Menges and Weinstock stated that evolution encourages ecosystems to survive using a consistently dynamic environment. They believe that every specie has two common characteristics: First, they operate through differentiated time frames. Second they come into existence through rapid embryological development process that converts them from just one cell to a fully-formed adult, and this goes on and on through generations(Hensel et al., 2010, p. 29). Additionally, O'Reilly, Hemberg, and Menges mentioned that complicated natural systems and forms emerge through evolutionary processes, and their growth process is also very complex accepting multiple varying contributions from the environment and going through "phenotype dependencies". According to biological principles, genotype has genetic makeup of specific species and phenotype is the outcome of environment-genotype interaction (O'Reilly, Hemberg, and Menges, 2004). Frazer believes that the evolutionary process had undergone plenty of experiments before creating biological perfection and natural forms. He believes that the nature went through many "flawed" experiments, which resulted in great biodiversity. Its outcomes are interdependent plants and animals, which created metabolic balance in the environment; therefore, evolutionary architecture is not advisable to be adapted as it is (Frazer, 1995, p. 12). On a similar note, O'Reilly, Hemberg, and Menges (2004) argued that genomes are behind properties of natural forms, because the natural generative system works with successive versions of genomes. Genomes are tiny storehouses of data, which are behind structurally complex biomass. Instrumentalizing evolutionary process should be combined with computational framework for truly inspiring designs. Bar-Cohen (2005) believes that biological forms were created when the evolutionary process continued, which created effective solutions, and those solutions can be used for inspiration (Bar-Cohen, 2005, p. 3).

Fourth principle is Emergence. Dynamic natural systems including bio forms, climate, and topographical forms shows multiple characteristics, which are significant to study the process of emergence. Most of the researches show that the life forms, climatic conditions and earth features gradually emerge in their current forms and the process is not over yet. Several definitions of development processes and evolutionary stages of the biological world around us have unfolded. Scientists have found evidences of what was believed half a century ago. In this context, De

Wolf and Holvoet made significant contribution when they defined emergence as system, which takes place in the presence of "coherent emergents" (including property, behavior, and structure) on macro-levels, which dynamically emerge out of the mutually interacting micro-level parts. This type of emergents is unique and comprise of the individual parts of the system (De Wolf & Holvoet, 2004, p. 3).

Fromm claims that emergence arises a basic question: “how things come into existence?” During emergence, we witness something happening but we ask ourselves how it was done because we want to know the logic behind it because mostly, things emerge without any obvious reason. Adding to that, Hensel et al. declared that emergence of varying multiple biological forms must be considered as separated from their structures and materials. Performance emerges out of complicated material hierarchies. When forms, structures and materials interact, their behavior cannot be predicted by analyzing just one of them (Fromm, 2005, p. 1; Hensel et al., 2010, p. 15).

Fifth principle is Form & Behavior. Hensel et al. believe that biological behaviors and forms are a consequence of a process, which creates, elaborates and maintains the structure as well as form of species (and non-biological things as well) and creates complex organism-environment exchanges. Moreover, almost every specie can continue reproduction by changing its behavior; therefore, behavior and form are practically intertwined (Hensel et al., 2010, p. 13).

Adding to that, Badarnah & Kadri asserted that form and morphology are transferable elements from nature to architecture. Additionally in the same context, any organism form has an affect over its behavior, which gives different outcomes under different circumstances. Behaviors are generally non-linear and situation-specific (Badarnah & Kadri, 2015, p. 1). Discussing behavior and form, Knippers and Speckan felt the need for expanded definition of biomimetics. In their opinion, form and function rules have a convincing potential to urge designers, engineers and architects to make innovative architectural design strategies and technically implement them (Knippers & Speck, 2012, p. 8).

Identifying human needs or design issues and finding solutions by experimenting on biological species are two crucial stages of biomimetic design process. Since species have specific behaviors, characteristics, and functions, their adapting to human designs create a focus on major biological rules; therefore, some special principles were chosen to develop computational strategies. Biomimietic designers follow some biological rules, which give close-to-ideal outputs. When a organism is not mimicked, the observation and experimentation phases are still considered as biomimetic because they are based on obvious biological rules and properties. Biomimetic methods consist of a series of occurrences, which must be followed during the design phase. It helps creating architecture using the best available materials and right according to the location and environmental situations. It helps imagining deeper, which results in unexpected outcomes pertaining to algorithmic development. Whenever a project is initiated, professionals start with defining goals, analyzing the ongoing situation and availability of materials, setting top priorities, and studying specific species in order to shift the needed for computational strategies. Later, the feedback and learning through implementation is recorded. Finally, professionals reach the desired result. Computational softwares and technologies have now great new possibilities and tools, which help the researchers to investigate some rules and explore their potentials. New modes of imaging have made it possible to see inside organism. Electron microscopes help observing several biological systems and happenings, which is a very interesting research area for morphogenetic computational design.

CHAPTER 4

MORPHOGENETIC COMPUTATIONAL GENERATIVE DESIGN

In the brief period of the modern digital architecture, the term morphogenesis became quite popular to describe sequences and types of generative design processes, which make use of biomimicry and computational design. The current chapter has been written to discuss the latest and contemporary researches on morphogenesis, which contains a dual concept called as natural morphogenesis that transfers natural design elements into integrated computational processes. The biomimietic approach to architecture design somehow needs further progress of the currently applied design methods and systems for better and user-friendly choices of material and integration of structure, performance and design. So here, the integrated computational designs should be created on morphogenetic principles, which allow architecture by letting them use Biomimetic approach to architecture design.

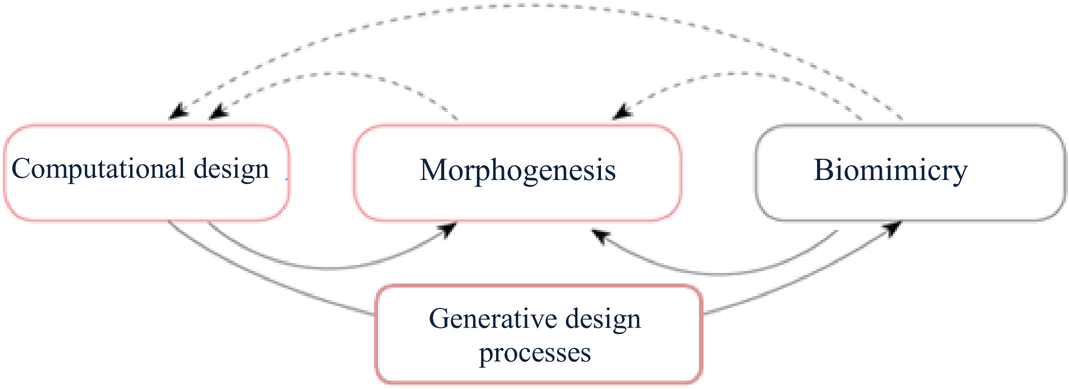


Figure 4.1: Diagram of relationship between Morphogenesis and Generative design processes (Produced by the author)

Herr, Gu, Roudavski and Schnabel mentioned that morphogenesis is a biology-based growth process that helps creating structures by learning from the structures and lifecycles of different organisms. In the field of architecture design, "computational morphogenesis" is a popular terminology, which means a bottom-up form-finding process to create form and output almost simultaneously; therefore, it facilitates the creation or emergence of new and highly useful architectural characteristics. Since theoretically, the concept has been subject to various researches, many researchers and experts tried to define "morphogenetic design" methodologies (Herr et al., 2011, p. 518). Moreover, Roudavski noted that the generative computer-based processes allow great customization and it creates room for automatic fabrication, which helps architects to produce complicated architectural designs. When the design process is automated, computer system makes it simpler and convenient to create new designs, which involves gradual adjustments and different versions of the design. The latest architectural trends show that all these approaches to design can be turned as morphogenesis (Roudavski, 2009, p. 345).

Herr et al mentioned that understanding of architectural form is central to latest "applied morphogenetic design systems," which contain complicated functions and assemblies. The natural ecology gained momentum in the context of design because it has emerged as a significant system to understand "morphogenetic" design processes for two major reasons. First, the natural ecology has the innate capacity for "extreme integration" of the main constituent elements, and it makes them very useful and adaptive, which is very different as compared to traditional architectural design. Second, natural ecologies are mainly self-governed or self-organized, which provides great potential for designing initial stages of a design (Herr et al., 2011, p. 517).

Discussing the same topic, Menges claimed that the use of materials in the latest architecture mainly rely on prioritized and sufficiently elaborated form. Sophisticated latest digital systems are used for creating awesome designs exploiting the full range of design options, which have built-in performance and morphological capacities of both technological edge and utilized materials. The process of producing, trying and using new materials in the final construction helps creating sufficiently engineered material solutions, which can resolve construction and design problems, and result in users' comfort and value-addition (Menges, 2009). Herr at al believe that in today's world, several examples of "morphogenetic design systems" exist, which link geometrical processes with the generative design techniques. This can certainly surpass optimization that uses genetic algorithms for creating architectural forms and shapes with the help of environmental feedback. Some remarkable and new "formal strategies" have emerged, which are way beyond the previous narrow spectrum of formations. Structuring alternative design strategy helps scripting and computation using computer programming and computer-aided design (Herr at al., 2011, p. 518).

Moreover, Menges supports morphogenetic computational design for architectural form generation or creating generative design against the orthodox form definition and form finding architecture design strategies. Computational design is very helpful because it lets an architect generate altogether radical approach for data processing, information generation, and final form generation using latest and cutting-edge technologies; however, generative design has limitations including physical constraints and phylogenetic issues (Menges, 2012, p. 2-3).

Discussing morphogenesis, Kolarevic stated that the new researches and latest digital generative processes are exploring new and flourishing areas for morphogenetic processes. He stresses that morphogenesis is now emerging as "form finding" system, which is linked with digital generative techniques irrespective of "normative formalism" and "heterotrophic composition". These properties have been observed in many designs, which were created in 2000s while some earlier designs are included in the same category as well (Kolarevic, 2003, p. 17).

This chapter further discusses morphogenesis both as a subject of biology as well as architectural design. Morphogenesis is a process that creates different examples through studying biological organism. These examples are useful in architecture as they give ideas to create nature-harmonized and effective designs. It is helpful because it is based on generative design, which is a consequence of knowledge transfer between biomimicry and architecture.

4.1. Morphogenesis in Biology and Digital Architecture

Discussing morphogenesis as an essential biological and digital architecture component, Roudavski mentioned that morphogenesis is a broader term, which implies various developmental aspects; however, in biology, it means natural shaping, reshaping or molding processes, which take place in cells and tissues. The term "morphogenesis" has two literal meanings: (a) Structural variations, which take place during embryonic development; (b) The natural processes, which bring about structural changes. Both the meanings of morphogenesis have interesting scope for researchers and especially architects who can take inspiration from it (Roudavski, 2009, p. 357). Rudge and Haseloff believe that the biological concept of morphogenesis includes shape and structural formation of cells, their enlargement, and division through mitotic cell division process (Rudge & Haseloff, 2005, p. 78).
Menges believes that morphogenetic computational design is totally nature-inspired as a developmental system that already exists in the biological system from basic development to further development and then maturation (Menges, 2012, p. 2).

