THE REPUBLIC OF TURKEY
BAHÇEŞEHİR UNIVERSITY

# FORM GENERATION STRATEGY INSPIRED BY NATURE: ANALYSIS OF CALATRAVA'S DESIGNS

**Master's Thesis**

**ZIKAR MOHAMMED ALI**

**ISTANBUL, 2019**

THE REPUBLIC OF TURKEY
BAHÇEŞEHİR UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTERS OF ARCHITECTURE

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**ZIKAR MOHAMMED ALI**

**Supervisor: ASSOC. PROF. MELTEM VATAN KAPTAN**

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Name/Last Name of the Student: Zikar Mohammed Ali

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The thesis has been approved by the Graduate School of Natural and Applied Sciences

Assist. Prof. Dr. Yücel Batu SALMAN
Graduate School Director

I certify that this thesis meets all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Emine Özen EYUCE
Program Coordinator

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

| Examining Committee Members | Signature |
|---|---|
| Thesis Supervisor | |
| Assoc.Prof. Meltem Vatan KAPTAN | ---------- |
| Member | |
| Assist.Prof. Dr. Elif SOMER | ---------- |
| Member | |
| Assist.Prof. Dr. Ezgi KORKMAZ | ---------- |

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Istanbul, 2019 Zikar Mohammed ALI

# ABSTRACT

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Zikar Mohammed ALI

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Nature has always been used as a source of inspiration by the architects. One of the issues in architecture is the process of form generation, especially inspired by the nature. So, integrating nature into architecture through form generation is one of the design tools. Observing the structures of the natural creatures, including their function, aesthetics, and structural principles with the aid of technology have helped the architects to design and generate impressive structures by following unique techniques for generating forms.

The main aim of this thesis is to explore the form generation approaches in architecture. Furthermore, the architectural production of Santiago Calatrava and his designs are analyzed as case studies. The outcome of the thesis may increase the awareness of the architects and provides them with opportunities for dealing with their forms and offers solutions for their forms of structural design.



**Keywords**: Nature, Structure, Santiago Calatrava, Form generation.

# ÖZET

DOĞADAN ESİNLENEREK FORM BULMA: CALATRAVA TASARIMLARININ ANALİZİ

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Doğa her zaman mimarlar tarafından ilham kaynağı olarak kullanılmıştır. Mimarlıktaki önemli konulardan biri, özellikle doğadan ilham alan form oluşturma sürecidir. Buna göre, form üretiminde doğayı mimarlığa uyarlama önemli tasarım araçlarından biridir. Doğadaki canlıların biçimlerini, işlevlerini, estetiğini ve fiziksel özellikleri, hareket kabiliyetlerini teknolojik olanaklar ile birleştirerek kullanmak üzere düşünmek mimarlara etkileyici binalar yapmak ve form üretimi konusunda yardımcı olmaktadır.

Bu tezin temel amacı mimarlıkta form ve biçim geliştirme yaklaşımlarının araştırılmasıdır. Ayrıca, Santiago Calatrava'nın mimari eserleri ve tasarımları analiz edilerek incelenmiştir. Tezin sonucu mimarların form üretimi konusundaki yaklaşımlar ile ilgili farkındalığı artırma ve form üretiminde yeni yaklaşımlar sunma ve form tasarımı konusunda çözüm önerileri sunmaktadır.

**Anahtar Kelimeleri**: Doğa, Strüktür, Santiago Calatrava, Form Üretimi

**CONTENTS**

**TABLES** ..... viii
**FIGURES** ..... ix
**1. INTRODUCTION** ..... 1
**1.1 BACKGROUND** ..... 1
**1.2 THE AIM OF THE STUDY** ..... 2
**1.3 QUESTION FORMULATION** ..... 3
**1.4 METHODOLOGY** ..... 3
**2.FORM GENERATION IN ARCHITECTURE** ..... 4
**2.1 FORM GENERATION INSPIRED BY GEOMETRY** ..... 4
**2.2 FORM GENERATION INSPIRED BY CONTEXT** ..... 7
**2.3 FORM GENERATION BY STRUCTURAL PERFORMANCE** ..... 8
**2.4 FORM GENERATION INSPIRED BY NATURE** ..... 13
**2.4.1 Biomimicry approach** ..... 13
**Levels of biomimicry** ..... 17
**2.4.2 Morphogenesis in architectural design** ..... 18
**2.5 COMPLEX FORM GENERATION APPROACHES** ..... 20
**2.5.1 Parametric form generation** ..... 21
**2.5.2 Fluidity or The Pliant Non-linear architecture** ..... 24
**2.5.3 Topological Architecture** ..... 27
**2.5.4 Algorithmic Architecture (Scripting)** ..... 30
**2.6 FORM GENERATION BY ANALOGY** ..... 33
**2.6.1 APPROACHES TO ANALOGY** ..... 34
**2.6.1.1 Visual Analogy** ..... 34
**2.6.1.2 Structural analogy** ..... 35
**2.6.2 ANALOGY IN ARCHITECTURAL DESIGN CONCEPT** ..... 35
**2.6.3 Biological Analogy In Architecture** ..... 36
**2.6.3.1 Organic analogy** ..... 37
**2.6.3.2 Anatomical analogy** ..... 39
**2.6.3.3 Ecological analogy** ..... 40
**2.6.3.4 Darwinian analogy** ..... 40
**2.7 STRUCTURES IN NATURE AND ARCHITECTURE** ..... 43

**2.7.1 Tree-like branching structure** ..... **47**
**2.7.2 Shell-like structure** ..... **48**
**2.7.3 Web-like structure** ..... **49**
**2.7.4 Pneumatic structures** ..... **50**
**2.7.5 Vertebrate skeleton** ..... **53**
**3. SANTIAGO CALATRAVA'S ARCHITECTURAL PRODUCTION** ..... **57**
**3.1 NATURE AS AN INSPIRATIONAL SOURCE** ..... **57**
**3.2 MOVEMENT** ..... **58**
**3.3 TYPES OF MOVEMENT IN CALATRAVA'S STRUCTURES** ..... **60**
**3.3.1 Functional movement** ..... **61**
**3.3.2 Symbolic movement** ..... **66**
**4. CASE STUDY ANALYSIS** ..... **72**
**4.1 THE PLANETARIUM OF THE CITY OF ARTS AND SCIENCES** ..... **73**
**4.2 MILWAUKEE ART MUSEUM** ..... **76**
**4.3 MALMO TOWER** ..... **79**
**4.4 SHADOW MACHINE** ..... **82**
**5. DISCUSSION AND FINAL REMARKS** ..... **86**
**5.1 DISCUSSION** ..... **86**
**5.2 FINAL REMARKS** ..... **87**
**REFERENCES** ..... **91**

## TABLES

Table 2.1: Types of biological analogy and their description ..... 42
Table 2.2: Classification of structure in nature and architecture by authors ..... 46
Table 4.1: Analysis of the planetarium of the city of art and science……..……..74
Table 4.2: Analysis of Milwaukee art museum-Spain ..... ……77
Table 4.3: Analysis of Malmo tower -Sweden ..... 80
Table 4.4: Analysis of Shadow machine -USA ..... 83

## FIGURES

Figure 2.1: Platonic solids ..... 5
Figure 2.2: Projects designed by Sullivan inspired by Geometry ..... 6
Figure 2.3: Unity temple designed by Frank Lloyd Wright ..... 6
Figure 2.4: Ronchamp chapel by Le Corbusier ..... 7
Figure 2.5: Teatro del Mondo in Venice designed by Aldo Rossi ..... 8
Figure 2.6: Hanging model of Colonia Guell by Gaudi ..... 9
Figure 2.7: The 1896 Nizhny-Novgorod Exposition ..... 10
Figure 2.8: Concrete shell of Wyss Garden Centre by Heinz Isler ..... 11
Figure 2.9: Otto's soap film conoid ..... 12
Figure 2.10:Munich Olympic stadium & Germany's pavilion designed by Otto ..... 12
Figure 2.11: Daimler Crysler bionic car inspired by the box fish and tree growth pattern ..... 16
Figure 2.12: Lotus Inspired Lotusan Paint ..... 17
Figure 2.13: D'Arcy Thompson classic fish transformation form through mathematical transformation ..... 19
Figure 2.14: The form of the geodesic dome designed by Buckminster Fuller inspired by the ridged radiolarian ..... 20
Figure 2.15: Mercedes-Benz Museum, Stuttgart ..... 23
Figure 2.16: Fluidity in Casa Mila designed by Antoni Gaudi ..... 25
Figure 2.17: Fluidity in TWA terminal ..... 25
Figure 2.18: Olympic stadium by Kenzo Tange ..... 26
Figure 2.19: Fluidity in Zaha Hadid's projects ..... 27
Figure 2.20: The Olympic Stadium and the Tennis Center in Hangzhou ..... 32
Figure 2.21: The Modeling Of the Tennis Center By Algorithm for defining ..... 33
Figure 2.22: Skeleton of fossil bison is compared to the Forth bridge cantilever structure ..... 40
Figure 2.23: Different structures in nature ..... 43
Figure 2.24: Different structures in architecture ..... 45
Figure 2.25: Load path in tree-like branching structure ..... 47

Figure 2.26: Tree-like branching structure in architecture..... 48
Figure 2.27: Shell structure in nature ..... 48
Figure 2.28: Shell structure in architecture ..... 49
Figure 2.29: Web-like structure in nature ..... 49
Figure 2.30: The Olympic stadium of Munich inspired by web structure ..... 50
Figure 2. 31: Pneumatic structures in nature..... 51
Figure 2.32: Pneumatic structures in architecture..... 52
Figure 2.33: Types of pneumatic structures in architecture ..... 52
Figure 2.34: The skeleton is used as inspiration for a building ..... 54
Figure 2.35: The structure of bridges inspired by the animal body ..... 55
Figure 2.36: Skull of a bird in architecture ..... 56
Figure 3.1: Types of kinetic structures..... 59
Figure 3.2: Unfolding movement of a door designed by Calatrava ..... 62
Figure 3.3: The rising movement of a roof designed by Calatrava..... 63
Figure 3.4:Rotation ..... 64
Figure 3.5: Puento de mujer bridge rotation ..... 65
Figure 3.6: Translational rotation..... 65
Figure 3.7: Translational rotation of the Swissbau concrete pavilion..... 66
Figure 3.8: Alamillo bridge designed by Calatrava with an inclined pylon ..... 67
Figure 3.9: Polyclitus sculpture of a twisted body ..... 69
Figure 3. 10: Sketches of a twisted human body drawn by Calatrava ..... 69
Figure 3.11:The design of a tower inspired by a twisted human body ..... 70
Figure 4.1: The steps of designing the Planetarium of the city of science and art……..75
Figure 4.2: The Steps of designing the Milwaukee art museum……..…...78
Figure 4.3: The steps of designing Malmo tower……...……81
Figure 4.4: The steps of designing Shadow……...……...…...84

# 1. INTRODUCTION

## 1.1 BACKGROUND

The form and structure in nature are essential sources for understanding the basics of structural concepts. Therefore the interest in generating forms and structures based on nature in architectural design is increasing to become a model for architects. The form is typically referred to the object's shape, whereas structure is defined as the configuration of the elements of the shape. Both are associated with the functions. The notion that function suits form and structure is one of the significant features of design in nature and well recognized both in biology and the design literature. Forms and structures in nature are compliant to the physics laws which compel the domain of designs obtainable for living systems. Geometric structures and forms are the outcome of the struggle for better performance under local and global restrictions. Thus, form and structural patterns are design solutions to issues that are set by the restraints of space. As an essential source for structural solutions with the aid of technology, it leads the architectural disciplines toward learning from nature for designing elegance structures. Furthermore, the architect who combines the aesthetics and technical principles of nature into architecture has the chance to design magnificent structures. Also, it is important to have general knowledge about structures in nature and follow a strategy that depends on imagination and knowledge to be able to use nature as an inspirational source (Alhussaini, 2007).

For centuries, different methods to architectural design based on form generation have been discovered by some famous architects like Frei Otto, Eero Saarinen, Antonio Gaudi, and Frederick Kiesler. They were using design approaches similar to the sophisticated computational methods that exist in today's architecture (Agkathidis, 2015). After the Industrial Revolution, when progress in natural sciences such as biology has been dominating the theoretical and practical world. It was specific for architects to get inspired by these significant improvements. They utilized nature as an imitation source for the symbolic and unusual forms. They find their structural stimulation from spider's web, plant

life, a piece of coral, and in the structure of animals (Rappaport, 2006). Joseph Paxton was influenced by the vast water lily, the Victoria Amazonian, that was used to the progress of the structure of the beam for the Crystal Palace 1851 and the greenhouse at Chatsworth Park.

During the development of architectural design, there have always been schools of thought that have promoted the design procedure depended on the stimulus or an early impulse. Whilst, others have advanced adherence to a definite design way, relied on principles rather than impulse, and many today contend that design approaches are important to help architects to deal with today's hyper-complicated design briefs. Others confirm that inventing computational design and fabrication techniques are altering the architect's duty, making design approaches a requirement (Agkathidis, 2015).

In last decades, innovative form generation techniques have been presented in architecture reforming design and production in architecture. These methods are frequently defined by terms such as, 'parametric design and generative design'. This show new design ways to architects by breaking with anticipated connections between form and representation in the service of complicated generated form by computer, thus allowing the progress of new topologies (Kolarevic, 2003).

## 1.2 THE AIM OF THE STUDY

This thesis aims to explore the form generation approaches in architecture and the way they have been invented and employed by architects. The architectural production of Santiago Calatrava is explored and the way he generates form and the inspiration sources are studied then his works are analysed as case studies.The outcome of the study will help to broaden the architect's concern. Furthermore, it will help to understand how nature as a generator tool brings aesthetic and structural preferences.

## 1.3 QUESTION FORMULATION

To achieve the aim of this thesis, the following questions are asked:

a. What are the form generation processes in architecture?

b. How do architects deal with the form generation processes in architecture?

c. How Calatrava generates forms from nature for his designs?

According to this question formulation, the hypothesis of this thesis is "The generation of forms and structures by inspiration of nature is possible by following a design strategy". The achievement of this hypothesis will help to raise the awareness of the architects and direct them towards nature as a source for solving their design problems.

## 1.4 METHODOLOGY

This thesis explores form generation approaches in architecture. During the study, firstly, a literature review has been made in a wide range and content about the form generation approaches in architecture. The method of learning from nature is explored. Consequently, Santiago Calatrava's architectural approach is studied and his works are analysed as case studies.

Four of Calatrava's projects are selected to be analyzed. Each of the projects is inspired by a different concept and element from nature. The selected Case studies are analyzed using the qualitative approach. The data collected for the analyzing process includes drawings, sketches and sculptures of the projects designed by the architect.

# 2.FORM GENERATION IN ARCHITECTURE

Generating form and design its structure can be considered as one of the significant questions in architecture. Architectural production is often escorted by the discussion about the legitimacy of its design method, enquiring the connection between form, function, aesthetics and construction, in all probable configurations.

Therefore, a discussion of the various form-generation philosophies that have dominated architectural design over the past century and are still being widely used today have key importance in architectural design.

## 2.1 FORM GENERATION INSPIRED BY GEOMETRY

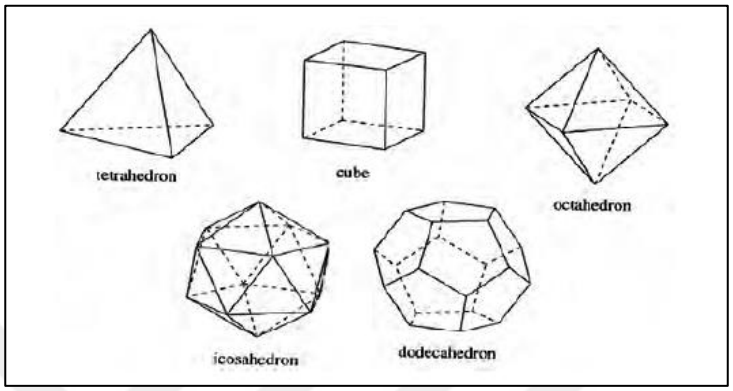
Geometry is defined as the basic science of the form and its order. The rules of geometry in the history of architecture is based on the concepts of proportion, which is considered as the main category of aesthetic in nature. In this regard, proportions such as the golden section were found as a powerful tool for creating harmony in architecture (Leopold, 2006).

In architecture, the composition begins with elements and their relations. Geometry contributes to the method of composition and design as the main science of form and its order. Geometry can contribute to this procedure by acting with geometric forms as elements, angles and transformations as well as proportions, and link between them (Leopold, 2006).

The Greek philosopher Plato (427-348 B.C.) confirmed that aesthetic of form is depended on mathematical and rational rules. Plato had found that forms that inspired by geometry were considered as “forms of beauty”. He had emphasised that employing geometrical forms such as lines, circles, planes, cubes in a design composition would lead to generating aesthetical forms (Fowler, 1999). Plato had demonstrated and clarified the creation of the five regular solids based on the “most beautiful of all many triangles” in his Timaeus. He also defined the five regular Platonic solids, which are the tetrahedron, the Hexahedron (Cube), the Octahedron, the Dodecahedron and the Icosahedron (Figure 2.1), (Cromwell, 1997). These Platonic solids are three-dimensional forms whose

surfaces comprise of regular, and identical polygons such as equilateral triangles, squares and pentagons that meet in equal angles at the corners.

**Figure 2.1:Platonic solids**

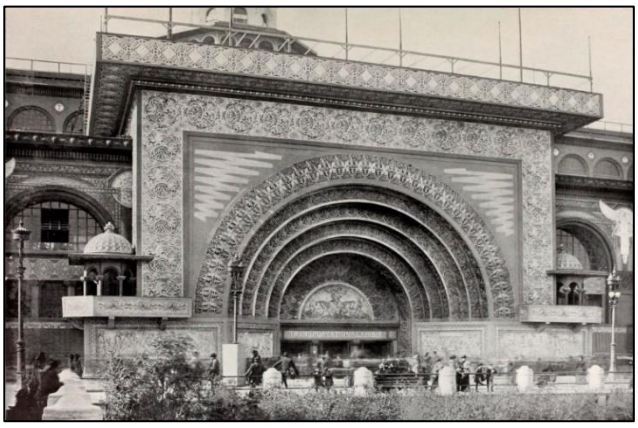



*Source:*(Gardner, 2008)

Furthermore, the architectural space is based on the concept of geometric space. Especially in the process of creation architecture is thought concerning a geometric space. Robin Evans investigated the association between architecture and geometry *"The first place anyone looks to find the geometry in architecture is in the shape of buildings, then perhaps the shape of the drawings of the buildings. These are the locations where geometry has been, on the whole, stolid and dormant. However, geometry has been active in the space between and the space at either end" (*Evans, 1996).

Geometric rules and proportions are the primary source of inspiration for some architects. Louis Sullivan, as one of the most famous architects of the modern movement (Figure 2.2), used simple techniques and methods of geometry such as triangulation and quadrature for inspiration (Menocal and Twombly, 2000).

**Figure 2.2: Projects designed by Sullivan inspired by Geometry**



*Source*: (Berman, 2016)

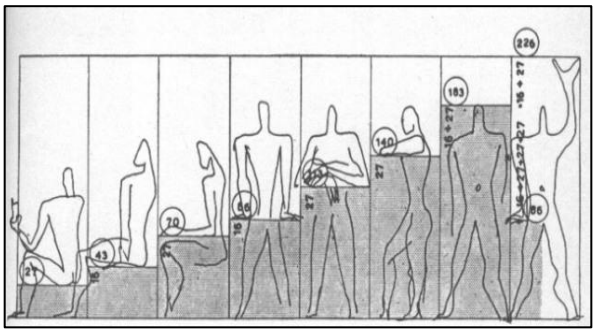
While Frank Lloyd Wright applied geometrical rules and proportions to the design of his Unity Temple in Chicago 1908 (Figure 2.3). His design was based on a 2 meter grid, improved with dimensions that derived from quadrature and were not convenient with the grid (Jormakka, 2007).

**Figure 2.3: Unity temple designed by Frank Lloyd Wright**

*Source*: (Kroll, 2011)

Later, in his book Modular 1948, Le Corbusier attempted to organise his proportional design approaches considering the golden section as the foundation and direction to beauty. He applied his famous Modular proportional diagram for one of his masterpieces which is considered as his most geometrically innovative projects the Notre Dame du Haut Chapel in Ron champ 1954 (Figure 2.4). Emphasizing that proportion rules of Modular could perform as a toolbox giving unpredictable productions (Agkathidis, 2015).

**Figure 2.4:Ronchamp chapel by Le Corbusier**

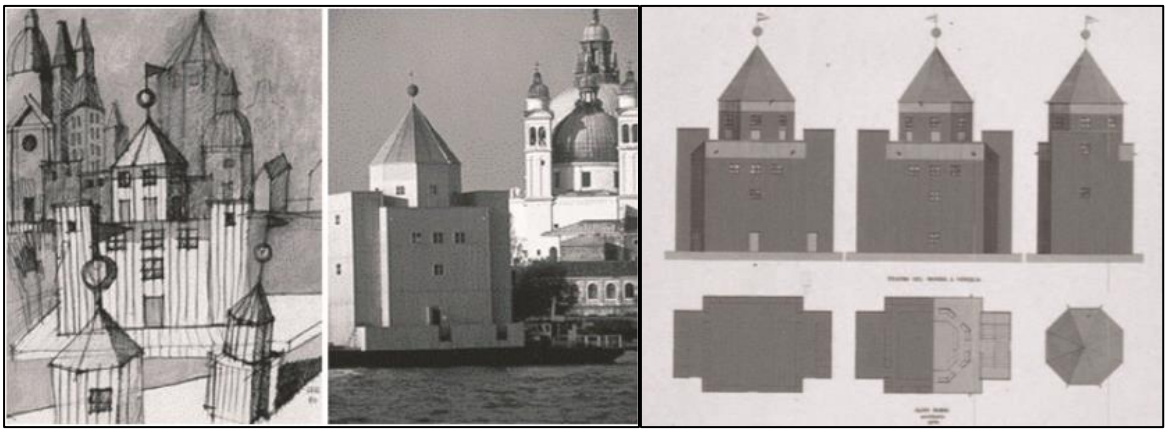


*Source*: (Winston, 2016)

## 2.2 FORM GENERATION INSPIRED BY CONTEXT

Context is the exterior element that affect the form of the building. These elements are Physical that might be the surrounding buildings, and landscape and non-physical elements include the climatic condition, culture, history also economic and political restrictions. The context defines the architectural style, selection of building materials and site layout, which is particularly helpful for creating an efficient design (Sahabuddin, 2011). Many architects are inspired by the context and have generated form by depending on the notion of context. Architects such as Aldo Rossi, for instance, inspired by the historical context frequently found in Italian cities such as the octagon, colonnade, and arch to be employed in very pure forms, regardless of function or scale. In his attempt to design the Teatro del Mondo in Venice 1979 (Figure 2.5), he was inspired by the octagonal tower shape, which is common in the historical context of Italian cities (Jormakka, 2007). Moreover, Mario Botta, inspired by conventional building approaches and techniques by employing forms that are simple, symmetrical, modernist in integration with site-inspired materials, and colours. His design for a house in Ligornetto, Switzerland, in 1976, for instance, reflects the feature strips frequently found in the region (Cappellato, 2004). Finally, Oswald Mathias Ungers, replied to the site and observed the features such as materiality, texture, arches, symmetry, roofs and angles, then tried to employ these principles in a new design (Ungers, 2011).

**Figure 2.5:Teatro del Mondo in Venice designed by Aldo Rossi**

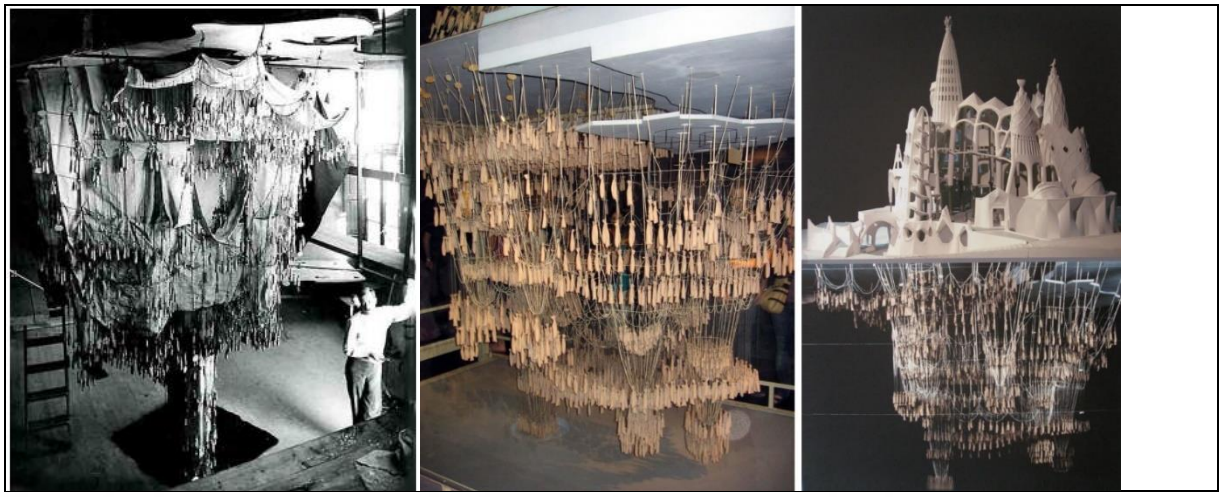


*Source*: (Munari, 2015)

## 2.3 FORM GENERATION BY STRUCTURAL PERFORMANCE

The term performance denotes to the structure's efficiency and the capability to generate forms with minimum amount of materials and to cover huge spans. Some architects and engineers have experienced a quite various form-generation approach. They concentrated on the minimum probable form generated from the performance of the structure and material properties this approach can be defined as *"optimizing the loading capacity of the construction without consideration of additional loading" or, the optimization of the path of the forces towards the reduction of the constructed volume"* (Stach, 2002). The relationship of the building with its context performs only a small role. Antoni Gaudi was the first architect who created a self-generating method accomplished on the physical hanging models to find out the completed structure and the form of the designed building (Wenland, 2008). The hanging model created by Gaudi demonstrates the flow of forces in the linear parts of the structure such as ribs and columns, offering tension only in the strings (Figure 2.6). So, by turning upside-down the formation of the model, a structure is acquired that, beneath its weight, is liable only to axial compression load in every element, without bending moments (Wenland, 2008).

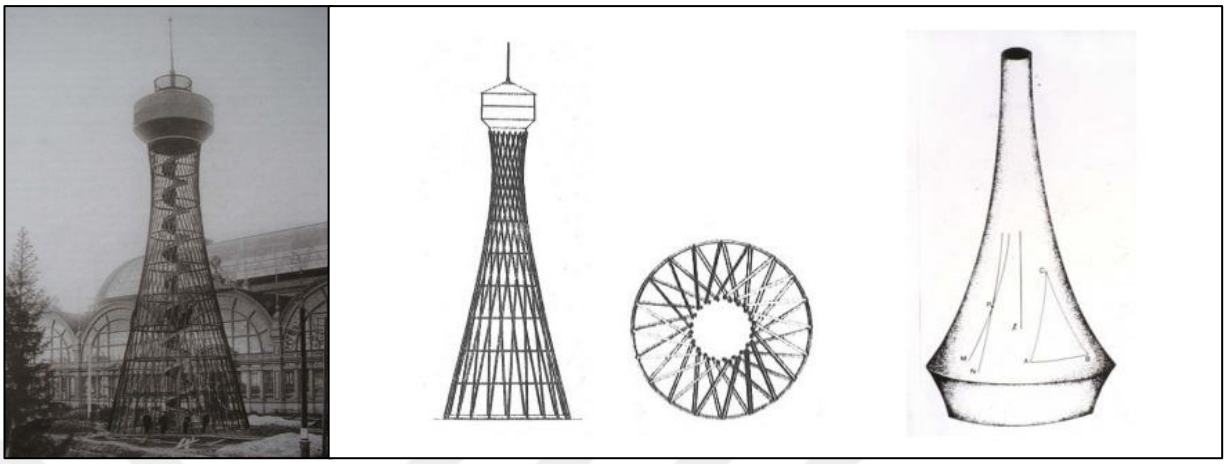
**Figure 2.6:Hanging model of Colonia Guell by Gaudi**



*Source*: (Ramirez, 2000)

Vladimir Shukhov's design for a steel tower, that was built in 1896 for an industrial exposition in Nizhny Novgorod (Figure 2.7), regarded as the world's first-ever hyperboloid diagrid form (Agkathidis, 2016). This structure attained a unique composition of mathematical shapes, enhanced structure and material performance ( Magomedov, 1987). Shukhov developed an easy and effectively built structural system in his design for the tower by holding a great demonstrated load of gravity at the top - the issue of the water tower. He found a solution which was stimulated by perceiving the movement of a woven basket carrying up a heavyweight. Furthermore, it acquired a non-Euclidean surface form of a negative double curvature built of a light grid of straight and angle-iron bars. Shukhov began experiencing with the idea of creating the tower from stacked sections of hyperboloids. Stacked pieces allowed the tower to take a taper form more at the top, with a less pronounced "waist" between the shape defines the tension rings at the top and bottom. Rising the number of sections would expand the entire form's tapering , to the point which it starts to look like a cone (English, 2005). This form was then repeated in much of Shukhov's later works, such as the telecommunication tower that was built in Moscow.

**Figure 2.7:The 1896 Nizhny-Novgorod Exposition**



*Source*: (English, 2005)

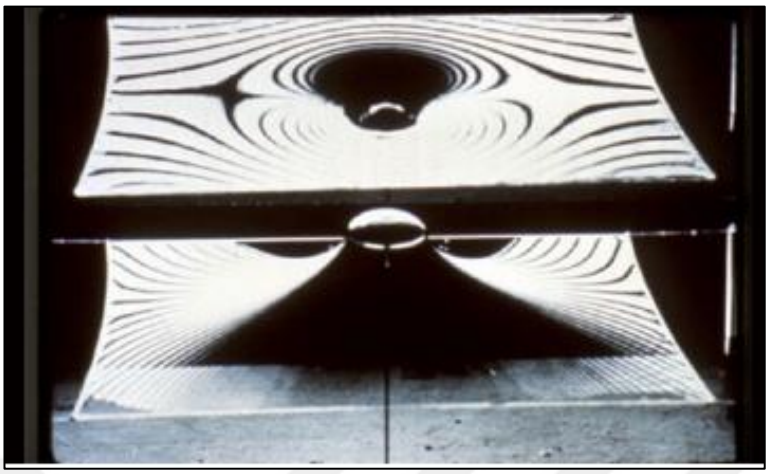
Heinz Isler built hundreds of concrete shell structures based on physical models for form-generation. The forms of his shells were progressed over constant forms created by, physical and mechanical models, pneumatic forms and floating forms made of various materials (Wenland, 2008). His free-form shells have elegant structural conduct in several situations, these shells have free edges, without the need of the edge-beams or structural elements in the facade due to the enhanced form of these shells (Wenland, 2008). Heinz Isler's concrete shell structure which was built in 1962 for the Wyss Garden Centre in Switzerland (Figure 2.8) presumes identical hyperboloid shapes, covering a span of 650 square meters, with a shell thickness of only 60 mm (Chilton, 2000).

**Figure 2.8: Concrete shell of Wyss Garden Centre by Heinz Isler**

*Source*: (Tang, 2015)

Moreover, the German architect Frei Otto was one of the architects who worked on the processes of form-generation inspired by performance; he depended on these methods to build and develop many of his designs (Nerdinger, 2005). He investigated the form generation depending on lightweight structural materials to decrease the mass of the material and offer structural efficiency ( Nerdinger, 2005). He carried out investigations on a model of the soap film of a minimum surface where the tension was identical over the whole surface (Figure 2.9). This nominal surface converted into a tensile structure directly without fabric crinkling and identical pressures all over the form. This investigation was used for understanding the conoid form for a tensile structure (Goldsmith, 2016).

**Figure 2.9:Otto's soap film conoid**



*Source*: (Goldsmith, 2016)

Frei Otto, who was examining tensile membrane structures, improved the Munich Olympic Stadium in 1972 and the World Expo in Montreal, 1967 (Figure 2.10) a particular highlights of his career (Otto and Rasch, 1996). The design of the world Expo in Montreal by Frei Otto was in cooperation with Rolf Gutbrod which was a lightweight structure "a tent-like roof made of a net of cables" (Koch and Hoberman, 2004). Although the original design was a tensile membrane structure, it was finally constructed as a cable net structure, employing the membrane as a secondary cover (Bechthold, 2008).