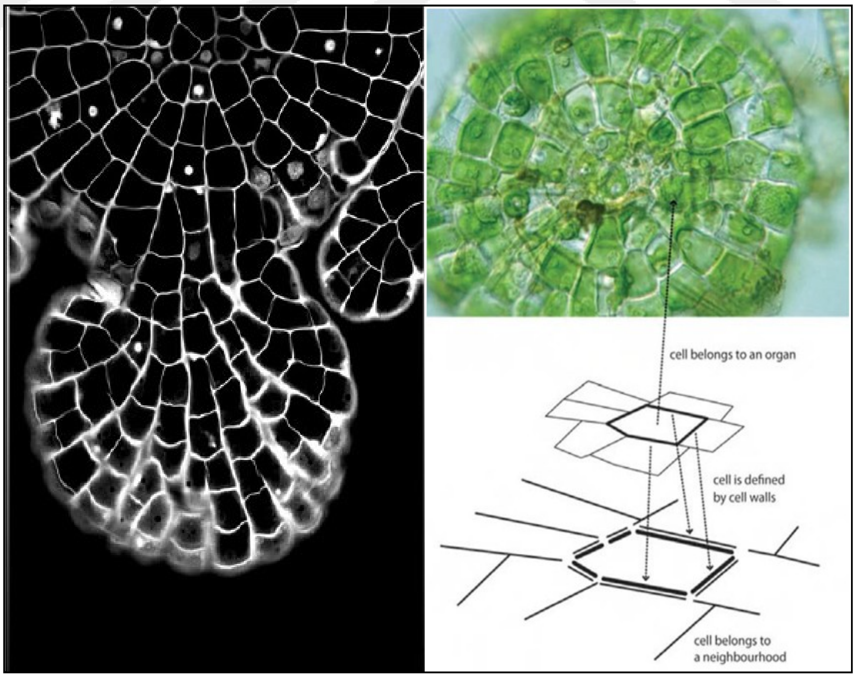


Figure 4.2: Cellular architecture of plants (source http://protist.i.hosei.ac.jp)

Roudavski claims that the plants' cellular architecture is divisible into various levels, which help formalizing the plant cells' functioning. A plant cell is horizontally attached with its neighboring cells while the properties defining growth and behavior of cells largely depend on inter-cellular functions and interactions [Fig.4.2] (Roudavski, 2009, P. 360).

Based on eminent biologists' discussions on morphogenesis, Menges explains that the morphological complications take place because of different materials. The natural development process and shaping systems work simultaneously, and they have no distinct formation and materialization processes. Therefore, architects need deep understanding of forms, materials and structures not separately but in relation with each other, and they should understand their complicated interrelations by studying integrated computational design (Menges, 2009).

Morphogenesis is a generally occurring continuous process that takes place in the living organisms. Other than morphogenesis, the cells undergo multiple processes including growth, ageing, repair, excretion, and adaptation. If the knowledge of the biological systems is appropriately and objectively transferred, it will help creating productive designs having productive inter-elemental dependencies and dynamic capacities. Morphology is now no more limited to its biological and historic confines. It has turned into morphogenesis that focuses on generating living forms by learning how natural forms and environments came into existence (Roudavski, 2009, p. 356). Discussing biological morphogenesis, Hensel and Menges mentioned that morphogenesis contains some processes, which manage distribution of cells depending on the type of specie. The cell distribution emerges in the embryonic stage, when organs, tissues, and the physical anatomy are formed (Hensel, Menges, 2007).

According to Roudavski, there are several advantages of studying and understanding morphogenesis because it sleds light on what should be the standard architectural design. Its advantages are as follows: a) Architectural design focuses on resolving design issues and finding their solutions in the nature because nature has already resolved most of them; b) Architectural design needs new and continuously improving concepts and techniques. Some concepts like growth or adaptation can be taken from the nature; c) Both architecture design and biology have a common language as they model growth, adaptation or morphogenesis (Roudavski, 2009, p. 348).

Menges claimed that morphogenesis has ever-increasing particularity and different morphological elements, which improve the entire system. In our environment, morphogenetic processes manage spatial organization and cell distribution. The morphogenetic system works through variations in the cellular distributions and interaction in growing tissues. This process takes place through Morphogens, which manage the cell differentiation with the help of other molecules (Menges, 2012, p. 2).

Morphogenesis in digital architecture: Roudavski defines computational morphogenesis in architecture as a sum of techniques, which use digital electronic and computing equipment not just for visualizing a project but also as generative tools to derive form and control the design transformation in the built form. In the same way, Menges mentioned that the core morphogenetic principles help creating relevant generative design concepts. The genetic aspects, which make the growth and development of a human or any other specie possible, apply to the evolutionary process through many generations. Since populations provide conceptual framework for growth, development and understanding of computational design, algorithmic development and formative design helps development process, and it supports the professionals to deal with internal and external effects (Roudavski, 2009, p. 348; Menges, 2012, p. 2).

The latest discussions on digital morphogenesis have linked the concept with several other concepts such as emergence, form finding and self-organization. Considering the advantages of architectural bio forms, the supporting designers and researchers have agreed that it has potential for further growth, structural benefits and capacity to perform multiple functions simultaneously. Further discussing the topic, Menges highlighted that within the morphogenetic systems, there is a rich interaction between material capabilities and intrinsic information, which can help creating complicated designs, structures and forms. Improving morphological differences and adapting the local as well as the overall system and its environment support creative processes have very admirable consequences. They include performance capacity, functional integration, and material resourcefulness that the nature possesses and it can be seen even in small species (Roudavski, 2009, p. 348; Menges, 2012, p. 2).

Hensel, Menges and Weinstock noted that rather than adapting modernist ideas of open interior spaces, and homogenized design, using some differentiation based on sensitivity can be gained through morphogenetic responsiveness, and consequently, it results in a flexible and environment-friendly architecture (Hensel, Menges, & Weinstock, 2006). Hensel and Menges have also pointed out that morphogenesis is linked with material system development, which should be based on performance capacities and size-specific behavior. It includes the systematic exposure of the process to a range of extrinsic influences and environmental stimulus (Hensel & Menges, 2007).

Roudavski pointed out that Parasite Research Project was created for the International Biennale of Contemporary Arts in Prague (2005), which serves as a good example [Fig.4.3]. Its installation, also called as Parasite installation, has a physical framework along with audio-visual interactive system mainly created for use in the Prague’s Museum of Modern Art (Roudavski, 2009, p. 350).

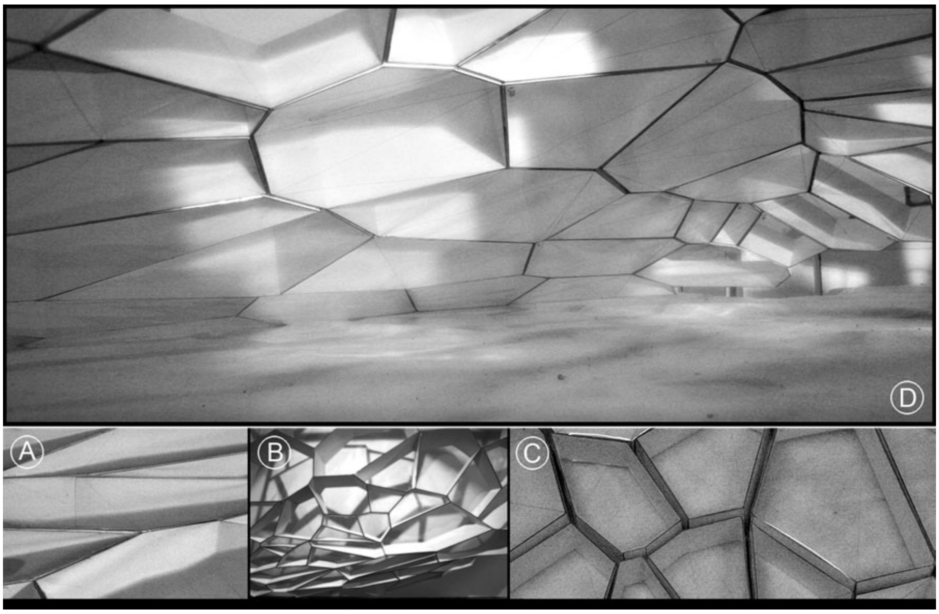


Figure 4.3: The Parasite project (source: Roudavski, 2009, p. 350)

Roudavski mentioned that during the Parasite project, (A) Cell walls produced a non-repeating visual condition, which is almost like the natural cellular patterns. (B) A fragment shows cellular structure in details and the variations existing in its cell walls. (C & D) Here cells form a patch, which is quite similar to the plant cells. Parasite's cells act as assemblies of walls (Roudavski, 2009, p. 350). Complicated and not-so-uniform structures have become commonplace in the architecture design, which shows increasing popularity of computational design and parametric modeling. Some new issues and opportunities have emerged ever since this type of structures have become trendy but still, this kind of precedents naturally exist, which is obvious from the fact that some complex structured organisms have continued to adapt to their environment for ages.

Further discussing the topic, Roudavski mentioned that actually, digital morphogenesis has a metaphoric relation with morphogenetic processes, which freely occur in the nature. In architecture, morphogenetic designs show dependence on gradual development but it does not mean that the actual growth or any other mechanism is adopted in its genuine form (Roudavski, 2009, p. 348). Moreover, Menges stated that in the context of morphogenetic form development, four aspects have significant relevance, which help transferring of biological methods, rules, or structures into computational design; therefore, morphogenesis is based on features, constraints, processes and feedback (Menges, 2012, p. 2).

Roudavski, in his concluding remarks, stated that the comparison between cellular arrangements, which naturally occur in plants and animals, show a complicated but flexible process, which gives thought-provoking ideas and leads to development of different objective architecture design procedures (Roudavski, 2009, p. 371). The design attributes practically link digital morphogenesis with biological morphogenesis, which has created endless possibilities for generating novel and sophisticated architectural designs. As can be called "bio-digital" morphogenesis, it is a new approach that leads to cutting-edge form design. The generated designs are not only digitally but have strong biological basis as well.