**Figure 2.10: Munich Olympic stadium & Germany's pavilion designed by Otto**

*Source*: (Henrysson, 2012)

## 2.4 FORM GENERATION INSPIRED BY NATURE

The will to pursue nature, to observe its fundamental forms in the pursuit of harmony, is dated back to antiquity, to the Vitruvius's writings, in addition to Goethe's work on morphology. In the 18th century, biologists began a movement that emerged from a will to comprehend the "universal laws of form" to describe and analyze the observed forms of living organisms. Observing around the end of the 19th century, at the pre-computational times, architects of avant-garde started enquiring the historicist architecture of their period, which they found was outdated because it did not succeed to reflect both technological evolution and social structure; it did not coincide to the characteristics of that era (Agkathidis, 2016). They began to impulse for design principles of the universe that would substitute individual palate and the mere proliferation of historical pattern. In their endeavour to do that, their concern turned to examples and solutions that exist in nature instead, coinciding with the works of pioneers of biology and naturalists, like Ernst Haeckel, who precisely defined, described, and demonstrated thousands of new species. Many projects have been inspired by nature although they have employed different techniques and tools, they all have mimicked the intelligent processes of living organisms, translating them into architecture rather than merely using them as inspiration for form and appearance (Agkathidis, 2016).

### 2.4.1 Biomimicry approach

Biomimicry is defined as an architectural style, mirrored in the entire form. (Jeronimidis and Gruber, 2012). As an architectural style, biomimicry is reminded as an abstract similarity of a natural form, not considering or generating the knowledge of its biological functions, and describes the whole of a building. This type of inspiration from nature in architecture is an old truth, but it is used mainly in movements such as Art Nouveau to the more current buildings. This method of form generation, giving only a decorative, stylistic of metaphorical impact, it is only a simple imitation of nature and can be identified as "biomorphic" architecture (Arslan, 2014).

The first emergence of the term "Biomimicry" in a particular literature was in 1962, and it began to spread particularly between scientists in the 1980s. Few of scientists of biology have written widely in biomimicry field such as Julian Vincent and Janine Benyus. Julian

Vincent, defines Biomimicry as *"the abstraction of good design from nature"* while Janine Benyus defines it as *"the conscious emulation of nature's genius."* (Nessim, 2016). The biomimetic method is depended on the idea of biomimetic architecture or generative, evolutionary architecture that utilizes biomimicry as taking stimulation from natural forms and procedures for problem-solving and to offer inventive solutions for future expansions in architecture.

There is a significant and obvious difference between bio-morphism and biomimicry at any level (Pawlyn, 2011). The Bio-morphism method is employing nature as a source for unusual forms and symbolic connection, and this was the standard method of modern architects. Biomorphic architecture has its origins in the works of the surrealists and Art Nouveau. A surrealist, Grefory Grigson, invented the term "bio-morphism" in 1936 ( Moore, 2014). Bio-morphism has created great architectural masterpieces such as the design of TWA Terminal by Eero Saarinen, which is based on the bio-morphism method inspired by the form of a bird (Nessim, 2016). So Biomimicry deals with the form and functional principles while bio-morphism deals only with symbolic principle, which is the form. To date, biomimicry has only been used in a restricted degree to building design, where some frequent instances like "termite mounds and spider webs" were the major source of inspiration. However, recently, biomimicry has extended rapidly and improved in other disciplines such as industrial design (Nessim, 2016).

In the field of architecture, many examples can be seen that are inspired by biomimicry. Forms like tree branches, flowers, network configurations, shells inspired the architectural design since ancient times. This imitation can be seen in two ways; the first one is to reproduce the form with the concern of form generation, which most of the time does not relate to a functional and an ecological approach. The second to transmit the procedure of appearance of a living creature like material, form, structure to design thinking, which is a diverse method, which offers to observe and understand the functionality and harmony within nature (Arslan, 2014).

The context of bio-inspired design and the progress of computing and its use has developed in architecture. After the appearance of this method that helps to make the association between biology, architecture and technology, biomimicry is described as an advanced useful approach and an innovative process of inspiration by nature for design.

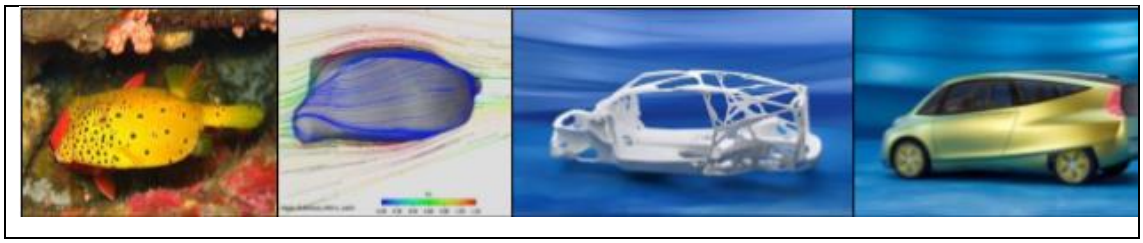
In architecture, the bio-inspiration is recognized as a better method for answering the stakes of the design of efficient forms and efficient structures (Raskin, 2017), also the materials made by nature (Benyus, 2011).

Biomimicry method as a procedure of design mainly consists of two approaches: the first approach is Design looking to biology (Top-Down approach)**,** which is the process of identifying the human requirements or designing issues and observing the ways other organisms solve. The second approach is called Biology influencing design (Bottom-Up approach, which is categorized as a specific principle, function or behaviour in an organism and transferring it into human designs (Zari, 2007).

**Design looking to biology**

In this method, the living world is observed by designers for solutions; it needs the designers to frame problems and biologists to then match it to organisms that have solved an analogous problem. Designers efficiently lead this procedure for recognizing primary parameters and goals for the design.  An instance of such way is DaimlerChrysler's sample Bionic Car (Figure 2.11). In an attempt to generate a big form, small wheelbase car, the car design was stimulated by the boxfish (ostracon Meleagris), an astonishingly aerodynamic fish. The car skeleton and structure are also biomimetic, designed by depending on a computer modelling technique based on the growth of trees in a way that reduces pressure attentions.

**Figure 2.11: Daimler Crysler bionic car inspired by the box fish and tree growth pattern**



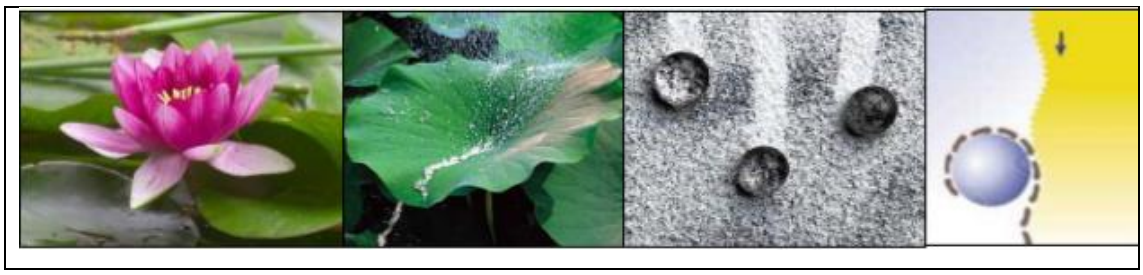
*Source* : (Zari, 2007)

The subsequent structure seems almost skeletal, as the material is specified only to the positions where it is most required (Vincent and Bogatyreva, 2006). The Bionic Car is more effective in terms of utilizing fuel due to the form, which is imitated by the boxfish that allows the form to be more aerodynamic. It is also more effective in the material because of its inspiration by the growth of the patterns of the tree to recognize the nominal quantity of material needed in creating the car structure (Zari, 2007).

**Biology influencing design**

This method relies on the preceding information of biological research and solutions, not to look for a solution in nature, then enforcing the design issue by the knowledge that previously exists. When the human design is affected by biological knowledge, the cooperative design procedure is firstly reliant on designer having information of related ecological or biological field rather than on defined problems of design. An instance is the lotus flower's scientific analysis appearing cleanly from swampy waters, that directed to a lot of design inventions, such as Sto's Lotus paint, which allows buildings to be self-cleaning (Figure 2.12).

**Figure 2.12: Lotus Inspired Lotusan Paint**



*Source*: (Zari, 2007)

Although humans as a species have been around for longer than the oldest living forest and are certainly an adaptable and learning species, resemblances amid design solutions of the human and strategies utilized by other creatures, have an unexpectedly small interfere considering their existence in the similar resources and context that are available (Vincent and Bogatyrev, 2006). One of the benefits of this way is that biology may impact humans in methods that might be outside a predetermined problem of design, causing in formerly unthought-of technologies or systems or even methods to solutions of design. The possible for correct moves in the method humans design and what is concentrated on as a solution to a problem, occurs with such a way to biomimetic design (Vincent, Bogatyrev, Pahl, and Bowyer, 2005). From a design perspective, the disadvantage with this method is that biological study needs to be conducted and then specified as related to the context of design. Therefore, biologists and ecologists must have the ability to identify the probable of their research in the formation of novel applications.

**Levels of biomimicry**

From the techniques and technologies of biomimetic, it is apparent and well known that there are three levels of mimicry that can be applied to problems of design: The organism level, behaviour level and ecosystem level. The organism level shows the imitating of a specific organism or the inspiration of a part from the entire organism. The behavior level is the imitation of the behaviour of which each creature behaves. The ecosystem level is the imitating of the complete ecosystem, it is thought to be the firmest level as it concentrates on a functionally substantial problem to imitate. There are five criteria throughout each level to select at which degree the imitation exists. The design is recorded as biomimicry in the method it resembles (form), what it is created of (material), how it

is built (construction), how it works (procedure) and what is its competence (function) (Zari, 2007).

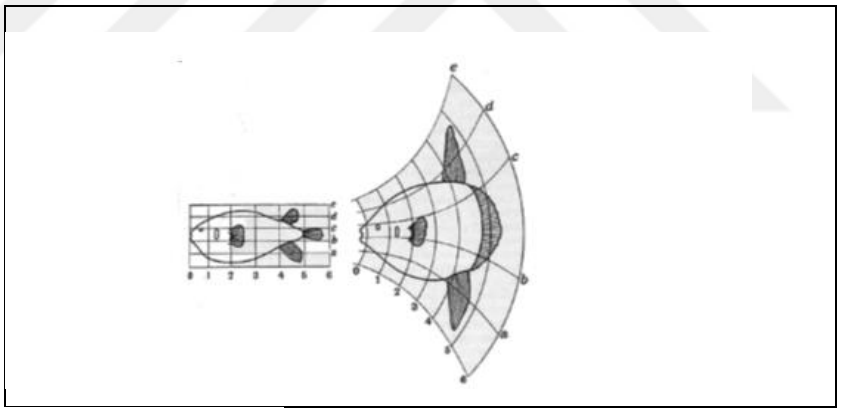
### 2.4.2 Morphogenesis in architectural design

Morphogenesis is a notion used in several fields such as urban studies, engineering, architecture and art. This diversity of practices shows abundant comprehension ranging from firmly formal to poetic. The field of biology is the original point morphogenesis were used. The form is the outcome of a morphological procedure,it can be defined through the values of the natural sciences. An investigation of the form expression certainly conducts to aesthetics. Because form and aesthetics are alternately reliant on. The expression of the form usefully is found in its structure, which is the rational arranging feature of the elements of any building; it can, then, be defined typologically (Stach, 2010). Typology makes probable the comparative inspection of the structure and its condition of equilibrium. The study of form in this sense makes a probable analysis of the form, the explanation of the fundamental associations between the physical forces and the form. Analysis of form is the foundation for the materialization of the structure in accordance with the stream of forces in the structural field. This commands to typical utilization of materials and as a consequence to a reduction of the outlay of materials.

The term morphogenesis in biology, is interested with the form of organs, tissues, and whole organisms also the locations of the different particular cell sorts and the essential question of how form and structure are generated in biology (Icmeli, 2014). Natural morphogenesis is a procedure of evolutionary improvement and growth that enables an organism to enhance its shape through the association of system-intrinsic capability and external forces of the environment (Hensel & Menges, 2008). This method gives the organism its characteristic shape and internal cellular structure. Through imitation, the mathematical representation of the interaction of real-world forms, these methods can be used for the benefit of architectural design. One of the original concepts on how mathematical and physical procedures and restrictions influence biological development emerges in the works of the Scottish zoologist D'arcy Wentworth Thompson. His works assume the existence of chemical signals and physio-chemical methods such as activation, deactivation and diffusion in organismic and cellular growth. D’arcy

Thompson in his famous essay "*On Growth and form"* declared that the development role is exaggerated, and the function of physical laws and mechanics as determining factors of the living organism's form and structure is minimized. He described the living nature's phenomenological phenomenon from a physical viewpoint and explained the form of any portion of matter, as due to the action of force (Stach, 2010). This view of phenomenology is shown in Thompson's classic fish transformation (Figure 2.13) in which he utilizes comparatively simple mathematical transformations to discover the level to which variances in the forms of connected animals could be described. He also made a comparison between the natural forms and their counterparts of manmade structure to include plants and skeleton (Steadman, 2008). He described how the skeleton of the vulture wing inspired architects to design the Warren bridge, and how the crane has been inspired by the femur bone to become one of the most important essays that stimulated architects (Steadman, 2008).

**Figure 2.13: D'Arcy Thompson classic fish transformation form through mathematical transformation**

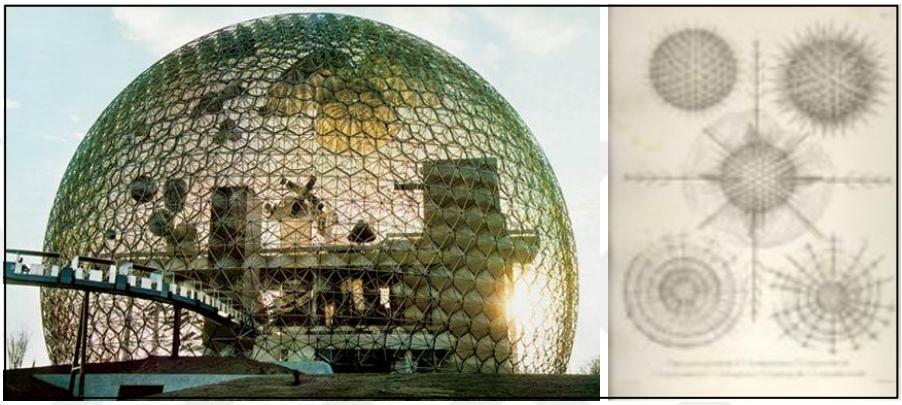


*Source*: (Stach, 2010)

In addition, structural morphology is identified as the study of the structure's shape and form and the connection between form, material, and forces, and is a significant area of research for structural design development (Motro, 2009). It also can be defined as "the study of shape regarding how forces transit inside the structural elements defining this shape" (Bagneris, 2009). Structural morphology can be onsidered as one of the architecture's most active areas of study, intends to bond the void between the architecture and civil engineering fields, it leads to a better understanding between the two fields. Structural morphology deals with the study of the association between the geometric form and structure and thus contains thoughts of a diversity of topics such as

structural behavior, structure shaping, the competence of structures, , structural topology, structures in nature, flexible structures, inventive structures and computational morphogenesis (Stach, 2010). It also works as a technique for generation and transformation of the form (Roudavski, 2009). Figure 2.14 compares the configuration of the structure of the natural organism with a manmade structure (Stach, 2010).

**Figure 2.14: The form of the geodesic dome designed by Buckminster Fuller inspired by the ridged radiolarian**



*Source*: (Stach, 2010)

The form of the geodesic dome designed by Buckminster Fuller and the ridged radiolarian shell assume a spherical form approached by a polyhedron with polyhedral and triangular faces. This configuration enables decreasing the quantity of material and its weight used for generating the structure. Both structures have no predominant bi-dimensional pressure-reluctant element and pressures are transmitting along the entire surface, in the instance of the radiolarian as a lattice shell mash and, in geodesic dome of Fuller, a plate shell mesh (Stach, 2010). By combining morphogenesis in both biology and architecture and comparing them; will help to comprehend similarities and variances of these fields. It indicates the possibility and advantages for the two research disciplines (Roudavski, 2009). So integrating morphology structural design, and materials in a combined design method will open up new views in designing complicated geometric forms.

## 2.5 COMPLEX FORM GENERATION APPROACHES

In reply to architecture's discovery digital-driven design process, several form generation processes are generally used in practice. These processes move away from conventional processes based on paper techniques to generate forms. It utilizes a form generation

technique depending on the physical modelling and the use of digital technology for generating new forms. So complex architectural forms can be defined as the forms that depend mostly on the computer based techniques and physical modeling due to the constraints that begin from the concept phase to the modelling and implementation phases such as the structure, specific materials fabrication, and implementation. These complex forms in this thesis include parametric forms, fluidity or pliant forms, topological forms, and algorithmic forms.