4.2. Computational Morphogenetic Design with Form Generation

Menges believes that both evolution and computational morphogenesis are predominantly intellectual concepts. Morphogenetic computational design is a pragmatic way to approach integration of functions, performance, capacity building, and material accomplishment, which is pivotal for handing economic, social, nature-linked issues using biomimetic computational design techniques for assuring a fully integrated practice of architecture (Menges, 2012, p. 10). Adriaenssens, Block, Veenendaal & Williams discussed computational morphogenesis as a process, which takes assistance from two major aspects of evolutionary algorithms. The first is full exploration of largest number of available possibilities while the second one is exploitation of options including the best solutions generated, which have harmony with natural processes. Effective designers appropriately manage algorithm, which creates a reasonable input to the evolutionary search. By definition, computational morphogenesis is a set of computational procedures, which helps form creation and transformation (Adriaenssens et al., 2014, p. 235; Kolarevic, 2003, p.17). Hensel, Menges, and Weinstock mentioned that the computational design techniques aimed at morphogenesis that can be joined with latest structures and material simulations. It is a part of the rethinking and understanding of "nature" as an agent of change, which is a shift from metaphor to model, from plain nature to multiple dynamic processes, which can be used for adoption in the architecture design and construction; therefore, computational form-generation has morphogenetic and evolutionary basis (Hensel et al, 2010).

According to Adriaenssens et al., morphogenetic processes show methods, through which, generative design systems operate, exploration and exploitation of design possibilities take place, and both architectural as well as structural issues are resolved. Architects should exploit maximum exploration opportunities in order to get viable options and to choose the best one with fewer problems. The generative design can offer solutions to different problems; however, it depends on the problem and its formulation. Almost all the architectural concepts can be changed into potential geometric shapes, which offer the alternatives for the architects to consider (Adriaenssens et al., 2014, p. 232). Hensel et al. mentioned that within the design context, computational morphogenesis is based on "perpetual differentiation." Continuously increasing functional as well as morphological differences of elements augment a system's capacity, which shows a system's divergent development directions, and those directions trigger through different environmental and functional criteria (Hensel et al., 2010).

Morphogenesis has validity and suitability in the architecture because of utilization of digital media as a tool to generate form, and besides, it gives information about the ongoing processes within the mentioned built form. Its design is based on some formative rules, which help generating form while taking care of internal and external elements, as they might affect the formation process. Digital architectural morphogenesis is linked with several morphogenetic processes that freely occurs in the nature, and they gradually take place, but morphogenetic architecture design, on the other hand, might not adopt actual growth and adaptation mechanisms. Renowned German architect Achim Menges used genetic algorithms, which were developed during the past 10 years, for reproducing active phenomena to give shape to natural elements for generative form finding. Moreover, Menges utilized those algorithms for reproducing pinecones natural hygroscopic behaviors. The pinecones are used but their use largely depends on the moisture in the air.

Hensel and Menges claimed that morphogenesis is primarily concerned with control processes, which balance the cell distribution, and they emerge during the organism development. They produce organisms' physical features such as organs, tissues, and other anatomic units. In this approach, morphogenesis is linked with the material system developments, which have scale and size-specific behaviors as well as required performance capacities. It also includes the system's exposure to a series of extrinsic influences at each stage while the given environment provides stimulus to it (Hensel, Menges, 2008). Menges mentioned that this phenomenon can be used for architecture design elements because of anisotropic nature of wood. It was a very inspirational finding for architects. He implemented his "HydroSkin" project in 2012 [Fig.4.4], which was a "meteoro-sensitive" aspect that had the capacity to react against climatic changes (Menges, 2012).

Figure 4.4: HydroSkin project (http://icd.uni-stuttgart.de/)

Hensel and Menges believe that so far unused potential behind computational design strategies and nature-inspired manufacturing technologies might initially approach just as an alternative design approach, which will be able to deal with complex morphological factors and have sufficient performing capacity with least attention on separating form-generation and materialization as two separate procedures (Hensel & Menges, 2008, p.56).

The use of Hygroscope for meteorosensitive morphologies by Menges is another example [Fig.4.5], which he accomplished along with Steffen Reichert and Centre Pompidou in Paris in 2012.

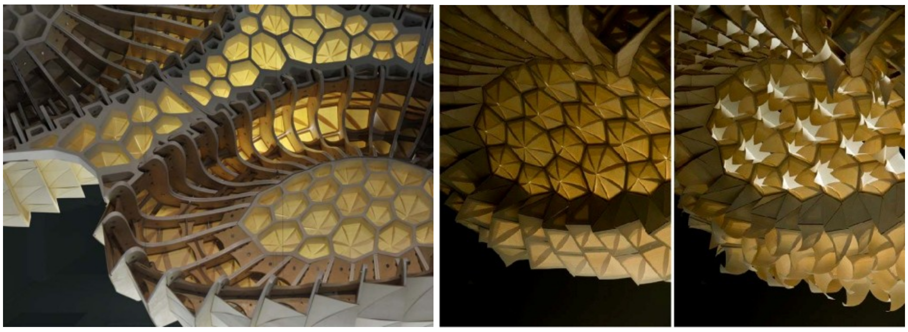


Figure 4.5: Hygroscope project (http://icd.uni-stuttgart.de/)

Their project explored responsive architecture, which was based on materials' natural behavior as well as options offered by computational morphogenesis. Menges showed that wood is dimensionally quite unstable when it is exposed to the moisture or moist air when it comes to constructing a climate responsive architectural design. Menges' model opens and closes to respond to the climatic changes and it does not require the use of energy (electricity or gas) or any technical equipment. The humidity changes cause the material to make slight and silent adjustments and movements according to the level of humidity. For that, Menges used a humidity controlled glass case; therefore, the material structure acts as a mechanical temperature controller (Menges, 2012).

The “Honeycomb Morphologies” example . According to Menges, this example aimed to advancing honeycomb structures through developing system in which shape, direction and orientation each cell size, can be different. The honeycomb structures has been developed from deriving growth algorithm which defines the morphology as overlapping strips [Fig 4.6] (Menges, 2007, p. 735). The computational design research in these examples and development of the generative code is a clear embodiment of computational morphogenesis.

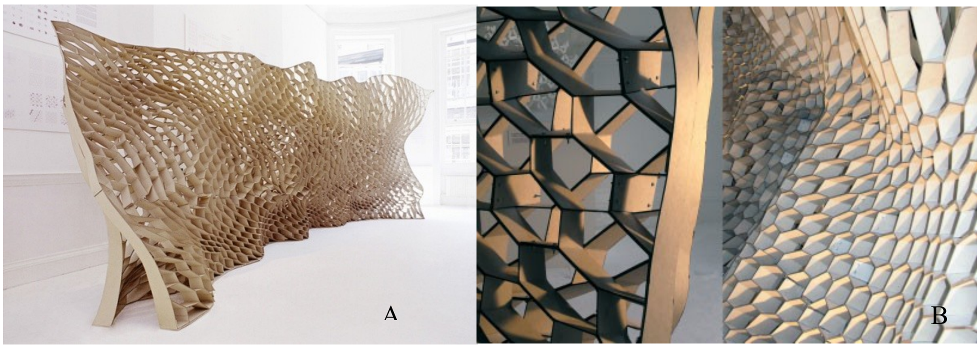


Figure 4.6: Honeycomb Morpholgies project (Hensel et al., 2006, p.85)

In the context of honeycomb morphologies, Hensel et al. had already described generative algorithmic definition in honeycomb morphologies as algorithmically derived honeycomb prototype at which each cell is single in shape, depth and size, allowing to changing double-curved geometry and cell densities [Fig 4.6a]. And close-up views showing planar connection tabs between honeycomb layers and double-curved global surface articulation [Fig 4.6b] (Hensel et al., 2006, p.84).

4.3. Experimental Examples of Computational Morphogenetic Design Strategies According to Biological Principles

The goal of this segment is to discuss specific projects as examples of biomimetic computational architectural design approach. Krieg, Dierichs, Reichert, Schwinn, & Menges mentioned in their separate and collaborative researches that the architecture requires maximum information sets containing the structural as well as other important characteristics such as spatial arrangements, lighting and insulation, etc (Krieg et al., 2011, p. 574). Since this is very complicated, research process was utilized to redefine the architectural principles and also introduce some natural biological input to make the architecture work more efficiently. This is possible through developing a performative catalogue, which contains architectural requirements and those requirements can be fulfilled through biological principles. By the end of this segment, one can discuss the results of the architectural design potential of biomimetic design. The transmutation and conversion of helpful principles takes place when some concepts are borrowed from a different field of science and incorporated with regular architecture design practice in a single major system. This segment includes examples of various projects, which were accomplished at the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE) at the Stuttgart University (Germany). These projects serve as brilliant examples of the design approach, as previously discussed in chapter 2 and 3. Computational design and some selected biological rules, which were discussed in the previous chapters, will be used for analyzing the architecture projects. Every project will be judged for consistency and effectiveness using these foundational principles and later, will be mentioned and demonstrated the major cutting-edge benefits of this design approach. These principles were selected based on the already available research literature on the subject, but certainly, this does not show the importance of these principles over others.

Bechert, Knippers, Krieg, Menges, Schwinn, and Sonntag mentioned that transferring biological principles, constructions, and processes are very important for the constructional morphology. Using examples of the structures and functioning of animal and plant species, and their ecosystems have great significance for inventing or improving engineering technologies; however, recent digital design developments have offered great options, possibilities and opportunities to incorporate implement biomimetic design concepts in practical architecture and model construction projects. These concepts are used in the generational, computational, and fabricational aspects of geometry, which forms the basis of architecture design process (Bechert et al., 2016, p. 156).

Magna, Gabler, Reichert, Schwinn, Waimer, Menges, & Knippers mentioned that scientists and researchers have accepted the fact that biological systems are highly inspirational to resolve the given technical problems. The reason is that almost all the species tried to adapt to circumstances in order to survive. These survival strategies included structural, functional and behavioural changes while some changed more and others less. When architects and engineers try to incorporate biologically inspired concepts in their designs, following questions arise: 1. Which principle suits the situation more and better?; 2. How architects can bridge the gap between the technically created model and its biological role model? (Magna et al., 2013, p.27).

Discussing the same subject, Bechert et al stated that biologically inspired solutions and their further possibilities have urged designers and architects to explore natural examples, which have complicated structures and better performance to offer. Normally, process-specific role models can be explored in the nature, as many of them exist within or beyond the defined building methods, types, and categories. Moreover, the complication of shapes needs digital design, for example, lightweight timber design. Certainly, bio-inspired role models have revolutionized the architecture design and construction (Bechert et al., 2016, p. 156).

Creative computational design tools and biomimicry have the capacity to revolutionize architecture design further because it helps creating final constructs and fabrication. Some of the remarkable architectural developments require sophisticated fabrication strategies. Dörstelmann et al mentioned that the latest fabrication design and development processes and computational design advancements help generating and processing very complex information pertaining to construction geometry. All these developments have made it quite possible to transmute biological functionality into technical reality using latest materials and systems. In a multidimensional system, it is possible to use reverse biomimetics and cross-disciplinary methods to generate biological and conceptual insights (Dörstelmann et al., 2014, p. 221).

The examples of computational design using biomimetic approach are given below. They show the steps involved while following the methodology, which makes it easy to identify biomimetic principles and their possible transmutation into prototypes.

- Example 1: ICD/ITKE Research Pavilion 2011

Institute for Computational Design (ICD) and Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart, Germany joined hands in 2011 to conduct research on bionic research pavilion and construct it with the help of wooden material. That project was focused on exploring the possibilities of transferring biological principles to latest architectural forms using morphology of sea urchin's plate skeleton using latest computer-based design systems, simulation methods, and controlled manufacturing methods (Menges, 2011).

Magna et al showed through researches and experiments that biomimetic-influenced approaches improve computational design and keeping in view principles of architecture and theoretical understanding, they can become part of morphological, structural and architectural developments. Biomimetic design depends on echinoids analysis, as a part of which; studies were conducted to observe the structures of sea urchin and sand dollar for converting their structural morphologies into prototypes, which further helps generating the form [Fig4.7] (Magna et al., 2013, p. 27).

Figure 4.7: ICD/ITKE Research Pavilion 2011

Menges claims that the biomimetic design strategies integrate organisms' performative functions with architectural design. While analyzing several biological structures, plate skeleton of sand dollar, and sub-species of sea urchin (Echinoidea) proved to be very interesting as their study provided the needed information about how to construct a bionic structure artificially. Sand dollar's skeleton shows a structure of different polygonal plates joined together through finger-like calcite joints. More weight bearing is possible through specific geometric plate arrangements and the system that joins them (Menges, 2011).

Magna et al. claimed that traditional engineering optimization process helps finding parameters, which are needed for the appropriate option out of many solutions. It is based on deterministic algorithms, which show convergence to the solution (Magna et al., 2013, p. 28).

Knippers & Speck mentioned that if top-down and bottom-up strategies are used for identifying proper biological options, and if their structures are explained with the design solution, it leads to better understanding of the structural behaviour of the biologically inspired design (Knippers & Speck 2012, p.6). The figure below shows both the approaches:

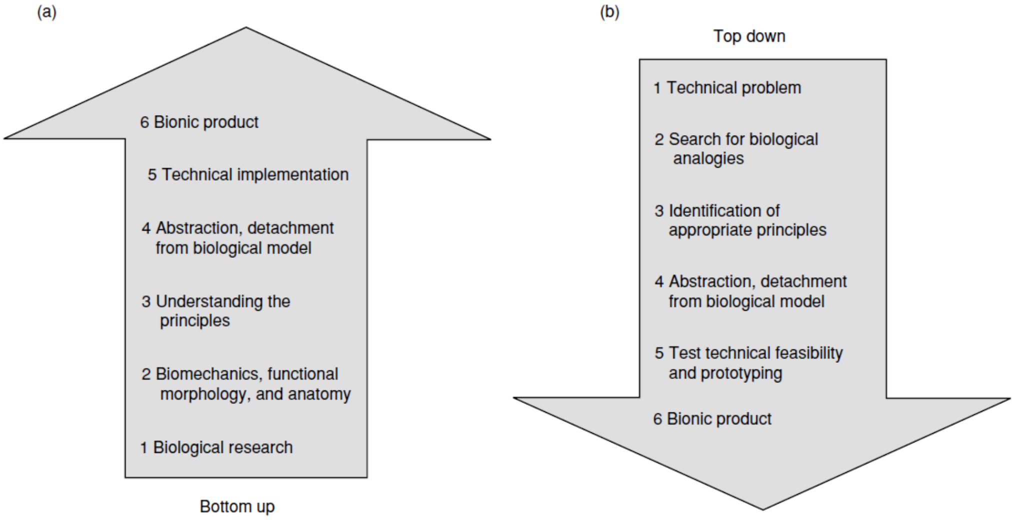


Figure 4.8: Bottom-up process of biomimetic research (biology push); (b) top-down process of biomimetics (technology pull) (Knippers & Speck 2012, p.6)

Moreover, Krieg et al believed that the biomimetic materials and systems are very useful for architecture and manufacturing as they are based on biological principles. Although the bottom-up processes are based on manufacturing rules, a performance catalogue utilizes biomimetic top-down approach that contains predefined constructional architecture design and structural rules, which provide impetus for objective biological research (Krieg et al., 2011, p. 577).

According to Magna et al. the sea urchin's outer covering has a module-like structure of polygonal plates [Fig.4.9a]. These plates are joined together through their own dynamics, which help urchin to resist the external pressures or shocks and also facilitates the growth process [Fig4.9b]. These plates join each other through finger-like calcite protrusions [Fig4.9c]. Higher load-bearing capability is assured through specific geometric plate arrangement, which is part of the segmented structure (Magna et al., 2013, pp. 30-31).

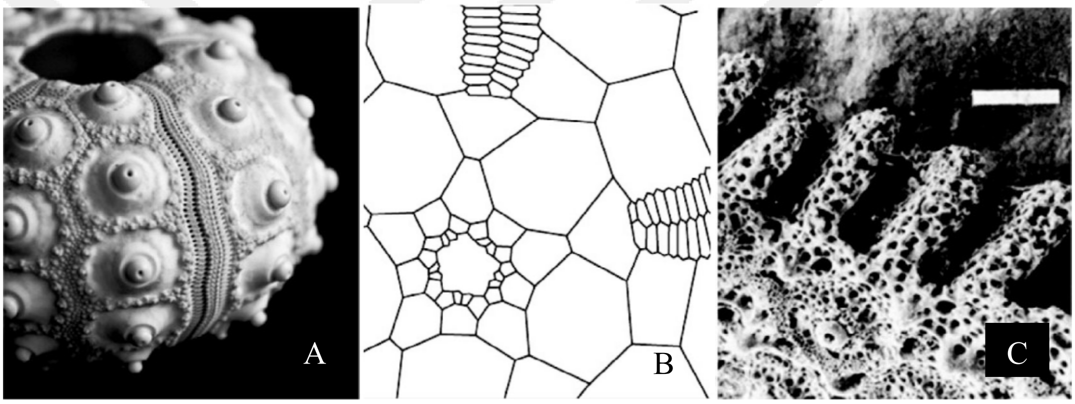


Figure 4.9: (a) Close-up of a sea urchin’s test; (b) schematic top view of a sea urchin’s test; (c) microscopic view of a plate edge (Magna et al., 2013, p. 30)

Generative computational design is used for transferring cellular morphology, as studied in chapter two and three. Menges stated that the sand dollar had three connecting plates, which can be included in any generative computational design tool. The implementation of Voronoi diagram shows that every Voronoi cell has a polygonal cell boundary around the fleshy parts of the cell (Magna et al., 2013, p. 31). This approach has possibilities of creating lightweight construction while the pavilion serves as an example because it was built using only 6.5 mm plywood sheets even though it had a great size for such a thin design. It made use of anchoring for managing wind pressures (Menges, 2011).

A customized computational tool normally has two representative models including a 2-dimensional topographic map along with a 3D geometric model having the same topology as the 2D map [Fig4.10a-b]. The 3D arrangement of plate-cell components consist of two level-based system. On higher level, Voronoi diagram helps describing the topological arrangement of cells while on the lower level, cellular plates represent the topological map. The cellular plates are arranged to form a 3D model, which creates a full-scale pavilion through fabrication [Fig4.10c] (Magna et al., 2013, p. 31).

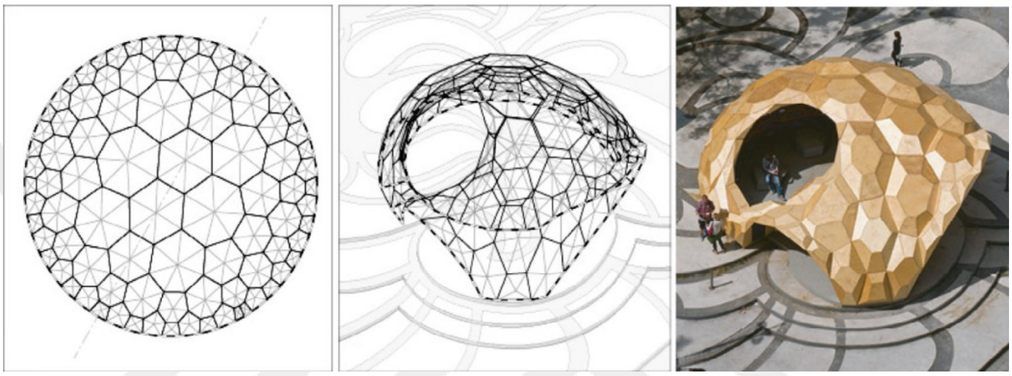


Figure 4.10: (a) 2D topology model; (b) 3D geometry model; (c) full-scale prototype (Magna et al., 2013, p. 31)

Discussing the same topic, Krieg et al. stated that by rely on predetermined principles of architecture and identify the relevant but critical parameters including the varying ranges, a spatial plate-like structure is possible to create using computational form finding. There is a remarkable difference between local and global plate structures and arrangements but they have shared geometry and plate permeability, which is tested through particular performance criteria (Krieg et al., 2011, p. 579). Menges further explained that some innovations recognize biological principles; therefore, performance of those innovations depends on complex geometrical structures, which is constructed using computational processes. It is obvious from the diagram that very complicated morphology of the pavilion has been built using only 6.5mm thin plywood layers (Menges, 2011).

Magna et al. mentioned that biomimetic design, which is inspired by living organisms, shows that abundance of dimensions appeared in the organisms during the evolutionary processes, which took place when those organisms faced changing environment. According to evolutionary biologists, individual morphological features of all the species are the outcomes of the species' struggle and interaction with their environment (Magna et al., 2013, p.28).

After analyzing biological role models and focusing on identifying their topological as well as structural principles, the designs are processed using generative geometric rules. These rules create foundation for developing computational tools, which can integrate the sea urchin’s biomimetic structural principles with the design, it fulfils the design and structural needs, and overcomes the fabrication constraints for better design exploration. Krieg et al. believe that integrated computational design tools help finding out biological principles and incorporating them in the architecture (Krieg et al., 2011, p. 579).

- Example 2: ICD/ITKE RESEARCH PAVILLON 2015-16

The Institute of Building Structures and Structural Design (ITKE), University of Stuttgart, Germany, and the Institute for Computational Design (ICD) corporate to create a research pavilion that demonstrates robotic textile fabrication processes using segmented timber shells. This is called as ICD/Itke Research Pavillon 2015-16, which is the first one that used industrially sewn wooden material for a sizeable architecture project. It belongs to a series of research pavilions that realized computational design potential along with fabrication and simulation techniques. A multi-disciplinary team of architecture students, biologists, engineers, students and palaeontologists accomplished it utilizing multiple sciences and design techniques. It is a true combination of science and design arts (Menges, 2016).