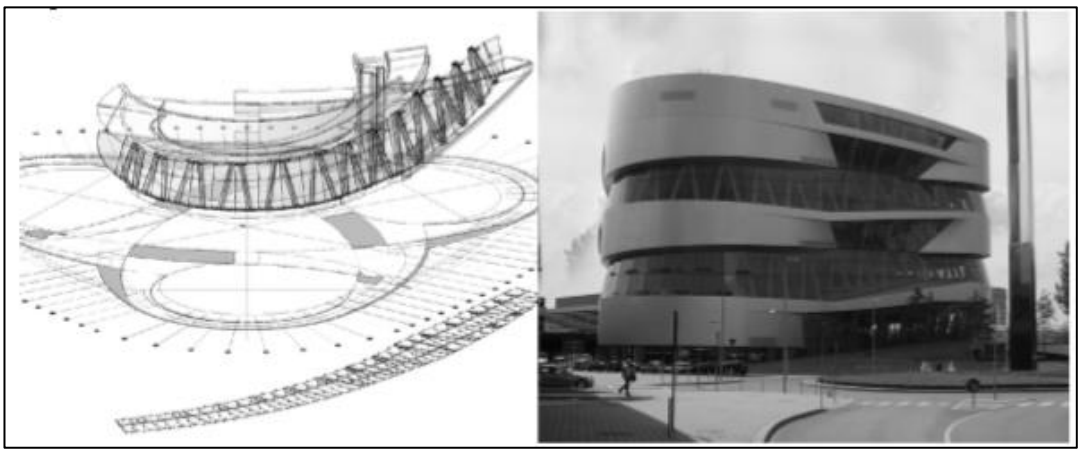
### 2.5.1 Parametric form generation

Parametric form generation is the field of studying algorithms that count geometry (Kelly 2013). Main obstacle interests the effort level essential to create the algorithms "the task is foremost; the tool needs only to be adequate to it" (Woodbury, 2010). The parametric method is based on parametric design features where the form in architecture is produced and characterized through mathematical parameters and equations. In parametric design, instead of the shape, the parameters of a precise design are proclaimed. By transfering various rates to the parameters, diverse forms or arrangements can be easily generated. Equations can be used to define the associations between objects, therefore declaring a connective geometry, the “constituent geometry that is mutually linked” (Burry, 2000). Consequently, the interconnection between objects can be started, and behavior of objects under transformations can be defined. The capability to determine, define and rearrange geometrical relations is of certain value (Kolarevic and Malkawi, 2005).

The parametric approach of recording geometry is described by a diverse association between the designer and the model if compared to the direct modelling, for example, manual manipulation of NURBS control points of the curve (Peschke, 2012). A parametric design does not include a depiction of a solid form, yet the description of spatial connections. The values of the legacy of precise geometric qualities by secondary structure elements, the way of distribution and approach of producing sequential levels of spatial associations. A pre-generated form may be changed by altering the value of specific parameters until it sees definite criteria, for instance, aesthetic or structural. The progress of tools for parametric modelling was highly inspired by intelligent geometry group founded in 2003 a nonprofit foundation which has set itself the goal of inventing an application for defining geometry and building into its internal logic and the tools for

optimization of the geometry (Peschke, 2012). Due to the smart activity of the geometry, generative components were improved and released an application (that runs on MicroStation) allowing the creation of sophisticated parametric models of geometry. An instance of the object where the parametric design approach was used to make the geometric elements of the entire structure, is the museum of Mercedes - Benz, designed by the UN Studio (Stuttgart 2005) (Figure 2.15). The concept of the project was based on the arrangement of three circles, tangents and intersections to be decreased progressively to the geometry required to generate the form. The description of the shape of each element of the building relies on the fundamental layout of the trefoil plane. All parts in this building are arranged and designed by the parametric model, that helped analysis of all substitute solutions that meet the given criteria. Parametric modelling is specifically beneficial for modelling the geometry of buildings with a complex form (Peschke, 2012).

**Figure 2.15:Mercedes-Benz Museum, Stuttgart**



*Source*: (Peschke, 2012)

Altering parametric values by the designer to find out various substitute solutions for a precise issue, the created model of the form will reply to changes by automatically updating itself without remodeling or deleting any elements (Marina and Stavric, 2011). "*Parametric modelling software is invaluable for both preliminary and developed design where there is a need for the definition, manipulation and visualization of complex geometry*" (Burry and Murray, 1997, p.1). Some of the most important benefits of modeling by parametric method are: adaptability; flexibility; alteration without the necessity to remodel or delete; less time consuming; providing solution spaces to be discovered; working with the historical based system where designers can return back at any steps; rapid in replying to alterations and updating of the entire model; Additionally, parametric modeling only allows differences, that allow the creation of connected forms within the identical type of forms; it does not allow geometrical and topological transformations to produce a countless number of solutions in design. It is also restricted in its elasticity to let the creation of advanced forms and curvilinear surfaces. The design progress method is suggested to predominate some of the restrictions of modeling by parametric method. Though, this method also has restraints, like limiting some sorts of transformations. Design methods must also be designed to offer solution to a particular issue, for instance, the producing columns of the Sagrada Familia, rod symmetry and twisted towers (Barrios, 2006). As Barrios states *"design can be described as a step by step process, where some things can occur over and over again. This can be interpreted as a procedural way of making the design"* (Barrios, 2005, p. 25). This proposes that the

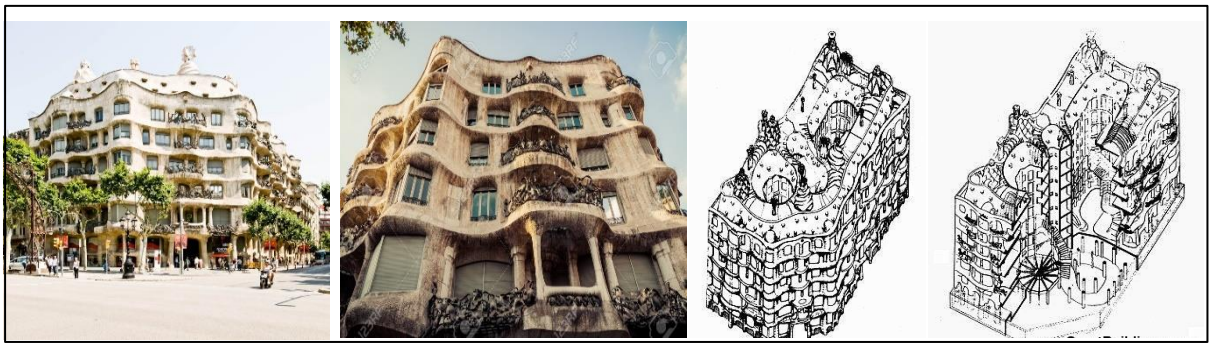
design approach is a step by step procedure to be pursued. It is also a type of generative system that the designers do not have complete control over the events. The method of design needs to be flexible to enable designers to begin from any stage and return to preceding stage when required. These problems make such methods less practical to more completely address the requirements of designers in the conceptual stage of the design.

Parametric design frequently requires a practical, algorithmic depiction of geometry. In algorithmic spectaculars, algorithmic examinations of "tectonic production" using mathematical software. Mathematical models and generative approaches had been created by Marcos Novak, which are controlled by many variables originally detached from all pragmatic interests. Each procedure or variable is a 'slot' into which an external impact can be mapped, either dynamically or statically. In his investigations, Novak was less interested with the manipulation of objects and more with the manipulation of relations, fields, higher dimensions, and finally the curvature of space itself. Finally, the parametric design does not necessarily generate only stable forms. One can invent a paramorph - an unsteady spatial and topological explanation of form with steady features (Kolarevic and Malkawi, 2005).

### 2.5.2 Fluidity or The Pliant Non-linear architecture

The pliant forms in their nature are based on flexible objects. As pliant forms are deformed and manipulated the elements that affix to their surfaces become combined within their interiors. Historically appeared in Baroque architecture in their concepts to go beyond the Cartesian grid and to further recognized principles of beauty and proportion. The biomorphic forms are attendant to Baroque organic design vocabularies of the early and mid-twentieth century nearly identical with the progress of Modernism. According to Kolarevic (2005), the early examples of fluidity forms can be found in Art Nouveau's biomorphic forms or more precisely in the winding curvilinear lines of Gaudi's Casa Mila (Figure 2.16).

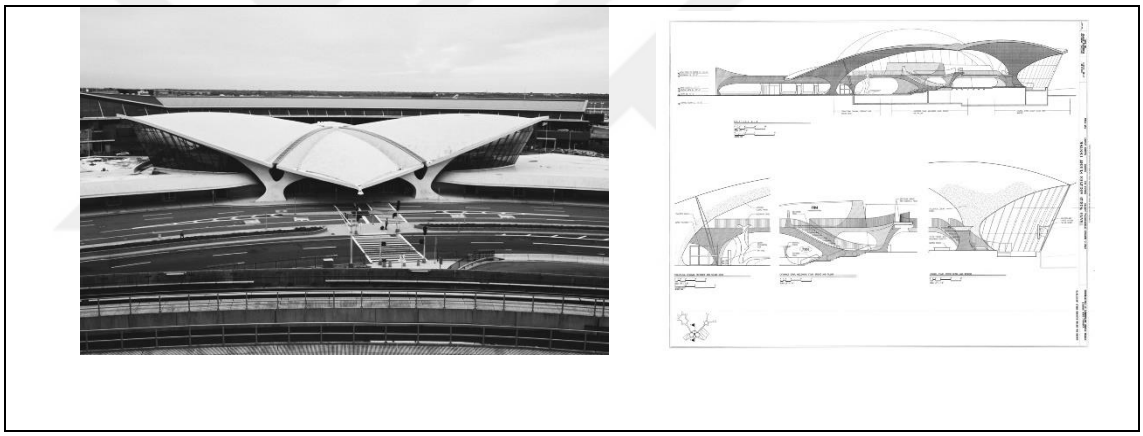
**Figure 2.16: Fluidity in Casa Mila designed by Antoni Gaudi**



*Source*: https://www.archdaily.com/367681/ad-classics-casa-mila-antoni-gaudi/5187c003b3fc4be35b0000ba-ad-classics-casa-mila-antoni-gaudi-image, [Accessed 17 July 2019].

Another example of highly sculptural buildings and significant instances from the early 1920s forwards is Eero Saarinen's TWA Terminal in New York (Figure 2.17).

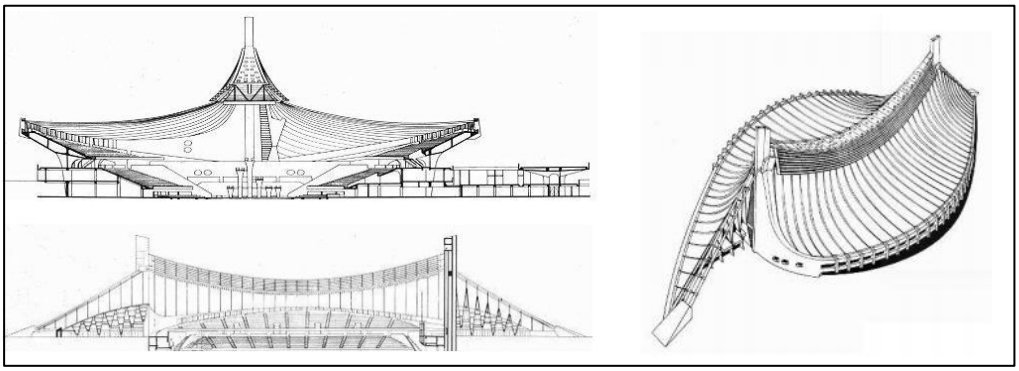
**Figure 2.17: Fluidity in TWA terminal**



*Source*: https://www.archdaily.com/788012/ad-classics-twa-flight-center-eero-saarinen/57414ce9e58ecee2f80001aa-ad-classics-twa-flight-center-eero-saarinen-image [Accssesed 18 July 2019

However, many other architects employed fluidity in their designs such as the Sydney Opera House designed by Utzon and Olympic Stadium by Kenzo Tange (Leach, 2007) (Figure 2.18).

**Figure 2.18: Olympic stadium by Kenzo Tange**



*Source*: (Hessmer, 2014)

It was only in the early of 80's when Reyner Banham's seminal book on Theory of Design in the First Machine Age that aroused a paradigm shift commanded to the appearance of super studio, archigrams, soft cities and robotic metaphors attached with Buckminster Fuller blobby shapes, and the use of formable material like steel, plastic and lesser concrete that stimulated architects to design curvilinear architecture forms once again. Due to the development that occurred in the digital technology of the 20$^{th}$ century, a new type of architecture has appeared and looks to be the mainstream of today's architectural progression. It is defined as irregular, non-standard, free random and dynamic. The fluid volumes are more associated with some shapes of digital tectonics, depending on the computer to create the design and to fabricate forms. In the past years, the exploration of architectural fluidity as a non-linear volumetric feature has increased and extended across the globe, and new developing technologies were presented in design procedures. It was immensely used to form diverse shapes and forms of buildings (Ramilo, 2007). Instances of these buildings can be seen in the works of Zaha Hadid (Figure 2.19), these designs are inventions of new methods to architectural design and digital architecture of topological non-Euclidean geometric space, kinetic and dynamic systems that are based on digitally-driven computational concepts.

**Figure 2.19:Fluidity in Zaha Hadid's projects**

*Source*: https://www.dezeen.com/2013/03/11/changsha-meixihu-international-culture-art-centre-by-zaha-hadid/,[Accssesed 10 July 2019].

Topology is the study of the features of geometric figures that, experiencing powerful alterations which cause them to lose all of their projective and metric features, but for instance it keeps the shape and size constant. Non-Uniform Rational B-Splines are mathematical models usually utilized in computer graphics for generating surfaces and curves. It provides precision and flexibility for managing both analytic (surfaces identified by mutual mathematical formulation) and modeled forms.

### 2.5.3 Topological Architecture

Topology is defined as the study of essential, specific forms that are not usually influenced by variations in shape or size, which continue stable through a constant transformation of elastic distortion, such as stretching or twisting. Greg Lynn's essay (1993) "In architecture curvilinearity" is one of the first instances of the new topological method to design that moves away from the leading deconstructivism logic of conflict and contradiction to evolve a more fluid logic of association and demonstrated by constant highly curvilinear surfaces (Kolarevic and Malkawi, 2005). The topological method is completely specified through its connection with all other parts within the system, depends on the identity and the location of each part or element. The formal order of elements is manifested by their locally determined common connection. The topological approach involves many potentials of created space that normally has curvilinear forms of differences. Modern, unexpected forms may appear, with casual distinctions, produced by the built topology of self-changing distortion.

**Non-Uniform Rational B-Splines (NURBS)**

Non-Uniform Rational B-Splines are mathematical models usually utilized in computer graphics for generating surfaces and curves. Non-Uniform Rational B-Splines are the curvilinear surfaces in digital architecture which are connected with topology that provides flexibility to the form formation after being distorted. So the crucial part of the topological architecture is its isolation from the Euclidean geometry of detached volumes performed in Cartesian space, and the inclusive use of topological "rubber-sheet" geometry of constant surfaces and curves, mathematically defined as NURBS - Non-Uniform Rational B-Spline curves and surfaces. Geometry in the topological space, is characterized not by implied equations, but by parametric functions, that define a domain of probability (Piegl and Tiller, 1997). Non-uniform rational B-splines (NURBS) have become an actual standard in commercial modeling systems due to their potential to embody the free-form shapes and some popular analytic shapes. NURBS offer an integrated mathematical formation for generating not only free-form curves and surfaces like B-splines, but also standard analytic shapes such as quadrics, conics, and surfaces of revolution, which NURBS can also represent exactly. Three-dimensional digital modelling software based on NURBS (Non-Uniform Rational B-Splines), have already been employed by aerospace, automotive and shipbuilding industries because of their complex forms along before it was utilized by architects. The use of digital modelling software in architectural design proved as design separated from Euclidean geometry. In digital architecture, Non-Uniform Rational B-Spline or NURB; is a very efficient tool for creating topology of curves and shapes. Its curvature can be controlled by manipulating the location of its control points, weights and knots to create diverse surfaces and curves (Piegl and Tiller, 1997). Its diverse shape is connected to both interactive manipulations and computational design. The request for the free forms in design increases when a curve is demonstrated by a series of measured data points. Various techniques and methods for the design and implementation of the curve are evolved recently. In CAD application, CAD modelling software is founded almost entirely on Bezier, B-spline and NURBS representation that provide simple mutual shape alteration and computationally effective examinations (Ball, Cripps, Lin, and Loftus, 2010). It can also be considered as one of the most common successful tools for curves modelling because of its smoothness features (Fung and Hung, 2013). Finally, B-spline curves have a great shape conserving

association to their control polygon by providing local control of the curve shape utilizing blending functions to offer local impact and also offer the capability of isolating the curve degree from the number of data points that define the curve (Hoofer, 2005).