Figure 4.11: ICD/ITKE RESEARCH PAVILLON 2015-16 (Menges, 2016)

Bechert et al. introduced the pavilion as the first architecture work which uses segmented shells. It utilized the already established models and also made best use of latest biomimetic discoveries and latest robotic textile fabrication processes, which processed thin shells of timber (Bechert et al., 2016, p. 156).

Biomimietic Investigation: Menges narrated that the making of the ICD/ITKE Research Pavilion 2015-16 was largely based on researches of natural segmented plate structures, their biomimetic studies, and latest robotic fabrication, which joins very thin plywood pieces. It was based on repeated analyses of the biological structure and function of sand dollars. Moreover, fabrication technique was pivotal in this context because it uses elastically bent and flexible double-layered pieces developed using custom laminated and robotically sewn beech plywood. Bringing new textile-connecting methods for timber construction helps joining multi-layered and very lightweight shells of timber (Menges, 2016).

Bechert et al. mentioned in their study that biomimetics is a very helpful design strategy that analyzes the structural morphology of a specie, discovers its functional properties, finds out its load-bearing potential and then shifts that natural concept for technological processing. So far, experts have explored and utilized concept generators for designing a system based on thin shells. Biological information collection of double-layered segmented shell structures was followed by detailed investigation of biological role models, which serves as a foundation for new and better designs. This project showed remarkable morphological features. Experts of different fields agreed to study the echinoids' skeletons and use its structural and functional information to create segmented shells for use in commercial architecture (Bechert et al., 2016, p. 157).

Later, Menges added that experts of different subjects of biology further analyzed natural segmented shell structures in cooperation with architects and engineers serving at the Stuttgart University and biologists working at Tubingen University for discovering more aspects for utilization in the construction processes. They aimed at transferring morphological and procedural growth processes to form a fully integrated architecture design process (Menges, 2016).

Bechert et al mentioned that the biomimetic observations and analyses of biological species nees repeated investigations of the following already established and researched principles: (1) Two-layer skeleton; (2) hierarchical materials, their composition, organization, and differentiation within the calcite stereom; and (3) the study of how segments are naturally connected through finger joints (Bechert et al., 2016, p. 157). Menges mentioned that the segmented lightweight structures have substantial performance and it not just depends on the arrangements of calcite plates but on geometrical two-layered system and material differentiation as well. It is significant that the calcite plates of sea urchins are naturally linked with each other through several organic fibrous materials as well as finger joints, which creates a multi-material connection and it helps maintaining and protecting the sea urchin's shell during physical pressures and growth processes (Menges, 2016).

Menges focused attention on the fact that the building elements were made up of very thin wood strips using the anisotropic information and properties of plywood. Experts custom-laminated the strips to create coordination between grain direction, thickness and the differentiated stiffness, which was needed for creating segments having different radii. The robot-aided sewing process locked all the elements, which made it possible to process 151 geometrically diverse elements. Finally, all the effort and precision resulted in tough double-curved shells when they were assembled (Menges, 2016).

Bechert et al believed that the foundation for system development was characterized by first, the abstraction of biological information and second, using that information as an inspiration to create something valuable in terms of architecture design. Using a double layer construction was derived from the structure of sand dollars, which was almost like the secondary growth [Fig4.12a-b-c]. This resulted in very thin and flexible plywood, and it became easier to bend it and join it with neighbouring elements for generating a stiff two-curved shell shape [Fig4.12d]. For reasonable and reliable interconnection between the layers allows higher geometrical flexibility.The physical forces, including shear and compression forces, are transferable through finger joints. Moreover, laces, which look like the fibrous connection found in the sea urchins, were used for resisting against the tensile forces (Bechert et al., 2016, p. 157).

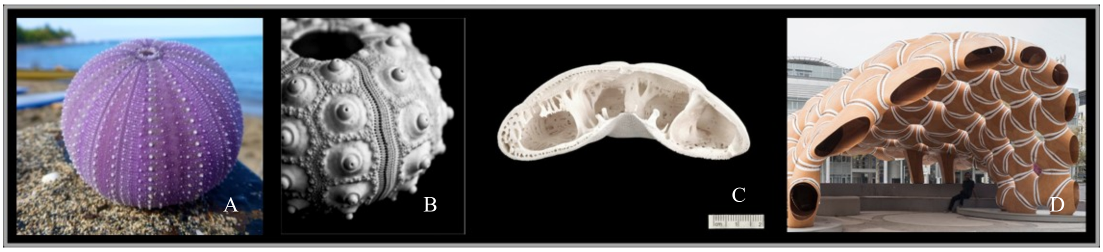


Figure 4.12: (a),(b),(c) Photograph of double layer of sand dollars; (d) The double-layered timber segments (Bechert et al., 2016, pp. 158-159).

Today, most of the experts have recognized that the self-organization and physical determinants influence morphogenetic processes; therefore, they have acknowledged the "intricate and irreducible" relationship between the formative processes and materialization, which is linked with morphogenesis (Menges, 2012, p. 3).

Generative computational design: This design process is actually a partially automated form-finding process, which uses biological role models for processes including plate growth and addition. In comparison with the morphological rules, its design process distributes segments within user-defined areas. In fact, it is an integrating approach, which functions by letting the design tool gather the information. It generates construction concepts and solutions, which are designed according to the architectural needs. It comprises of a digital process that has proven its capacity, when it was used to generate a complex design containing 151 segments having novel connection details. It has complex but effective material distribution, and importantly, custom-fit finger-joints [Fig4.13] (Bechert et al., 2016, p. 163).

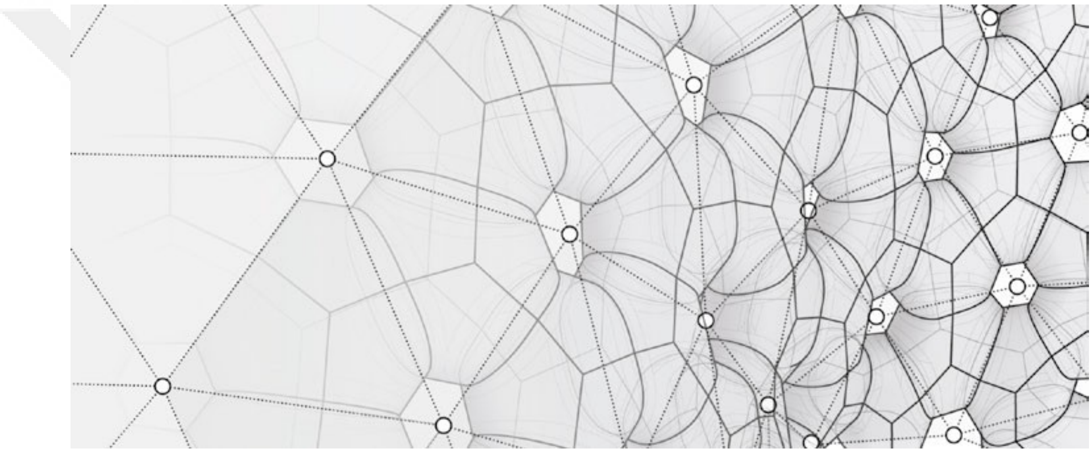


Figure 4.13: Visualisation of the geometric information in the computational design tool, a mesh forms (Bechert et al., 2016, p. 163)

Moreover, Bechert et al mentioned that creating double-curved structures using planar elements has gained much focus of the architects because double curvature is advantageous for improving the structural behaviour. One option is assessing double-curved surfaces using single-axial bending process for getting planar strips, and bending the entire structure to form a shape. For this, experts have developed a form-finding algorithm, which allows computation of material layout more accurately and facilitate curvature distribution of every strip (Bechert et al., 2016, p. 164).

Hensel & Menges (2009) pointed out that the architecture design forms are generally representative of the architectural design but they are profoundly questioned. Rather than relying on finely calibrated formation synthesis and materialization processes of self-organized natural systems, experts should focus on definition and different types of material systems (Hensel & Menges, 2009, p. 92).

Discussing form-finding while integrating biological principles with architecture, Bechert et al stated that a form-finding model relies on procedural biology, which has several benefits for the design. When the simulation takes place, segments are seeded in specific spots for creating a customized design. The growth results created a segmented layout, which resembles sea urchin's skeleton. The farther they are from the starting point, the larger they become. It is an important geometric characteristic, which has many structural advantages. Experts noted that smaller segments show high interconnection density, so, those points are comparatively stiff (Bechert et al., 2016, p. 166).

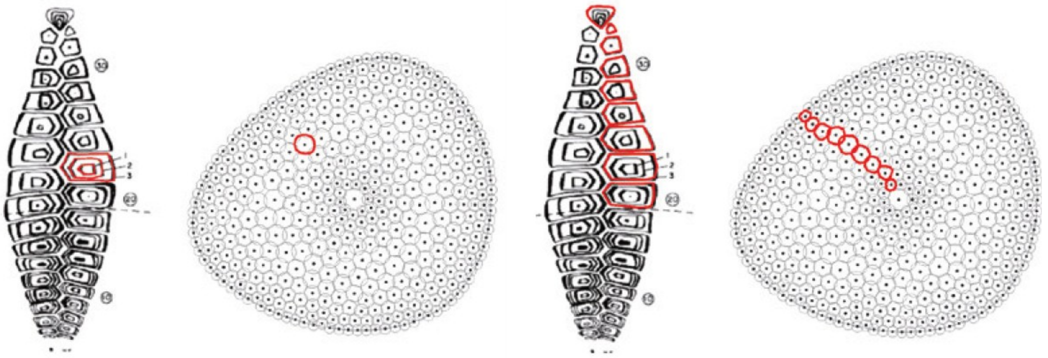

A   B

Figure 4.14: Diagrammatic representation (Bechert et al., 2016, p. 166)

[Fig.4.14a] shows plate accretion (left). It shows a row of calcite plates, which are bigger when they are located in the centre and smaller when they are in the corners. This growth principle has been shifted to the computational design (right). [Fig.4.14b] shows that the plates add (right side), which start from top part (ambulacral plates). These plates are shifted to the computational design tool (right) (Bechert et al., 2016, p. 166).

This is a glaring example of successful fusion of computational generative design and biology. It shows bottom-up research process of biomimetics, through which, biological role models are used for inspiration the way segmented shells were used in for the timber design. We can conclude that the structural space is adjusted using segmented shells, which was accomplished using the mentioned construction technique as a part of computational design.

- Example 3: ICD/ITKE 2013-14 Research Pavilion

For creating integrated design consisting of fibrous architectural structures, a combination of appropriate form generation and materialization is used, which leads to synergies in materials and forms. The mentioned example attempts to monitor the computational design framework that incorporates morphological principles. In this context, materials and the designed structure consist of lightweight components made up of fiber. ICD/ITKE Research Pavilion 2013-14 serves as an example to discuss it (Dörstelmann, Parascho, Prado, Menges, & Knippers, 2014). Design spaces define all possible outcomes, which are now possible to generate using computational architecture design inspired biological principles.