**Non-Euclidean Architecture**

Non-Euclidean Geometry is mathematics' abstract part. It depends on the idea that two parallel lines never meet and displays how they can meet at a point. Within the domain of this geometry, if two equivalent lines are bowed about a sphere, the two lines meet at the top and bottom of the sphere. Non-Euclidean Geometry brought the innovation of two kinds of geometry, Spherical and Hyperbolic Geometry (Carter, 1996). Throughout the past centuries, architecture was based on Euclidean geometry. On Dan Pedoe's book Geometry and the Visual Arts, it was assumed that Gauss in 1830 gained the theorems and later found out the existence of non-Euclidean geometry. The works of Gauss illustrated that space is not only curve but also multi-dimensional spaces. One of the interesting theories is the notion of curvatures of space and the space of positive and negative curvature. As architectural ideas of space move from the three dimensions of the Cartesian space to the fourth-dimensional range of connections between time and space, other dimensions and other inception of space start to open new potentials for architectural thought.

Euclid's elements suggested five basic geometric postulates, of which all were thought self-evident excluding the fifth postulate of "parallelism" that emphasizes that two lines are equivalent, non-interconnecting, if there is a third line that interconnects both vertically (Kolarevic and Malkawi, 2005). Such a design is based on parameters and statistics and allows a spatial morphogenesis in a non-Euclidean environment. Through the use of calculus-depended tools, architectural design may become more abstract and less representational, at least in comparison to its conventional and standard types of predecessors (Lynn, 1999). There are two types of non Euclidian geometries that can be used for generating various forms, the elliptic geometry and hyperbolic geometry (Gawell, 2013). The elliptic geometry, also recognized as spherical geometry or surface which is a particular state of the Riemann geometry for a positive and constant curvature. Spherical geometry is a two-dimensional metric geometry in which, specified a point not located on a line, there is not even one disconnect line move through that point and the

aggregate of inner angles of any triangle is bigger than 180°. Furthermore, in elliptic geometry, all the straight lines are closed lines with a limited length and two diverse points may be associated by two segments. An instance of such a structural form design is the 30 St Mary Axe in London designed by Norman Foster. Hyperbolic geometry may be gained from the Euclidean geometry when the parallel line axiom is replaced by a hyperbolic assumption, according to which, given a line and a point which is not on the line, there are least two various lines moving through the point that have no common points with that line. In hyperbolic geometry, a plane is the surface of a saddle, geodesic lines are hyperboles and the sum of internal angles of any triangle is less than 180°. One of the hyperbolic geometry models is the inside of a circle. An stimulating instance of such structural form is the Cathedral of Saint Mary in San Francisco, California, designed by Pier Luigi Nervi in collaboration with Pietro Belluschi built in 1971 (Gawell, 2013).

### 2.5.4 Algorithmic Architecture (Scripting)

Scripts are characteristically mathematical solutions that are described by a series of principles and depend on parameters. It is a programming language that dominates a software application and frequently preserved as different from programs that perform separately from any other application. Scripting offers several features when used as a technique for generating forms in architectural design. It provides the power of recursion and permits executing repetitive functions in an effective and a faster way. Recursion offers speed for calculating a great number of operations or functions that are of the identical type. It allows automating repetition, to build complicated forms or approaches utilizing simpler and smaller functions, which are refined numerous times (Ramilo and Embi, 2013).

Algorithms are vastly employed in architecture throughout the history. Even before connecting the idea of algorithm with computer, there have been architectural rules and strategies that are the same algorithm (Golabchi, Garmarodi, and Bostani, 2011). The designer can specify data and input approach to the algorithm, and the method of procedure of algorithm and the consequence of this procedure seems as a form in cyberspace. In this method, relying on demands of design, one or hundreds of strains are designed and modified and emerged in virtual space. As a consequence, the designer in this procedure is not generating a default form but organizes a series of instructions and

arranges an algorithm that based on its procedure, the form of architecture is produced. Thus, the architectural form is not only the major problem, but the way of its generation is at the control of the architect who generates various choices by altering diverse parts of design in the algorithm so that at the end typical option is selected (Khabazi, 2012).

An algorithm is a clear series of orders that receives data as input, processes them and offers its answer in output. In algorithmic architecture, it is endeavored to create the parameters that affect the physical performance of the building (like materials and structure). In structural design, the origin of algorithmic architecture is the structure of plants and copying biological representatives which the functional and aesthetic features are higher than ordinary pattern. In recent years, the most popular use of computers in architectural design is an integration of original design and significant decision making by early conventional design approaches and then persisting to develop the concepts by computer software (Golabchi, 2011). Algorithmic design enables architects to discover complicated geometric space and designs to enhance solutions to complicated geometric and architectural space.

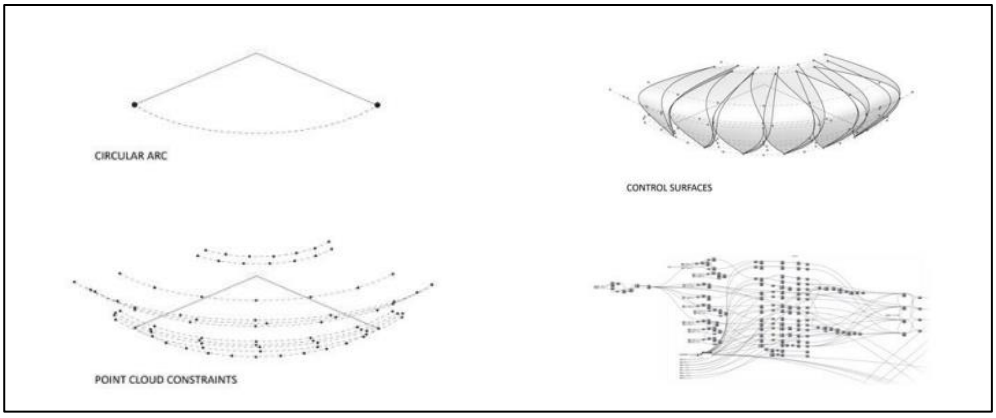
An example of Algorithmic is  Hangzhou sports park in Hangzhou sports park designed by NBBJ and CCDI, two symbolic structures are selected: the Olympic Stadium and the Tennis Center (Figure 2.20). Their forms are identified by recurrent sculptural trussed geometries, that comprise the exterior envelopes. The two designs are generated in Rhinoceros 3D, using Grasshopper, but the tennis center surpassed the major stadium in numerous competences. The algorithmic description employed for the Tennis Center was developed to comprise parametric geometry design, structural analysis, coordination in file exports. (Miller, 2011).

**Figure 2.20: The Olympic Stadium and the Tennis Center in Hangzhou**

*Source*: ( Miller, 2011)

The main model of the truss units was progressed in Grasshopper and this plug-in was, all through development of the project, contributory for both design and documentation procedures. Since several entities utilizing various software cooperated in the project design, file exports were essential along the way (Branco, 2017). The project's form experienced structural analysis method on the hands of CCDI structural engineering team. The team had to generate another alternative model. The analysis software needed a structural centerline model only, so the team prolonged the algorithm of the stadium to make the generation of a wireframe model of the structure automated. The surface was also examined so as to imagine and determine quantity areas of curvature in the geometry, for fabrication process each petal had to be divided into panels (Branco, 2017). Figure 2.21 shows modeling of the Tennis Center by algorithm for defining the geometry of external shell.

**Figure 2.21: The Modeling Of the Tennis Center By Algorithm for defining**




*Source*:(Miller, 2011)

Finally, another series of costume script had to be created to automate the process of exporting of the model to 3D DWGs that could be then exported to Autodesk's BIM tool, Revit which enabled the team to generate documentation sheets comprising orthographic drawings of the external shell. However, this interoperability was not as effective as the team anticipated, since the model experienced enormous alteration of data structure (e.g. from NURBS to precise meshes) and from a loss of parametric editing capability, when transmitted to the BIM software (Kensek and Noble, 2014).

## 2.6 FORM GENERATION BY ANALOGY

MCarrell (1977) defines analogy as "cognitive processes for describing the shared features between two objects". Analogy includes transferring of knowledge from one known field (source) to another field (target) (Blanchette and Dunbar, 2000). Moreover, analogical reasoning refers to a basic cognitive process that can support learning (Brown, 1989; Gentner, and Toupin, 1986), scientific discovery (Dunbar and Blanchette, 2002), and creativity (Ward, 1998). Analogical reasoning is considered as an efficient tool in problem-solving (Dunbar and Blachette, 2002).

Based on the above definitions, it can be stated that analogy is the process of transferring knowledge and comparing between two sources, where the first one which is the source is used as a reference to solve an issue in the second which is the target.

### 2.6.1 APPROACHES TO ANALOGY

The analogy is categorized into surface or visual analogy and structural analogy according to theoreticians like (Gentner, 1983; Rips, 1989; Smith 1990; Vosniadou, 1989). The biological analogy is categorized into four types, which are the organic analogy that deals with the visual appearance and the function of the organic forms. Anatomical analogy deals with the structural aspects and statics and the comparison between the structure of the building and the skeleton of humans and animals whereas the third type of biological analogy is labelled as an ecological analogy dealing with the function of the form and its relationship with the environment. The last type is the philosophical analogy which deals with the theories related to biology such as the Darwinian theory.

#### 2.6.1.1 Visual Analogy

Visual analogies refer to visual appearance and concepts of object assets. However, the visual analogy has always been considered as significant tool and utility in solving design problems (Goldschmidt, 1995). The visual analogy has a significant role in the design, studies have empirically shown that the employment of visual analogy leads to the improvement of the quality of design solutions (Verstijnen, Wagemans, Heylighen, and Neuckermans, 1999; Casakin and Goldschmidt 1999; 2000; and Casakin, 2002). Most of these studies have proved that using the analogy in designs can be considered as one of the strong factors of success. It is worth mentioning that the conceptualizing influence of visual analogy allows transferring the elements of the target into an entire coherent structure. (Goldschmidt and Smolkov, 2006) postulate that “When designers are exposed to visual stimuli, with or without guidance to make analogical use of these stimuli, they have good chances to enhance the quality of their design ideas and conceptual solutions”. On the other hand, Hannington ( 2003) believed that even though the idea of generation depends on the use of different kinds of inspiration sources, visual aids are strongly preferred as visual sources. Thus, the characteristics of the design activity are the repeated and rigorous use of visual stimuli, whether it is imagined or external. Images are frequently employed as problem-solving aids that include different sources such as industrialized objects, works of art, elements from nature and everyday life, as well as diagrams, basic shapes, architectural precedents, free-hand sketches, and technical drawings.

Consequently, the use of visual analogy is an important cognitive strategy with a particular contribution to design problem-solving. The creation of new structures of knowledge using visual analogy provides a suitable framework to support the development of basic skills, and for the generation of successful ideas.

#### 2.6.1.2 Structural analogy

Structural analogies demand an advanced system of associations that are based on deep characteristics of a usual condition. These kinds of analogies have significant effects on the quality of the solution (Casakin, 2004). The similarities drawn in this analogy are based on structure. Structural analogies tend to be more complex than a superficial analogy. Many structural analogies involve the mapping of causal structure and, as such, can be used to help explain behavior in poorly understood domains (Craig, 2001). Broadbent (1973) stated, "where powers of tension and compression in the human body are referred to ,they sometimes refer to it in terms of the depth of the analogy between the source and the target, or the nature of the similarities taken in the analogy process, how deep these similarities are in relation to the source and the target as well. It can be said that structural analogy is of a higher level, advanced instruction relations depend on deep features, which undoubtedly considering an issue more deeply leads always to better outcomes that is better solution amongst the target and source. structural analogy is the deepest principle in natural forms such as the balance and the movement and the skeleton of natural forms.

### 2.6.2 ANALOGY IN ARCHITECTURAL DESIGN CONCEPT

The main parts of a design activity during the conceptual design stage are the design methodology and practice. Because the generation of ideas at this early stage of the process will have a big effect on many subsequent design decisions. Also, any errors or failures made at this point will negatively affect the quality of the final design. So it is of great importance to help architects right from the first phases of the design process to deal with their design problems, and assist them in the generation of good ideas (Goldschmidt and Tatsa, 2005). In education, the analogy is determined as an imitation technique; both experts and novice designers employ design-by-analogy (Ball, Ormerod, and Morley, 2004). (Casakin and Goldschmidt, 1999) discovered that the use of analogy could help the students of architecture. The use of analogy plays a key role in generating new ideas

in design. In both education and design practice, the use of external sources can be useful to enrich the quality of design solutions (Goncalves, Cardoso, Schaub, 2014), enhance design knowledge and skills (Cai, Do, Zimring, 2010) and improve creativity (Casakin, 2012). Researchers have studied and found out how analogies mediate, facilitate, or improve design thinking. Moreover, Christensen and Shunn, 2007 have identified three specific roles of analogies that are related to architectural design thinking, which namely are clarifying, solving, and identifying a problem to others. Generation of ideas can be activated by various sorts of sources; however, in architectural design, there is a remarkable preference for the use of visual sources (Hannington, 2003). In this case selection of source is considered as an essential step in design-by-analogy, which affects the success of analogy (Casakin and Goldschmidt, 1999; Goldschmidt, 2001). In this aspect, the sources for generating forms include different sorts of drawings, objects, and sketches. Moreover, the main concern is how to direct the architects towards nature and how they can imitate the forms in nature by analogy, to handle with various design activities, and how this tool affects form generation especially in the conceptual stage of the design process.

It can be implied from the above statements that analogy in architecture is a process of transferring knowledge and principles from one object (source) that might be a form taken from nature or a sketch or a sculpture to be employed in creating a new form in architecture or solving a structural issue which is the (target) by applying features from the source to the target. Furthermore, for improving the design education the analogy can be taken as an alternative approach; it can be used at the first phase of the design process which involves the concept, form generation, and structural issues of design ideas made by the students of architecture regardless the source that might be either from the nature or any other source.

### 2.6.3 Biological Analogy In Architecture

Biology is defined as the study of living organisms from the microscopic view of a cell to the whole living planet including their form, structure, function, growth, origin, evolution, distribution and the interaction of the organism with one another and their environments (Rye, 2013). The analogy between architecture and nature can be classified into two categories, according to Mauro Coucerio. The first attempts to imitate biological

forms and the second to simulate biological procedures" (Coucerio, 2006). For designers, the first demand for biology is generally connected with the method living creatures combine form and function harmonically. The second demand for biology is associated with the simplicity of some geometric rules and methods that nature utilizes for generating an almost countless number of forms (Mezini and Eryildiz, 2011). Philip Steadman in his book "the evolution of design; biological analogy in architecture and applied arts" divided biological analogy into the following four types: organic analogy, anatomical analogy, ecological analogy, and Darwinian analogy. He also classified the organic analogy into visual analogy and functional analogy (Steadman, 2008).

#### 2.6.3.1 Organic analogy

In ancient Greece philosophers and Critics were looking to organic forms as a source of providing ideal models of that consistent proportion and balance between the elements of a design that is identical with the classical model of beauty. The assets of perfection, of wholeness, of unity in a structure such that all elements participate to the impact or intent of the entire, and no part may be detached without some destruction to the complete. These are essential ideas in the natural history and aesthetics of Aristotle and are features in the Aristotelian opinion both of living creatures and the greatest works of art. J. A. Stewart outlined Aristotle's perspective of the analogy in this way "*Living organisms and works of art are schemata, definite after their kinds, which Nature and Man respectively form by qualifying matter. The quantity of matter used in any case is determined by the form subserved; the size of a particular organ, or part, is determined by its form, which again is determined by the form (limiting the size) of the whole organism, or work. Thus, animals and plants grow to sizes determined by their particular structures, habitats, and conditions of life, and each separate organ observes the proportion of the whole to which it belongs. The painter or sculptor considers the symmetry of the whole composition in every detail of his work"* (Steadman, 2008).