Figure 4.15: ICD/ITKE Research Pavilion 2013-14 (Dörstelmann et al., 2014, p. 227)

Menges mentioned that both research institutes including ICD and ITKE, University of Stuttgart cooperated with each other to construct this project. It is an important accomplishment of a series of research pavilions. These pavilions were constructed and in future, the research institutions will continue constructing them to show the computational design potential and how successfully biological principles can be applied to architecture. Students and researchers took one and a half year to construct it while a dedicated team of biologists, palaeontologists, architects and engineers worked to make it successful (Menges, 2014).

As mentioned by Webster, natural morphogenesis shows the capability of any specie to respond to many similar, contradictory, intrinsic and extrinsic stimuli. The obtained form uses these conditions for needed, robust, and adaptive outcomes instead of providing a unique optimization solution (Webster & Goodwin, 1996).

According to Dörstelmann et al., classic architectural planning processes function in a very different way because they normally appear as linear sequences of architecture design, engineering and construction processes. It might result in discrepancies, which might create issues in the initial design. They might need multiple repetitions because of the linear process. Integrating techniques need architectural processes, which look like natural morphogenesis. The intrinsic material designs drive generative design instead of form receptors, which results in bottom-up morphogenetic design approach that takes place with the help of computational design tools (Dörstelmann et al., 2014, p. 20).

Parascho et al stated that the fabrication advancements resulted in continuous geometric design development, which apply to the architectural applications. The ICD/ITKE Research Pavilion 2013/2014 shows a different design based on biomimetic and fabrication techniques that led to an extraordinary integrated design. Biological rules, characteristics of different building material, structural effectiveness and fabrication limits all contribute to the computational design using architectural morphology. In all the mentioned factors, computational design acted as a point of confluence (Parascho et al., 2015, p. 30).

Dörstelmann et al. add that the natural morphogenetic intricacies comprise to form a complex system of interrelated factors. The possibilities of this kind of design can be architecturally explored using computational design processes, which need new design strategies. It is possible through design methodologies, which have the capacity to transfer morphological rules to the computational design. Experts learnt morphological principles from biomimetics, material properties, possibilities and limitations of robotic fabrication, structural strength, architectural framework and organizational issues (Dörstelmann et al., 2014, p. 20).

Parascho et al. believe that the computational design provides a useful field to integrate the knowledge of biology and knowledge and expertise of architecture and engineering to conduct bottom-up studies, which helps creating a meaningful synthesis. Biomimetic investigations lead to components' structural and geometric variations as well as their universally recognized arrangements. On the other hand, the investigation studies on fabrication and materials help finding geometrical solutions and space for implementation (Parascho et al., 2015, p. 35).

Similarly, Dörstelmann et al. mentioned that the integrative design computation, which is conducted through multidisciplinary design processes, helps translating many inputs into information that becomes a part of tool parameters. Design computation also facilitates by processing the found interrelations and encoding them to form algorithms. It leads to optimum utilization of digital design processes, and besides, computation helps understanding and processing complicated interrelationships, which perform as tools to implement the formation of the interface and extension of design thinking. Computational design strategies facilitate the interdisciplinary data transfer by creating points of confluence and that substantially affects the operations (Dörstelmann et al., 2014, p. 221). The mechanism has been described in the Figure below:

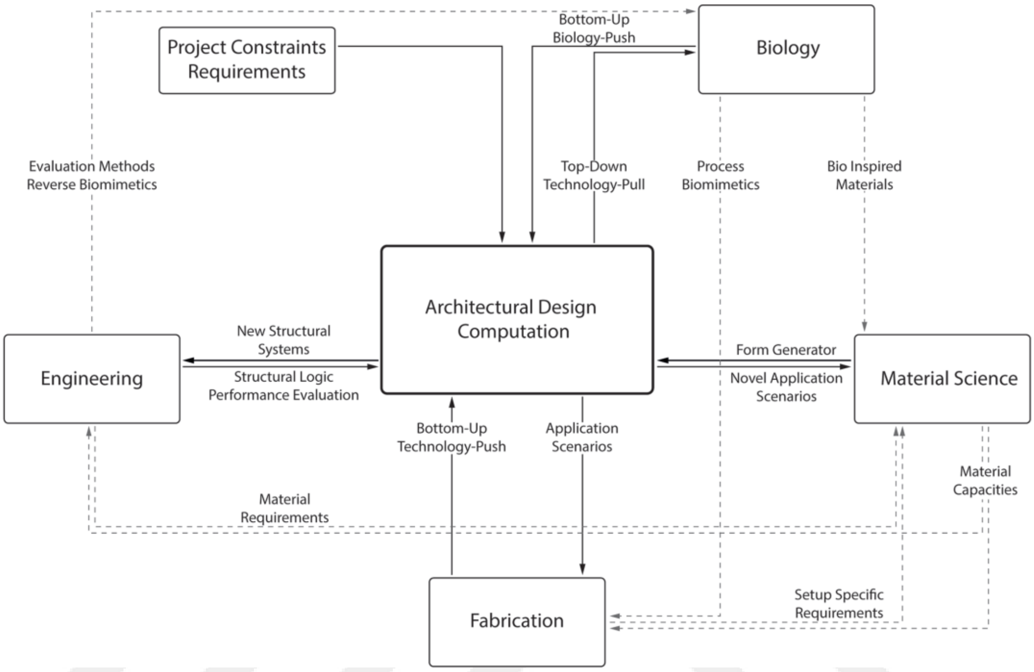


Figure 4.16: Generic integrative design process diagram (Dörstelmann et al., 2014, p. 221)

Biomimetic investigation: Menges mentioned that target-oriented studies on naturally occurring lightweight structures became possible through cooperation between architects and engineers from Stuttgart University and biologists from Tubingen University. Their researches were about bionics of animal constructions. In the process of research on Elytron, which is the name of outer protective shell of beetles' wings and abdominal part, it was found that its underlying biomimetic principles are very useful for material efficiency in construction. These ultra-lightweight structures depend on their geometric properties for protecting their two-layered systems and physical properties of their natural fibrous bodies (Menges, 2014).

Dörstelmann et al. believe that the functional morphology and material organization are quite effective for architecture as compared to synthetic structures and material choices. The very basic tasks of architecture include materializing forms and integrating functions in a highly efficient way in terms of materials used. If we reconsider the example of ICD/ITKE Research Pavilion 2013-14, considered, one can that several natural fibrous structures were assessed and used during its construction. The second example is beetle elytra, which has useful structural morphology specifically its flying beetles specie because it is a very productive role model its light weight construction [Fig4.17a]. Elytra's structure, for Dörstelmann et al. shows complicated geometrical and anisotropic organization. Since it is made up of natural chitin fibre, which is a composite material, a two-layered shell has been created maintaining the beetle's complex inner hyperbolic shape [Fig4.17b]. Its final form is shown below [Fig4.17c] (Dörstelmann et al., 2014, p. 222).

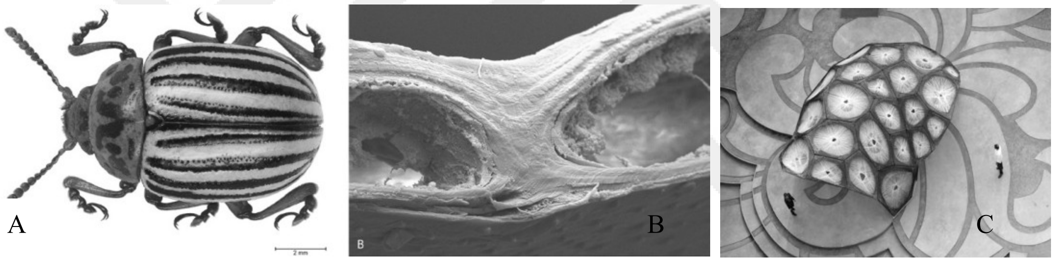


Figure 4.17: (A) Top view, light microscopy;(B) Section view into elytron’s internal structure; (C).final form (Dörstelmann et al., 2014, p. 222)

Moreover, Van, Kamp and Rolo claimed that the complicated morphology of elytra beetles have many useful and functional features. They explained the investigative processes and documented a comparative study, which fully explains the underlying logics as well as structural dimensions. This information is specifically interesting for those architects and project developers, who are interested in lightweight constructions. The elytron beetles have hollow and thin outer structures while the inner layer, called as internal trabeculae, creates a possibility to mimic this double-layered shell having interconnected internal braces (Van, Kamp, & Rolo, 2015, p. 151).

Material and Structure**:** Dörstelmann et al. proved that the integrated computational design and its materialization are intrinsic segments of the design process, so now; the design does not have a subordinating role to match the pre-determined geometric form. As a result, the interrelationships between materials, their behaviours and form generation create a final design, which is based on the information of potentials and constraints of the utilized materials. Researchers collect information through biomimetic investigation and then test the outcomes topologically and conceptually keeping in view particular material geometries. Core-less filament winding process defines the material geometries. It is a type of fabrication system that works without needing a positive mould for generating double-curved designs (Dörstelmann et al., 2014, p. 222).

Menges argued that all the ongoing computational morphogenetic researches acknowledge the significance of simplifying or at least understanding the complications of the material effects specifically their interrelationship and reciprocity. It helps during their usage in the dynamic environments by integrating their physical situation that helps knowing the parameters of materialization (Menges, 2012, p. 43).

Discussing the same topic, Menges mentioned in another study based on the morphology of differentiated trabeculae that the fibre arrangement in a two- layered modular system was created for implementing and determining the architectural prototypes. Experts chose glass and carbon fibres with specifically arranged polymers as the key building materials as they possess some remarkable properties including high performance, less weight, and more strength (Menges, 2014).

The creation of projects like ICD/ITKE Research Pavilion 2013-14 using computational design strategies opened debate and revealed possibilities of using structural principles learnt from the biological role models. Dörstelmann et al. mentioned that the architectural prototype materialization consists of 36 fibrous components having different fibre layouts, which resulted in a double layered, very useful and lightweight structure [Fig4.18]. The research pavilion covers 50.3 m² area having a total weight 594 kg (Dörstelmann et al., 2014, p. 226).

Figure 4.18: Pavilion (A: Overhang image, B: Interior image, C: Component system) (Dörstelmann et al., 2014, p. 227)

The figure 4.18 of the research pavilion shows how a biological structure has been synthesized using computational design strategies with the help of robotic fabrication, material reciprocities, and form creation techniques. Techniques like robotic fabrication help generating innovative construction methods, which creatively utilize fibers [Fig 4.19]. In the ICD/ITKE Research Pavilion 2013-14, computational design resulted in creating solutions until the project appeared in its final form. The distribution principles of trabeculae commonly exist in beetle elytra. This layout component acts as a starting point for very complicated solution. Integrating the possibilities that fabrication offers and particular geometric rules, which deal with biomimetic component distribution provide reasonable solution space for computational design (Dörstelmann et al., 2014, p. 224).