An analogy can be interpreted in two different interrelated perspectives; the first perspective is the one that deals with visual aspect or composition whereas the second one is functional aesthetics which two types are interrelated (Steadman, 2008). The first perspective takes the 'organic' integrity of the artwork into consideration in a way it makes a balance between the proportional connection of the elements to the entire form

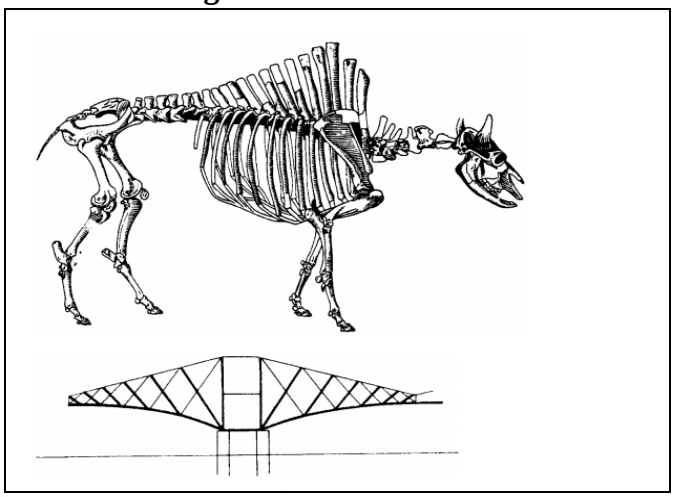
and of the entire form to its parts, which in turn is found to be the origin of beauty in that work. This quality of wholeness or consistency offers the foundation for the similar types of content as is originated from the meditation of the prettiness of nature, where the two sources of aesthetic satisfaction are one. The second understanding of the organic analogy is functional, which is a progress from and more explanation of the first interpretation. In this type, the analogy shapes one part of the more general aesthetics of functionalism, the equivalence of the beauty with the expression of usefulness. The idea of the well-designed object and adjusted for its intention will be seen to be beautiful through understanding of this fitness for usage (Steadman, 2008). It is worth mentioning that this idea is not new but very ancient one, and it goes back to Aristotle, who found out that the awareness of the beauty of animals lies in rational gratefulness of the structure of their elements and their organs functions. In the natural history of Aristotle not only is every member or isolate structure found as helping some specific aim, some precise function; yet each of these functions of the elements is submissive and contributes to, the bigger objective of the entire body. The part only has a functional meaning in connection to the entire: the legs provide support and movement for the body, and without the existence of the body they are useless. The heart has 'sinews' which prevalence through the body and transfer motion to its parts. The entire body counts for its constant functioning and presence on each and all of the different organs working together. For functionalist aesthetics, then, it is this essential functional role of each member and organ in the working of the complete body which is the reason for deriving aesthetic desire from the forms of plants and creatures (Steadman, 2008).

It can be argued that the organic analogy in architecture can be interpreted in two methods which are interrelated  the first one that deals with the visual principles of the inspired source that might be an element of the human or animal body such as an eye, hand, head, finger without taking its function only the appearance can be taken. On the other hand, the functional analogy depends on the function of this organ. So the first one can be employed in architecture and can be seen in many projects that have been inspired by nature specifically the parts of the human and animal body.

#### 2.6.3.2 Anatomical analogy

Anatomy is a description of the 'structure of organic bodies' or parts. Accordingly, the anatomical analogy as employed to a building takes the form of an analogical comparison of the skeleton of animals with the supported structural framework of piers and vaults or columns and beams. It is prudent that both architects and civil engineers use the anatomical analogy in their works, which deals with statically issues and the allocation of weight and strength (Steadman, 2008). Furthermore, Georges Cuvier believed, in the 'stable functional integrity' of the organism, which means that all the organs and parts have vital and corresponding function in propping the actions of animals and way of life. Horatio Greenough in the 1850s acknowledged that "*the principles of construction can be learned from the study of the skeletons and skins of animals and insects*" (Steadman, 2008). Moreover, the analogy is also used poetically taking into consideration that both in art and nature the organism is an accumulation of mutually dependent parts where the structure is defined by the function and the form is the expression of the structure (Steadman,2008). The Forth Bridge is one of the famous designs of Victorian architecture to which architects consider as representing the anatomical analogy that derives from applying the rational, and mechanical design features. The tubes that have been used for building the bridge match in detail the structure of cylindrical plant stalks. Their reinforcement rings correspond to the joints in the bamboo stem, one of the most powerful vegetable structures. Additionally, the skeleton of the quadruped, like that of the ox or horse, could be considered for the mechanical analysis aim as a sort of double cantilever structure, comparatively similar to the Forth Bridge where the legs match the bridge's piers, and the backbone, neck and tail are cantilevered out from these supports (Figure 2.22).

**Figure 2.22: Skeleton of fossil bison is compared to the Forth bridge cantilever structure**



*Source*: (Steadman, 2008)

It can be argued that the anatomical analogy is the concept of describing the internal part of the organic form which is the structure or the skeleton of the organic form. Moreover, architecture depends on the equilibrium configuration of the body which is the deepest principle in the natural creatures that can be employed in architecture. This type depends on the process of how the human and animal body stands up and how they can keep their bodies in a balanced configuration even in motion that relies on the skeleton of the organ.

### 2.6.3.3 Ecological analogy

It is functionally based on the assumption that form is referred to function, and function is referred to the environment in both animals and objects (Steadman, 2008). Therefore, the ecological analogy has been very much in use in the functional writings of the 19$^{th}$ century and the modern movement. Leopold Eidlitz asserts how "*in nature forms are the outcome of the environment. Environment determines function, and forms are the result of the function*" (Steadman, 2008). Huxley (1858) also maintained that the form of the building must be adjusted in an equal way to the environment in which they are placed, through the architect's skills "*until the functions resulting from this environment are fully expressed in the architectural organism*" (Steadman, 2008).

### 2.6.3.4 Darwinian analogy

This type of analogy had been introduced by Charles Darwin. He compared nature with plant and animals propagation. Darwin's theory of organic evolution is very much related

to the analogy of artificial and natural selection, which is one of the matters that gave his ideas permanent popularity. In 1859 In his book ‘On the Origin of Species by Means of Natural Selection’, Darwin wrote down his accounts based on general consideration from a huge number of zoological and botanical data that he had gathered. One of his first observations is that most living beings give births to many more offsprings than is actually needed in order to substitute their number. A population tends to increase in geometric ratio if only the number of births is counted (Steadman, 2008). The second is the fluctuations do happen in the population of plant and animal; generally, the number of any one species remains almost the same from a generation to the other. The third examination that Darwin made from his researches on nature is the idea of distinction. Within any one species, all entities are not precisely similar; they differ in all kinds of methods, some of which may give a benefit in the contest for survival, others a disadvantage (Steadman, 2008). Table 2.1 shows the types of biological analogy and their description briefly.

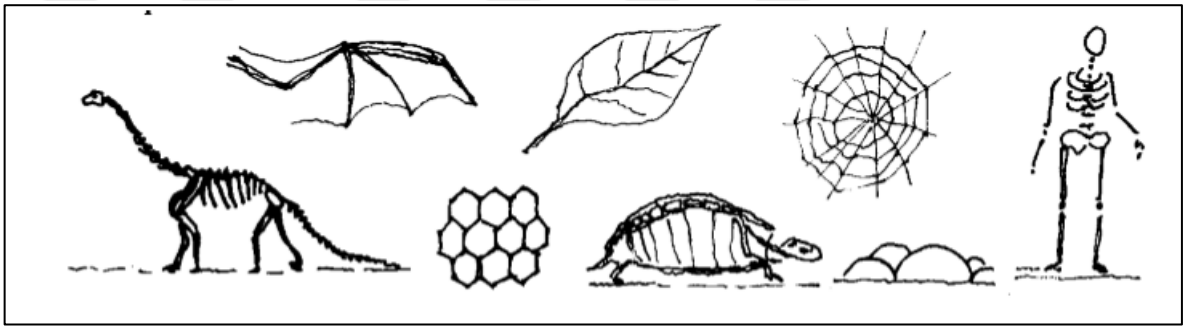
**Table 2.1: Types of biological analogy and their description**

| Biological analogy | Description | Types of analogy |
|---|---|---|
| Organic analogy | Discusses two types of the analogy of organic forms, which are interrelated. The first one deals with the visual appearance or composition of the form | Visual |
| | The beauty of form lies in rational gratefulness of the structure of their parts and the functions of their organs. | Functional |
| Anatomical analogy | It deals with the structure and equilibrium configuration of the human body | Structural |
| Ecological analogy | The form is referred to function, and function is referred to the environment in both animals and objects | Environmental |
| Darwinian analogy | Deals with fluctuation that occurs in plant and animal population and the variation of the species | Philosophy |

## 2.7 STRUCTURES IN NATURE AND ARCHITECTURE

The relationship between human and nature is as old as the creation. Humankind, since then, has always been inquisitive to discover his environment. He started observing and imitating what nature has offered him and what has been going around his environment. Thus, he was able to learn and develop skills that helped him get examples from nature, which was the only source of living available at his hands. Although the bond between nature and mankind is as old as the history of mankind nature was the only source available for him, but the level of inspiration in architecture was limited due to the lack of sophisticated materials, technology for analyzing the features of the natural structure. Figure 2.23 shows different kinds of structure in nature.

**Figure 2.23: Different structures in nature**



*Source:* (Mosseri, 2004)

The industrial revolution changed Man's perspective on nature because the industrial revolution introduces new technological tools and means to deal with life. By the use of available technology, it became possible to observe and generate forms from nature. Also, the human began to inspire new ideas taken from manipulated examples taken from nature (Portoghesi, 2000). Architecture, as a science, began to be influenced by natural structures and make use of those structures in different ways. Thus it began to take ideas and knowledge from biology and transfer them to architecture and engineering disciplines. Figure 2.26 illustrates structure in nature employed in architecture. In the same way, architects at this stage referred, whether directly or indirectly, to nature as an analogy in order to inspire ideas from it to solve designs problems. Gruber 2011 maintained that abstraction should be used to transform ideas from one discipline to another; consequently, the forms and models are an abstraction from nature. In terms of structure, both nature's form and structure have always been sources of inspiration and motivation

to architects and offered them horizons for innovation in different ways whether they were aesthetics, functional or structural. In this regard, Garcia and Gomez (2009) claimed that the integration of structure's knowledge in nature and the potential of creating new prototypes of structure encouraged architects and engineers to turn their eyes back to nature to study about ideal morphology, lightning, functional combination, and efficiency.

To sum up, the above ideas can be implied that any structure or form in nature with its aesthetic, functional, and structural concepts can be used as a model for architectural innovations by transferring concepts from the discipline of nature to the architectural discipline by abstracting the forms.

Moreover, nature has a variety of structures which makes their classification diverse, taking into consideration that forms and their visual features have developed due to the fact that environmental forces affect both animate an inanimate forms. According to Wolfgang von Goethe, " the emergence and the constant formulation and transformation of the form in nature is the result of environmental forces ". He also believed that "the organic and inorganic forms in nature are affected by the process of a generation with the help of natural forces" (Menges and Ahlquist, 2011). Philip Ball (1999) believed that "patterns and forms in nature are not only generated through biological coding but also there are simple physical laws behind them". Finings ( 1956 ) in his book "The Anatomy of Nature" also maintains that assessing the structure of the form is a wise reaction for a living. In fact, a compromise with the environmental powers leads to form and structure. Typically, all-natural structures consist of textural layers, which are the reasons of form changes because of pressures that make them elastic or cause pressure reactions in them (French, 1994).

It can be argued that the form in nature whether organic or inorganic, animate or inanimate is a result of the external forces; these forces and physical laws affect the generative process of every form in nature. They also affect the efficiency of the form in terms of their use of materials, lightness, rigidity, and stability.

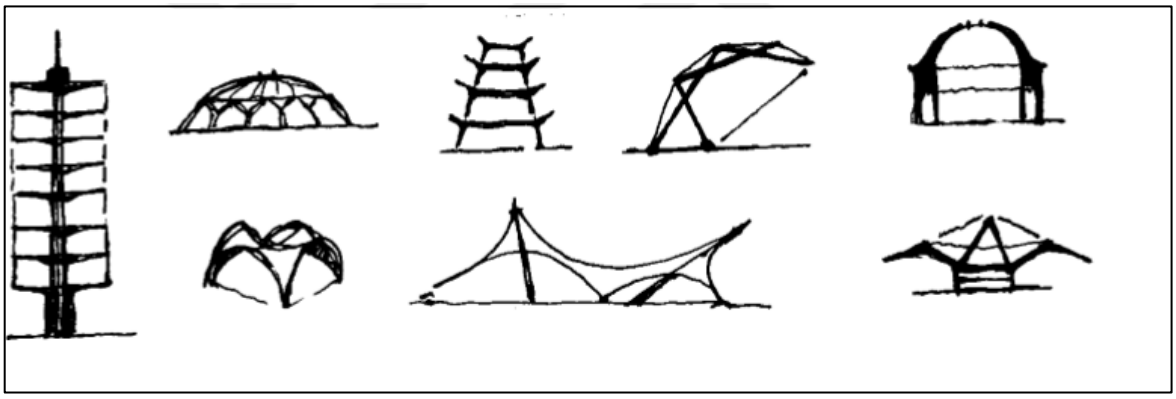
Architects, authors, and researchers have classified structures in nature in different ways by depending on different criteria. Arslan and Sorguc (2004) and Garcia and Gomez

(2009) classified structure into five main types derived from natural models according to their capacity of load-bearing as follows: tree-like structure, shell-like structure, pneumatic structure, web like structure, finally skeleton-like structure.

Senosian (2003) believed that structures in nature come under four 'lightweight' structures, which are: cable structure inspired by a spider web, pneumatic inspired by bubbles, vaults inspired by shells as well as eggs, and geodesics, which are inspired by radiolarians. Furthermore, Senosian 2003, in his book "Bio-architecture", classified Cactus, trees, animal legs, the skeleton of four-footed animals, the human body, bones, mollusk shells and insect, radiolarians eggs, and spider webs as natural structures.

In a similar way,Silver, Mclean and Evans (2013) gave the following classification to the structure in nature according to their resistance to the load and forces: tree structure, spider web, eggshell, soap bubbles, and the human body (Figure 2.24).

**Figure 2.24: Different structures in architecture**



*Source:* (Mosseri, 2004)

Yeller 2015 classified structure according to their lightweight as follows: Tree-like branching structure, Surface structure, pneumatic structure, suspension tension web structure, vertebrate skeletal structure and finally cellular structure.

Furthermore, Mosseri (2004) made a distinction among structures in nature he classified them as structural systems in living creatures, which include animals and human beings, on the one hand, and botanic entities, and, structural systems in inanimate entities, on the other hand. Moreover, the design process of the structural system design of a living system is a living design process of development and growth. The structural system in plants and animated entities can be a hydroskeleton fluid, gas or other material under pressure covered with an envelope cell, bladder, lung, heart, fruit or a rigid skeleton which

is built from many hydro skeletons because the cell itself is a hydroskeleton (Mosseri, 2004). Table 2.2 shows different ideas about the classification of structure in nature and architecture.

**Table 2.2: Classification of structure in nature and architecture by authors**

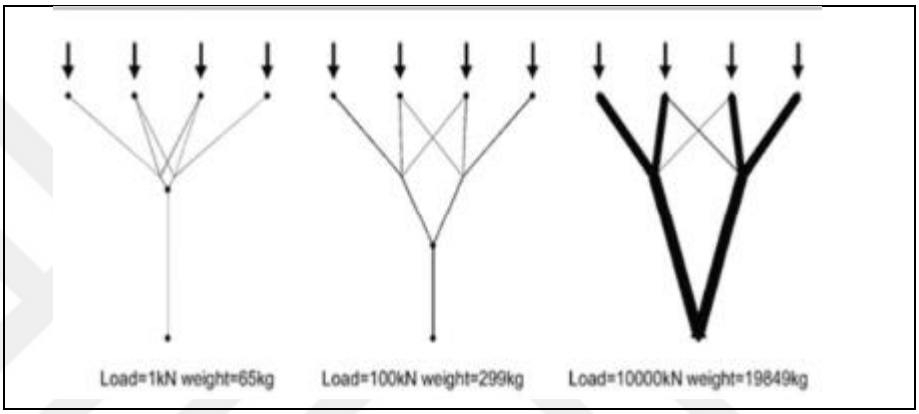
| Author | Criteria | Classification of structure in nature and architecture | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Arslan and Sorguc, 2004 Garcia and Gomez, 2009 | Load bearing capacity | Tree-like structure | Shell-like structure | Pneumatic like structure | Cable like structure | Skeleton-like structure | | |
| Senosian 2003 | Lightweight | | Vaults inspired by shells as well as eggs | Pneumatic inspired by bubbles | Cable structure inspired by a spider web | | Geodesics, inspired by Radiolarians | |
| Mclean And Evans 2013 | Strength, resistance, tensegrity | Tree structure | Eggshell | Soap bubbles | Spider web | Human body | | |
| Yeler,2015 | Light weight | Tree like branching structure | Surface structure | Pneumatic structure | Suspension tension web | Vertebrate skeletal structure | | Cellular structure |

The structure can be classified into five types, which are: Tree-like branching structure, shell-like structure, web-like structure, pneumatic structure and human and animal skeleton-like structure (Arslan and.Sorguc, 2004) . Due to the relationship of these structures with the form generation approaches in architecture and the employment of these structures by some of the architects as a form generation approach such as Antoni Gaudi, Heinz Isler, Frei Otto, Buckminster Fuller and Santiago Calatrava it is important to have a general idea about each one of these structures. This five types of structures have been used mostly in architecture and have been mentioned more in sources. This types of structures will be discussed briefly according to their form, stability efficiency, and lightweight.