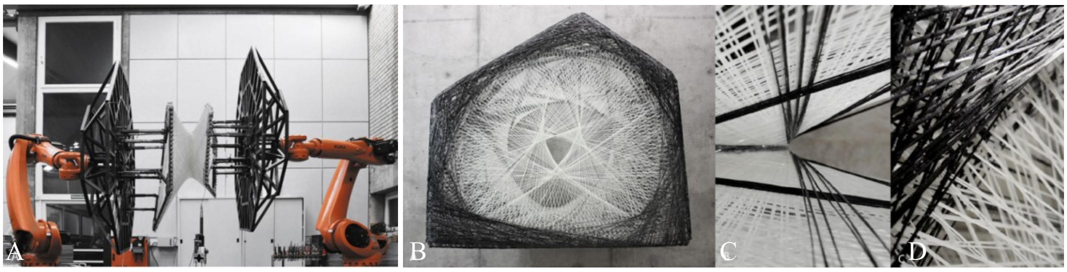


Figure 4.19: Carbon and glass fiber building component: (a) Fabrication setup; (b) Front view; (c,d) Differentiated carbon fiber reinforcement (Dörstelmann et al., 2014, pp. 219-222)

Discussing the same point, Parascho et al. claimed that this kind of integrated design based on biological structural analysis helps validating the results as well as act as design drivers on multiple levels. Experts have found some structural options partially based on biomimetic investigations, for example, elytron beetle structures have provided many new morphological principles for constructing fine and effective architecture. Its double-layered shell increases stability and improves the structural performance, so it is a more viable option as compared to single-layered structures (Parascho et al., 2015, p. 38).

Some computational designs, which emerged while finding the solutions to the design issues and instrumentalization of processing, act as design drivers. They discovered novel and impressive design exploration and materialization possibilities to create state-of-the-art building structures. So far, as we mentioned earlier, some model construction projects have shown remarkable morphological variation through lightweight construction but still, it depends on material capacity and availability, and the functional integration, which need further research. In future, the computational design might become more effective against harsh climates. In the nutshell, there is a great possibility to conceptualize even more and better designs using the integrated concepts.

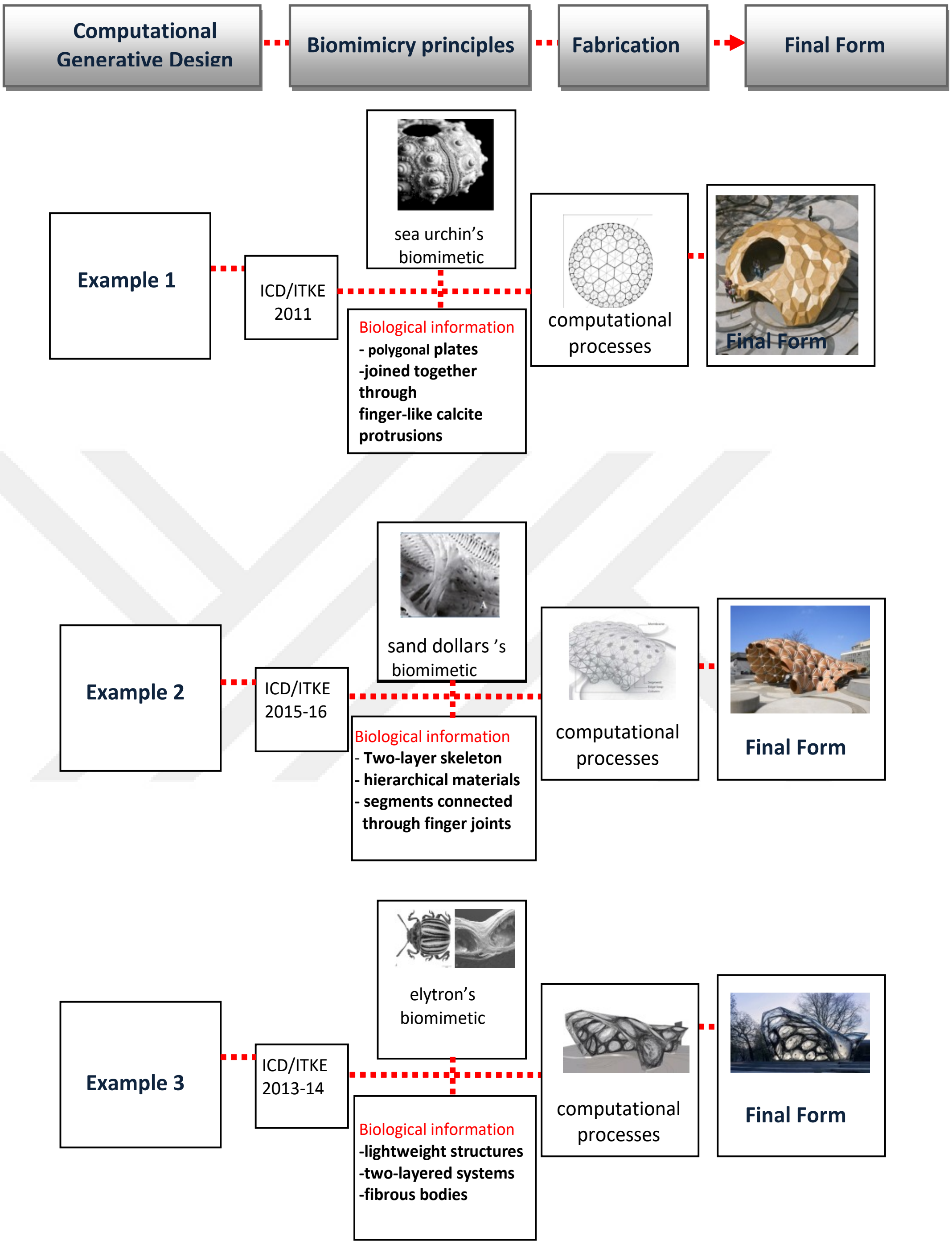


Figure 4.20 : Experimental examples of successful fusion of computational morphogenetic design strategies according to biological principles (Produced by the author)

The analysis of several pavilions [Fig4.20], designed and fabricated by morphogenetic design encompasses designs, which found in the natural morphogenesis of different species. Today, architects are shifting the biological processes to the latest integrated computational process. Other morphogenesis-related concepts, were necessary to understand for getting an insight into the presented approach. The presented approach has given a new life and importance to morphogenesis, which is now a very interesting concept for both biologists and architects who use computational modeling for showing effectiveness of techniques adapted from Botany and Zoology. Every technique has been discussed and analyzed according to the architectural principles. After that stage, evaluations and calculations show major advantages of each approach. In this chapter, it is tended to explain how effective a computational design can be and why biologists, researchers, and architects should make efforts to tap the still-untapped potential of the computational design methodology.

CHAPTER 5

CONCLUSION

Digital architecture consists of various cutting-edge technologies, architectural principles, and conceptual changes, which are way beyond traditional use of software for architecture design. In today's technological scenario, many options are available in terms of hardware and software, traditional use of software for design is now changing into form generation, which makes use of algorithms, biological simulations and biomimicry for architectural design. All of the mentioned factors enable to create complex architectural forms based on morphogenetic principles. "Scripting language" facilitates to generate design through transmuting thoughts with the help of digital software. Smart software are now available, which help designers think beyond conventional architectural design concepts, conceptualize better ideas, improve existing ideas, perform complex calculations, and compare alternatives.

Generative designs make use of complex algorithms in decision-making process . It shows that the generative design is applicable despite some difficult-to-handle design issues, which architects have been facing starting from the concept creation to final phase of the architecture design. Generative design is the future of architecture because it provides several acceptable options, design alternatives and out-of-the-box possibilities, which no other tool offers. Moreover, the computer operations of generative design offer advanced features; therefore, fully integrated computation is very helpful during the design process because it allows designers to handle complicated data to design very complex building dimensions. It is a fact that digital design is way beyond basic parametric modeling; however, latest features have made it possible to enhance and enrich the design using generative algorithms. It is important to note that unlike other innovative technologies, generative design does not finish the designer's role. It only facilitates designers to create better designs and allows better execution as compared to the traditional design. Based on the mentioned fact, it is possible to declare that generative design processes give some highly valuable results through pragmatic and mutually supportive collaboration between designers, engineers and programmers. While performing this technique, designers use computer-aided design generation function based on algorithms of a programming language. In the nutshell, it connects human brain with the computer system.

The current study depicts what nature can offer in terms of architecture. It indeed analyzes plenty of ideas and architectural solutions that is derived from biomimetics. It is the need of the current era that the architects, real estate investors, governments, and designers realize the importance of natural or nature-inspired ideas. These ideas offer great potential to raise the living standards of people, and make life more liveable on our planet. The consistent interaction between nature and architecture helps creating friendlier living spaces, more useful buildings and more habitable indoor atmospheres. This study highlights the past, present and future of biomimicry and computational design. Through this study, one can realize that the designers should develop deeper understanding of biological systems to create inspiring methods and models.

The study also focuses on the fact that meaningful collaborations between biologists and architects help creating "biodesign approach," that may be environment-friendly. Experts have acknowledged the fact that collaboration between biologists and architects leads to get designs environment-friendly, comforting, and weather-resistant living spaces. Both the kinds of professionals need to collaborate in order to design better versions of the available computational design softwares. Those hybrid softwares might make the organic growth possible.

Initiating any architecture design using a biological base creates impact on its form, structure and function. Computational design technology has provided architects with equipments, which have remarkable features that allow investigation of biomimetic principles, their usefulness in particular cases, and their architectural potential. Nowadays, there is a widespread cult of nature-inspired designs specifically those projects are getting attention, which resemble internal structure of an organism and at the same time, they use mathematical and biological principles.

As discussed before, morphogenesis refers to an architectural design approach, which investigates natural morphogenetic principles and gradually shifts them to integral computational process. There are many benefits to this approach particularly the one that compares computational botanical morphogenetic modeling with architecture design techniques. Experts believe that integration of architecture and biology can substantially develop digital morphogenetic application in practical architecture. This has opened new avenues because now architects can collaborate with experts of other sciences to discover and use useful shapes and phenomena for improving architecture design.

The integration between the computational generative design, biomimicry and morphogenesis, Certainly, can be achieved by computational form generation, which depends on programming language in addition to following a biomimetic approach to design. This takes place through observing and making use of similarities between architecture and biology. Moreover, both computational morphogenesis and evolution are intellectual concepts, and their implementation is a question to a certain extent because they pose social, economic and ecological challenges. Architects and engineers joined hands to create cutting-edge computational tools, which evaluate and simulate complicated natural forms into smart architectural solutions.

The examples given in Chapter 4 depict that there is a great potential of computational generative designs based on biological principles. Naturally, there are some implications to this design approach. It is evident that biomimetics can help generating optimum solutions to the architectural problems and convenience issues such as temperature control, humidity control and building costs. The computational design is indeed a revolution that creates endless possibilities to integrate natural design properties with the design process. It is clear that building fabrication has become a significant part of today's building design [Fig 5.2]. In fact, fabrication is beyond traditional prototyping and has brought change in design generation, which further leads to higher design efficiency.

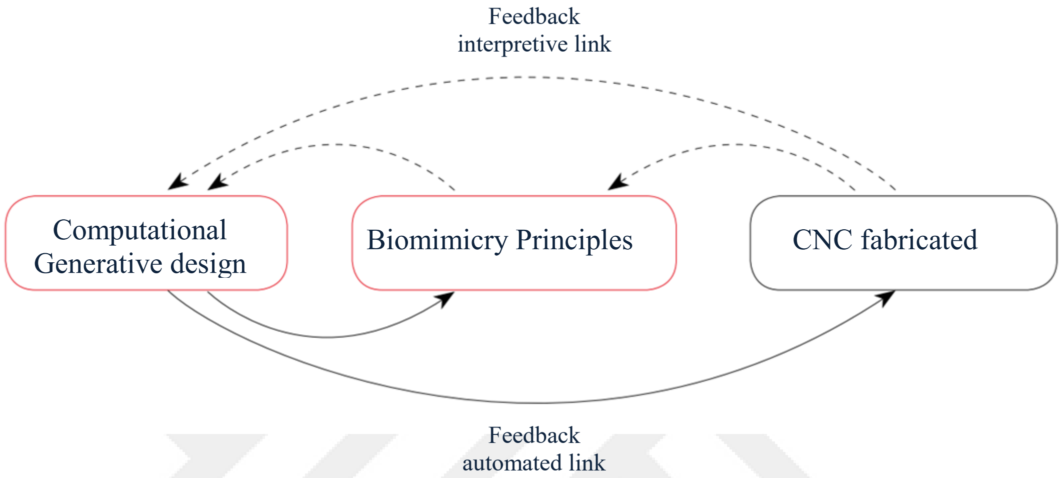


Figure 5.1: The diagram of relationship between design process and fabrication (Produced by the author)

The previously analyzed experimental examples all share a set of common advantages that significantly imply the importance and potential of the suggested design approach. Through the analysis and evaluation of these projects, the following issues were observed:

- Biological role models have been analyzed, their topological and structural principles have been identified and transferred into generative geometric rules. Such rules form the basis for the development of a computational tool integrating biomimetic principles with architectural and structural requirements, and the fabrication constraints.

- A form is a product of all the influencing factors interacting with biological principles. This setup enables iterative analyses and evaluation cycles to make the specific form of the system unfold from the reciprocal influences and interaction of form, material and structure within a simulated environment.
- Integration: Rather than aiming for rationalization or single-objective optimization, computation becomes the means of integration, which includes integration of system-inherent material constraints, manufacturing issues, and a wide array of external influences and forces.

Finally, one can state that using a computer as a generative tool to create forms depends on programming knowledge or ability to handle a programming language. Besides, following a biological approach to design requires making full use of the similarities between architecture and biology. They both deal with inputs and outputs, and both need a computer for simulating models. The only way to produce a close-to-perfect model is to follow the bio-inspired design approach with previously mentioned abilities.

The presented design approach, on the other hand, has various disadvantages. As a matter of fact, this sort of approach is quite achievable in areas such as product design, where computational design with biomimicry means following just a few principles; however, in architecture, it is a serious challenge.

Since the main goal is to support the decision-making process in the design work, this approach relies on multi-disciplinary collaboration of architects, engineers, biologists, and palaeontologists. They study architectural morphologies and morphogenesis through several complementary viewpoints such as forces, materials, environmental considerations including energy consumption or lifecycle implementation and fabrication processes, functions, costs, and perceptions. An architect cannot accomplish this process on his/her own. The importance of team work turns into an obligation during this process.

While underscoring the complexity of computation design packages, another issue is difficulties pertaining to education and training. Since there are great benefits of using computational programs, their integration into a practice is a major challenge. Practitioners should learn how to use them properly and how to understand their overall management. More likely, this is the reason why the number of those, who can effectively operate computational softwares, is remarkably lower than the other practitioners in a design group. For instance, Greg Lynn refers to this training problem and in particular, the difficulties of scripting in parametric programs:

> "We do some scripting and programming in Microstation Generative Components, but this involves sending people in the office to training sessions with Robert Aish as well as emailing him back and forth for specific tasks and having him come to the office every six to nine months" (M. Rocker, 2006, p .95).

Another criticism related to the manufacturing and assembly costs of buildings has been made from different circles. The criticism regarding this design approach is the role of a designer. Some might argue that the increasing software development in computational design has gradually diminished the human role in design. Although the presented design approach heavily depends on computer software and technology, the architect‘s role remains significant and it is summarized in the following points:

- The knowledge of biomimicry, computation and engineering is indispensible as a first step
- Need to define a material system components according to these requirements and constraints, and its geometric description and properties
- Need to analyze project requirements and constraints
- Defining relation between these components

- Description of the afore-mentioned points as design parameters in the computational model
- Knowing principles of biomimicry
- Selection of suitable algorithmic growth processes
- Recurrently interfacing with appropriate analysis applications
- Continuous evaluation and feedback [Fig 5.2]

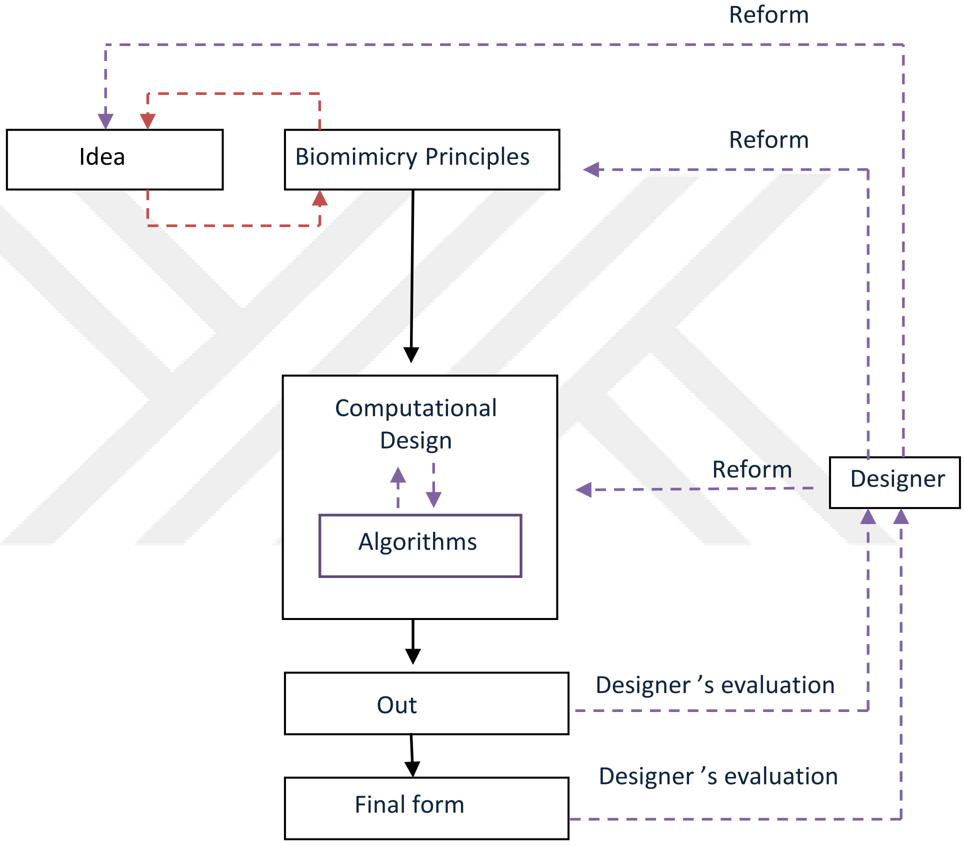


Figure 5.2 : The architect‘s role in design process (Produced by the author)

In conclusion, I believe that the architecture schools can be a reliable starting point for the application of computational design for biomimicry, and they can act as a potential place for the assessment of current computational tools. Idiosyncrasies can be found among students and their supervisors in the design schools. This could make the realm of inquiry more intriguing. Several reasons that emerge from architectural practice entail digging even deeper into architectural education to emphasize/realize the significance of the computational approach and biomimicry. As a result, I believe that one of the potential topics of investigation in the architecture schools is to seek the extent of alignment of computational modules with practical needs using principles of biomimicry. The real challenge lies in developing computational tools in such a way that they allow cooperation between different modes of design and disparate design mediums in an open system. The projects, which are analyzed in this thesis, are not too significant because the research on this subject is still in the early phases. I believe that in the near future, true biomimetic designs will take the shape of actual projects and will appear with their full forms, features and functions.

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APPENDIX

ABBREVIATIONS

CAD – Computer Aided Design

CAM – Computer Aided Manufacturing

BIM – Building Information Model

GD – Generative Design

GA – Genetic Algorithm

CGD – Computational Generative Design

GLOSSARY OF TERMS

Building Information Modeling - An approach that offers the possibility to build virtually, simulating the construction environment with all the information needed for construction

Generative – Refers to a rule based system where complex behaviours emerge from the interaction of simpler elements

Generative Design - generative design is process based on rules or algorithms, through which various elements and design possibilities can be created.

Generative System - A system that generate options for design problems.

Computational Design - computational design is the transition from currently predominant modes of Computer Aided Design (CAD) to Computational Design allows for a significant change of employing the computer‘s capacity to instrumentalise materials‘ complex behaviour in the design process.

Computational approach - An approach to design that is controllable and can easily handle change. It allow the generation of several different variations of the same design.

Scripting - An approach that allows the user to access the underlying structure of existing software and embed new functionality to it.

Algorithm – A sequence or procedure for calculation.

Biomimicry - It is an applied science that derives inspiration for solutions to human problems through the study of natural designs, systems and processes.

Morphogenesis - It is a term broadly meaning the formation of shape and structure by a coordinated growth process and or mechanism. The word is derived from the Greek terms ‘morphe’ (shape or form) and ‘genesis’ (creation). It originated as a branch of biology in the early 1800s that focused on the variation of biological forms.

Computational morphogenesis - Computational morphogenesis is a design process that takes advantage of the two main features of evolutionary algorithms: exploration, of a wide set of possibilities, and exploitation, of the best solutions generated, in analogy with natural evolutionary processes.