### 2.7.1 Tree-like branching structure

The tree structure is the first structure that has inspired architects depending on the form, weight, and efficiency in nature, which makes it a well-known classifying criterion of analogy. Referring to nature, one can see that a tree is systematically made up of structured parts, including a trunk, branches, and twigs. All these parts are connected with each other, and they are all cantilever, elastic and flexible (Silver, Mclean and Evans, 2013). Figure 2.25 shows the load path in tree branching structure.

**Figure 2.25: Load path in tree-like branching structure**




*Source:* (Rian, Md, L and sassone, M, 2014)

History shows that humankind first used the tree as a materials for building houses. The tree was also the first choice for the man, he learned that the tree has several properties which can be useful for understanding life around him. The structure of tree branches shows specifically a close connection between the course of the forces and their shape, both in their appearance and in the quality and performance of the structure itself (Nerdinger, 2005). This relationship is functional in the sense that there is an integration between the construction of the roof and supporting structures. In architecture, the tree-like branching structure has an advantage as it has short distances from the loading points to the supports (Nerdinger, 2005). Figure 2.26 shows examples in architecture inspired by tree-like branching structure.

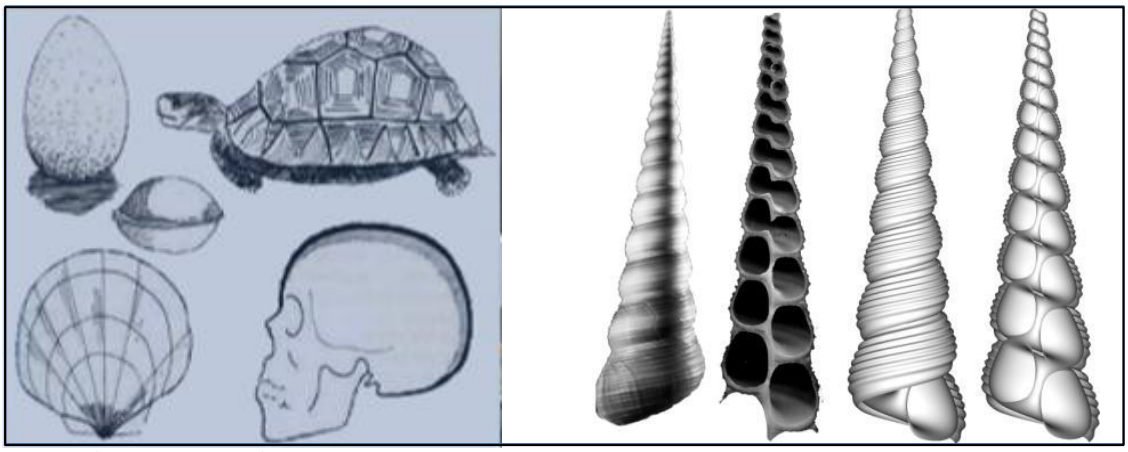
**Figure 2.26: Tree-like branching structure in architecture**

*Source:* (Arslan and sorguc, 2004)

### 2.7.2 Shell-like structure

Shells are considered as one of the most important structures found in nature due to their characteristics, which include their high resistance to loads, minimum material, large spanning capacities and sheltering characteristics (Figure 2.27). (Yeler, 2015) defined Shell structures "*as the systems which do not exceed the specific cross-sectional thickness, consisting elements that resist to the pressure and pulling and in which carrier and transporter elements considered as a whole, thus, the form itself creates the structure* "(Yeler, 2105, p.15).Figure 2.27 shows shell structure in nature.

**Figure 2.27: Shell structure in nature**



*Source:* (Senosian, 2003)

shell structures as " the building elements which can cover the place with their mostly curved surfaces and very light thin structures, they constitute volume, they do not need extra carrier except for support points and with those features, they can cross large

openings" (Yeler, 2015). Figure 2.28 shows Sydney opera house inspired by shell structure.

In this regard, Senosiain (2003) maintained that that shell structures are efficient, useful and beneficial structures to be used in architecture because they are rigid with least thickness, and three-dimensional curvature with least materials.

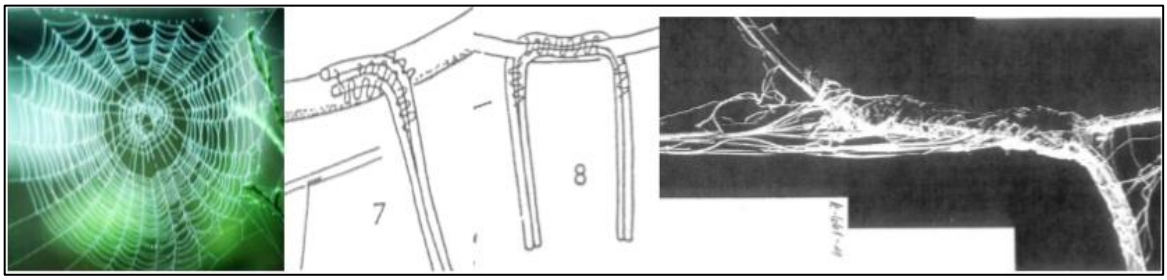
**Figure 2.28: Shell structure in architecture**

*Source:* (Kim and Park, 2018)

### 2.7.3 Web-like structure

These structures belong to the tensioned active-form structures, like tents. They are made with materials which only work in tension configuration as it is shown in (Figure 2.29) so the shape is determined by the supports and loads (Garcia and Gomez, 2009). But the main difference between webs and tent structures is that webs can easily adapt their shape when those conditions changes, while tents would "wrinkle". This ability to adapt by deforming is highly linked with the geometrical pattern. By studying spider webs, it can be found that the most common pattern is the radial tetravalent plane net, which is just stable (Wester, 1993).

**Figure 2.29: Web-like structure in nature**




*Source:* (Garcia and Gomez, 2009)

However, as these webs are pre-stressed to reach a plane configuration, when they are over-loaded they lose the pre-stressed and adopt the corresponding funicular shape. Spider webs have higher efficiency (span/weight) than man-made nets, due to the quality of the material but also because of the design of the nodes: spiders just join the threads and wrap together with a softer one, while nets are joined by metal brackets (Garcia and Gomez, 2009). Figure 2.30 shows Munich Olympic stadium designed by Frei Otto inspired by web structure.

**Figure 2.30: The Olympic stadium of Munich inspired by web structure**

*Source:* (Wouters and Heide, 2014)

### 2.7.4 Pneumatic structures

Pneumatic structures are based on load bearing capacity of air and ideas derived from nature. This type of structure has the following characteristics: it is made up of small amounts of materials, its weight is light, it is very flexible, it is durable and finally it has surface tension (Senosiain, 2003). So it is one of the most efficient structures in terms of span and weight. A pneu which "comprises an elastic tensed envelope, is internally pressurized by a fluid and surrounded by a medium" (Otto, 1979). So they are self-stabilized structures, and because of this dependency of the internal pressure made by a fluid, the result is a very adaptable structure which can easily change its form to accommodate to the surrounding geometry.

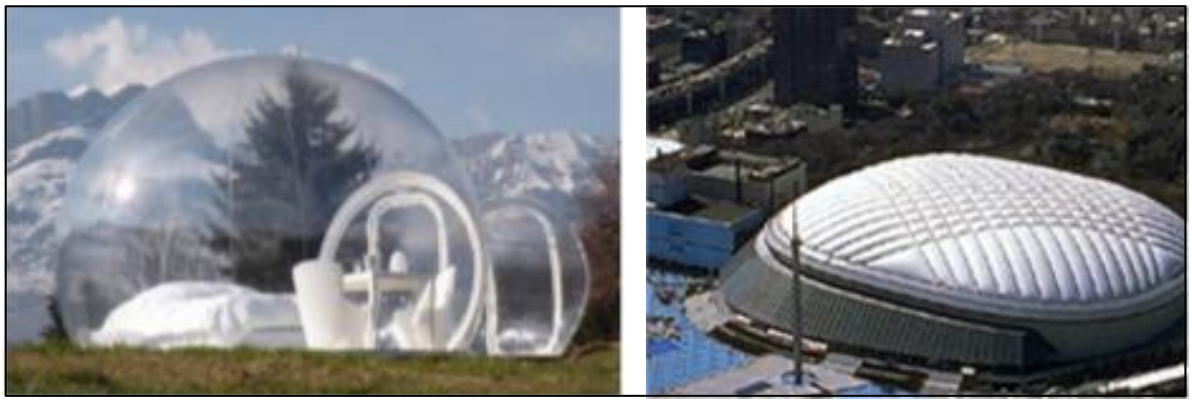
In Nature, as it is shown in (Figure 2.31) they can clearly be seen in soap bubbles, worms, jellyfish, bacteria, cell (Garcia and Gomez, 2009). The key of the issue is that the cell itself is a pneu: a flexible stressed envelope (membrane) enveloping a filling. The growth is produced by cell divisions which re-locate themselves strategically, so it can be assured that growth is the result of a pneumatic behavior. And in most cases, final structures are only the solidification of pneus: eggs, bones, skeletons, shells, also webs (Garcia and Gomez, 2009). Thus, it can be assured that pneus and tensegrity travel across the scales in Nature.

**Figure 2.31: Pneumatic structures in nature**

*Source:* (Garcia and Gomez, 2009)

Moreover, architecturally this structure is resistant to tension and it has a flexible envelope that surrounds a filling; the envelope and the filling together form a load-bearing structure (Arslan and Sorguc, 2004) (Figure 2.32). Air halls are support systems that have a membrane that is supported by air pressure. Thus these structural systems are described as pre-stressed structural systems (Dent, 1972). This system was first used by Montgolfier Brothers in 1783 who found that the air halls were very light because the air is a supporting element. Dent (1972) stated that an “air hole can be seen as a balloon under weak air pressure that is fixed to the ground”. However, they can be made in big sizes which allows them to afford the “multifunctional spaces, that they are soft, round, light, and easily transported, repaired and reinstalled ; they have the highest energy conservation, and that they have a highly aesthetic appearance are the positive aspects of these kinds of structures” (Ludwig, 1972).

**Figure 2.32: Pneumatic structures in architecture**

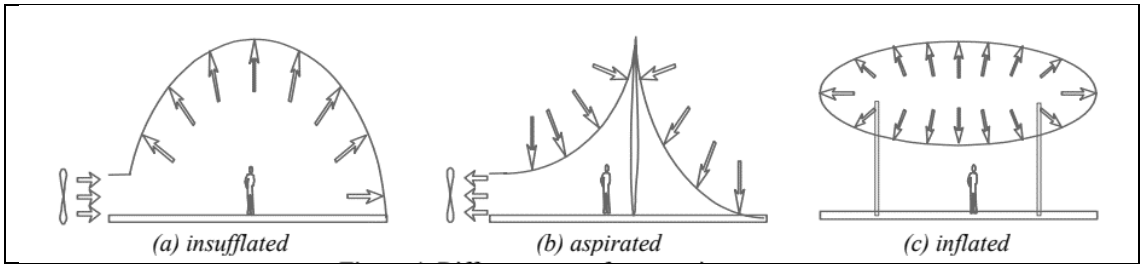


*Source:* (Yeler, 2015)

Pneumatics are taut structures par excellence, since only with them it is possible to have all structural elements working exclusively in tension. As what usually occurs with tensile structures, in a pneumatic structure, shape cannot be imposed, since membranes do not withstand bending, and thus geometry and loads have to interact until an equilibrium configuration is reached (Chi and Pauletti, 2018)

The pneumatic structures consist of three types: structure that is an insufflated which comprises of a membrane enclosing a space beneath an internal compression somewhat greater than the atmospheric compression; in an aspirated structure, internal sub-compression is used; an inflated structure utilizes pressurized balloons, working as columns, beams, and arches as weight-conveying elements ( Pauletti, 2010). Figure 2.33 shows the three types of pneumatic structures in architecture.

**Figure 2.33: Types of pneumatic structures in architecture**




*Source:* (Chi and Pauletti, 2018)

Form and pressure allocation are powerfully attached in tense structures. It is hard to identify their form a priori, since they have no difficulty to bending –thus neither to compression– it originates that form, internal stress level and external loads, entirely in tension, have to cooperate in order to fulfill equations of equilibrium. The preliminary

design of taut structures therefore includes the determination of an initial formation, in which both the pressure state and the geometry create a single equilibrium, functional configuration. Also, the feasible form has to provide needs, both architectural (form and use) and structural (stability and strength). Due to the connection between form and pressures, it is usual to choose a compromise solution, between the desired form and what is probable structurally. (Chi and Pauletti, 2018)

Before the extensive usage of computer techniques, the design of pneumatic structures was carried out analytically or by physical models. Analytical approaches are accurate, but it needs be applied only to regular forms. Physical modeling is a multipurpose technique, it has the ability to cooperate with all forms of functional concern but precision is absent. In specific, form generation method of pneumatic structures by physical models provides the need of resistant films or fabrics, capable to endure the stress tendency that remains a model in its inflated configuration. In addition, it is fundamentally an experimental and inaccuracy method, in which the forms of the unstressed patterns, from which the model is made, are settled according to the experience of the designer (Pauletti, 2010).

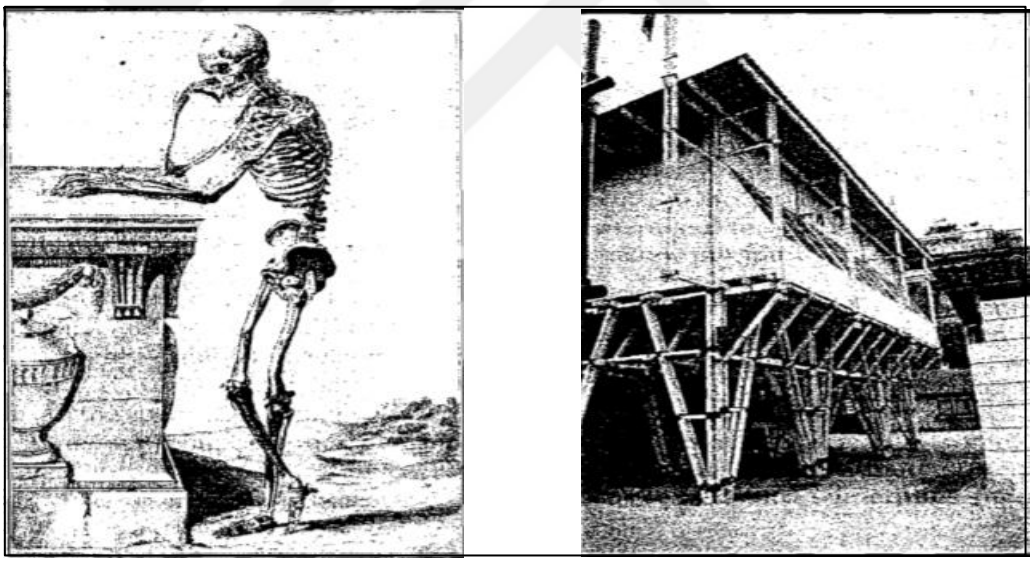
### 2.7.5 Vertebrate skeleton

Vertebrate skeletal structure is derived from nature used in architecture because it is rigid and light. Le Ricolais stated that *"It was a great mistake to say that the art of building is to build with match sticks, that if you want to build light structures, you must use light members because a group of light members will be light. It took me quite a long time to see that it was just the opposite; it's the art of making a light structure with big, heavy members. A paradox"*(Mcleary, 1996,p.22). In architecture, the skeleton offers building construction flexibility and firmness (Figure 2.34). On the other hand, the skeleton offers the man a balance against gravity and hold up the body tight. Human's and animal's skeletons are considered one of the greatest inventions that nature offered. Baldridge. (2003) thinks that as well as the rigidity of skeletons, they can fly, manoeuvre underwater and support big body weights against gravity and act as shields against outside body effects.

Furthermore, the human body is considered as a significant example of the design in dynamic balance (Senosian, 2003). The human body consists of bones which are

connected by ligaments and muscles which are associated to the bones by tendons (Silver and Mclean and Evans, 2013). The skeleton is the internal structure of the body; the human skeleton is made of two parts. The pivotal skeleton comprises of bones that structure the hub of the body neck and spine vertebral section and support and secure the organs of the head skull and trunk sternum and rib confine (Silver, Mclean and Evans, 2013). Arslan (2004) also biologically maintains that the structure of the skeleton based on the spine, which is supported by the pelvis, the ribs works as a less dominated structure to support the spine. The spine works in conjunction with ribs; they provide support and protection. The entire structure is held and moved simultaneously with muscle frameworks. The system in this strain (muscular system) and the resistance of the structure of the human body can be clarified by the connection of delicate and firm, adaptable and unbending systems that resists weight (Senosian, 2003).

**Figure 2.34: The skeleton is used as inspiration for a building**



*Source:* ( Mcleary, 1996)

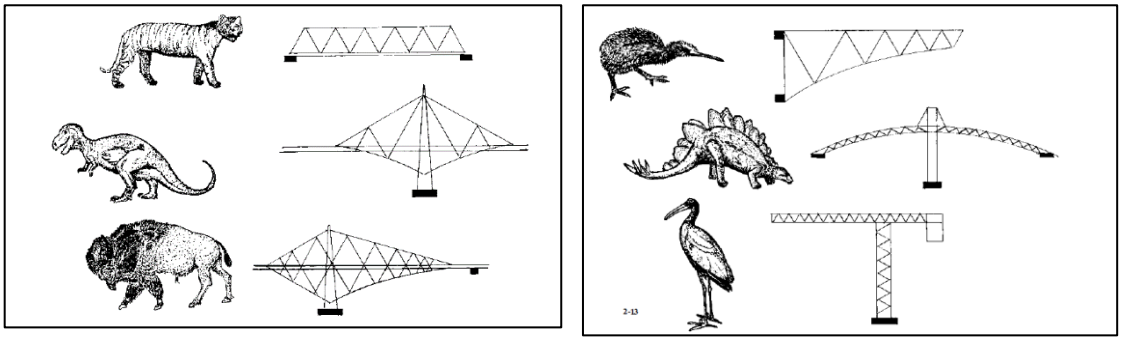
Furthermore, the human's skeleton contains rigid bones attached to it the soft tissues and body organs. The human skeleton is a structure consists of holes, which are different in distribution and dimension, but with a unique intention in their occurrence.Most bones are made out of both dense and spongy tissue. Compact bone is hard and dense and frames the external part of all bones. Spongy bone is found inside the compact bone and is permeable full of very small holes. Bone tissue is made up of a few sorts of cells installed

in a web of inorganic salts (for the most part calcium and phosphorus) to give the bone strength, and fibers to give the bone adaptability (Silver and Mclean and Evans, 2013).

The hollow nature of the bird's bones can be compared with the structure of the hollow tubes which resists bending (Silver and Mclean and Evans, 2013). In terms of

architectural engineering, bones represent an architectural model in the sense that they represent a natural lightweight construction which has some powerful attributes serving to efficiently perform the task of the organism's primary construction. It is additionally an ideal case for a dynamic versatile structure (Gruber, 2011). Robert Le Ricolais (1894-1977), a famous French engineer, remarked when working with the structure of bone one has to think about voids rather than working with a rigid material, and then the truth becomes evident. There are similarities between the functions of bones in animal bodies and architectural designs as they both need a structural balance (Figure 2.35). The skeleton structure of the animal body builds up an arrangement through stretchable components, for example, muscles and ligaments and joints, for example, the ligament that the most exhaustive engineering does not reach it. The structure is made up of openings, all unique in measurement and dimensions, but with an obvious intention in their occurrence. In this regard, Le Ricolais likewise expressed: "The speciality of the structure is the place to put the openings" (Mccleary, 1996). Le Ricolais also stated: "The art of structure is where to put the holes" (Mccleary, 1996).

**Figure 2.35: The structure of bridges inspired by the animal body**



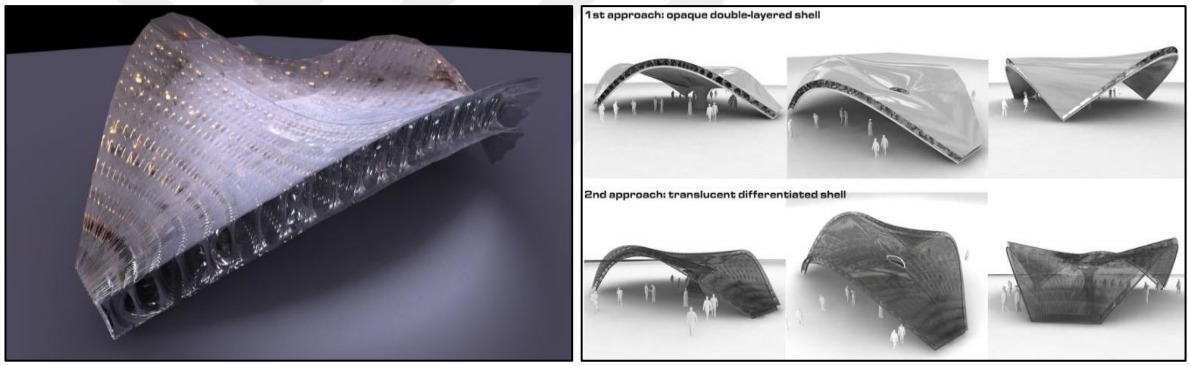
*Source:* (Williams, 2013)

Furthermore, structure and function are interrelated at all levels of biological organization. Birds are one of the very remarkable instances or examples of that structure

especially their wings which have aerodynamic functions. It is biologically that the skeletal structures of birds, help minimize the energy needed for a flight due to their lightweight bone structures. Dumont 2010 considered this as a very important factor, because from a functional point of view “the mass of an animal relative to its lift-generating surfaces is a key ratio if optimum efficiency of flight is to be achieved. The muscles used for flight are controlled by neurons - cells with long extensions, which due to their specific construction, are suited to the transmission of signals”.

Andre Harris discloses what he looked like to the lightweight yet the strong structure of bone found in the skulls of birds to rouse his plan for a biomimetically streamlined surface. He found that the skulls of feathered creatures are cunningly separated over its width: denser in the zones that experience high outer burdens, and less thick in the territories that are less influenced by these weights as shown in (Figure 2.36).

**Figure 2.36:Skull of a bird in architecture**




*Source:* (Harris, 2010)

In the same way constructed gridshells preserve material while accomplishing lightness through its one of a kind grid, so the skulls of these flying creatures are additionally comprised of a sort of network. The bone tissues comprise of non-directional spongiosa cells, which basically are pneumatized cells that take into account air "bubbles" in the material. (Harris, 2010).

# 3. SANTIAGO CALATRAVA'S ARCHITECTURAL PRODUCTION

The Spanish architect believes that nature can be used as an inspiration source for creating new structures.By studying the laws of nature and the complex structural principles of bones as well as animal and human skeleton which are quite stable in their fundamental and structural principles man can discover the secrets hidden in nature that can be employed in architecture including aesthetic and structural principles (Tzonis, 1999). Nature, which brings aesthetic and structural solutions turns to become the form generator tool for his designs and his original creative inspiration. There are two principles that Calatrava relies upon while imitating nature, the main superseding principle is displayed by Calatrava as "the ideal utilization of materials" (Tischhauser and Von Moos, 1998). The ideal utilization of materials taken from the natural structure, for example, trees, animals and human skeleton systems is the consequence of eager research to find proper and useful techniques and materials for his designs. The second principle is " *the capacity of organisms to change shape, to grow, and to move*". (Tischhauser and Von Moos, 1998). This principle is considered as the fundamental basis of inspiration.

## 3.1 NATURE AS AN INSPIRATIONAL SOURCE

Calatrava derives influential concepts from the natural biological structure that incorporates versatile solidity, aesthetic and functional thoughts (Tzonis, 1999). He makes use of the skeleton of humans and animals in a considerable number of projects by analogy. There are two profound main approaches to imagine and create a design scheme the analytical and the analogical (Tzonis, 1999). With regards to the division of work and the institutional split of Western architectural engineering and design, engineers are in favor of the first, architects and artists the second; whereas Calatrava has employed both (Tzonis, 1999). As it is explained in details in chapter two analogy is a concept that deals with transmitting knowledge from one discipline to another; it also involves inspiration and originality, it is the "mental leaps" that underlie creativity(Tzonis, 1999). In contrast to the process of analysis which starts with a list of principles and definitions presented in order to build up a structure following a certain process or a procedure that actually existed in a world, the process of analogy tries new design which has not been existed yet by reconsidering models, it creates unprecedented design through the rethinking of precedents. Looking at what Calatrava has done from this viewpoint, and considering

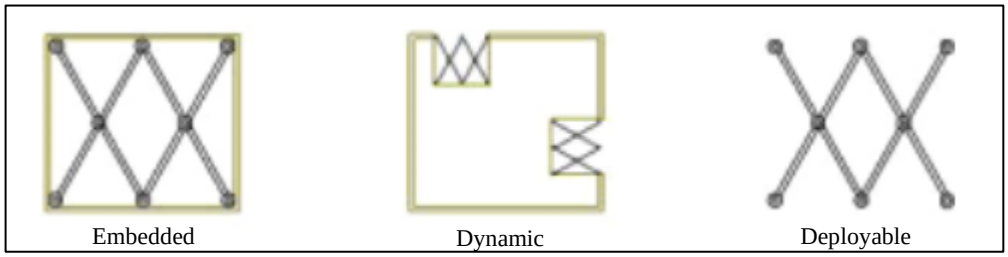
his drawing of human body and animals he has drawn in his notebooks whether they were individuals or groups and the way he combined them with architectural designs, the function such precedents played as sources for analogies can be seen in his architecture. Moreover, Positions, gestures, profiles, skeletons and muscles, organs, skin, wings, and horns are continuously recalled, reinterpreted, and projected into the project design. They call new methods of looking at structure and enclosure. They make the unfamiliar familiar and make potential creative solutions to difficult issues of program and site (Tzonis, 1999).

It can be argued that Calatrava has been much motivated and inspired by the human and animal skeletons as he understood their principles and features to transfer them into architectural concepts and values by analogy that is characterized by innovation and ability to give answers to a new question that is envisioned by the mind, or rather resorting so quickly to a model example that can meet the new demands .

### 3.2 MOVEMENT

Movement is defined as" *the process of relocation of objects in space over time*" (Schaeffer, 2010). It is the result of a change in position from one stationary condition to a new stationary condition through time (Schaeffer, 2010). It is possible to attain movement in buildings by changing the position or direction of buildings or their elements. The movement can take the following forms that are described as transformable, kinetic and deployable. Kinetic architecture can be defined as buildings and/or building components with variable mobility, location and/or geometry (Fox, 2003). Michael Fox classified Kinetic structures into three general types: Embedded, Deployable, and Dynamic kinetic structures as shown in (Figure 3.1). Embedded Kinetic structures are systems that can occur in larger architectural whole in a constant location. The main purpose is to control the larger architectural system or building, in restraint to changing factors (Fox, 2003). Deployable Kinetic structures exist in a provisional position and are easily transferrable. Such structure possesses the immanent capability to be built and deconstructed in the contrary (Fox, 2003). Finally, dynamic kinetic structures similarly exist in larger architectural whole but work independently with regard to control of the bigger context. Such can be subcategorized as transformable, mobile and incremental kinetic systems (Fox, 2003).

**Figure 3.1: Types of kinetic structures**




*Source:* (Fox, 2003)

However, different terms are used to refer to those buildings which are made up of parts or components that are capable to move and alter in shape. On the other hand, movement can be attained by figurative entailment as it is the case with paintings and sculptures. The idea of 'movement' has become one of the inspiring subjects Among the 20th-century philosophers, theorists and sociologists who were influenced and motivated by the movement as a concept are Gilles Deleuze a philosopher, Paul Virilio a theorist and Manuel Castells a sociologist. The concept of movement has been included in many academic modern studies taking its theoretical and practical domains into consideration from which a common perception has been derived. In the 20th century, more than any previous time in history, the movement has, become one of the most accepted realities of life. In perspective on the significance of remarkable speed and the effect of global mobility and change on human lifestyle. The integration of movement and structures has attracted the attention of numerous architects; this is most likely most obvious in the architectural designs of Santiago Calatrava (Tzonis, 1999). Calatrava has always been intrigued by movement, and it has become a source of motivation and advancement for his structures. He thinks that movement is an intrinsic part of architecture and building is a lively and vibrant entity at the first place rather than a visual image that is constituted of various volumes and textured surfaces (McQuaid, 1993). Furthermore, looking at the relationship between the analogy and the movement analogy is "an abstract cognitive process taking place in the mind using sensory material that can be visual, acoustic, or kinesthetic. Analogical "recruiting' can be an effortless association. but it can also involve negotiation and deliberation" (Tzonis, 2004). Accordingly, drawings can be of great help as the mind struggles to recall, focus, match, and test. As much as Calatrava's sketches are aesthetic objects to gaze at, their aims are to record and reflect. They helped him not only to reveal similarities between static forms but also to visualize resemblances between

the movements conducted out by objects. Therefore the type of movement happening in an object prototype could be projected to the movement performed by an object conceived sometime in the future (Tzons, 2004). In addition to the use of analogy from imitating objects from nature in his works, Calatrava also uses both analogy and analysis in order to “become two complements in his poetics of movement”. Designs have to be analyzed in order to decide constraints and analogy to creatively produce within those constraints. Analogy tests and experiments increase the rigor of the scientist and artist alike within Calatrava chameleon scientist-artist identity (Tzonis, 1999). Moreover, in terms of movement, the influence of Edgar Degas’s and Auguste Rodin’s drawings of dancers can be seen on Calatrava ‘ drawings of the human body, though his purpose was not the same as theirs; he meant to capture the abstract morphology of the moving figure. Looking at Calatrava's structures, their acrobatic gestures, their dancelike, falling, flying stances, it creates the impression that the structures corporate movement and that Calatrava, innovatively or allegorically, actually or figuratively, explicitly or implicitly, endeavors to negate stasis instead of protecting and saving it (Tzonis, 2004).

### 3.3 TYPES OF MOVEMENT IN CALATRAVA’S STRUCTURES

Calatrava is interested in the analogy of animal movement and their skeletons elements that have the ability to move practically like the movement of fingers and the folding of the wings or the figurative movement that deals with the conceptual movement of the human and animal configuration like twisting of the spine, the flying bird and the attempt to maintain the body in a balanced configuration to avoid it from falling. Alexander Tzonis in his book “The Poetics of Movement” depicts how Calatrava treats movement in his works. Calatrava brings movement into the three features of the building that include construction, vessel, and envelope through which movement has a figurative or functional role (Tzonis, 1999). The types of the movement included in Calatrava's works can be divided into two approaches the first one is functional movement and the second one is figurative movement. Climent 1998 states that Calatrava's works take their concepts from the explicit or suggestive movement (Climent, 1998). Functional or explicit movement is the real moving process of the part of the structure. Figurative or suggestive movement is the process of giving the viewer the implication that the building is moving. It is possible to accomplish “functional movement” by the following three methods: first, “the unfolding or opening of the element of the structure such as the doors,

roofs. Second, by rising which can be achieved by vertical movement; it can also be called folding accordingly. Finally, the revolving which is the type that the structure moves around a center or around itself" (Tzonis, 1999). The figurative or suggestive approach is expressed figuratively by its form that represents or derived from nature, and by its illusion of instability where the structure is suspended between the past and the future to entail that the structure is about to fall. Finally, the symbolic movement is expressed through counter position, which is a form that is taken from the human body or the spine of the human skeleton while turning or twisting, which entails the intention that the body is trying to return to its original point (Tzonis, 1999).

### 3.3.1 Functional movement

Functional movement is defined as the type of movement where the parts of a structured move. It is a technique used by architects for designing structures that have a movable body or movable elements (Tzonis, 1999). According to this type of movement, structures have the ability to change their positions and directions completely or partially. In 1970, Zuk and Clark described the movement, in their book " Kinetic Architecture" as follows *" the architectural form could be inherently being displaceable, deformable, expandable or capable of kinetic movement"* (Zuk and Clark, 1970). Robert Kronenburg (2013) affirms that looking at kinetic from a moveable or mobile viewpoint it is "building or buildings components with variable mobility, location and/or geometry". He also went to say, in 2007, that transformability in architectural context "*includes changing design buildings, space, form, and shape by physically altering its structure, interior or skin. It is an architecture that opens, closes, expands and contracts*" (Kronenburg, 2007). However, some mechanical systems are incorporated into this type of structures because they are fundamental sources of the movements. Thus, Calatrava's use of doors and roofs in his designs mean to represent those elements of structures that have the capability to alter their position and posture. It is worth mentioning that Tzonis (1999) introduces three distinct means ("unfolding", "rising", and "revolving"), which Calatrava has functionally used in his mobile structures or designs.

**Unfolding**

Architecturally, Hoberman (2004) defines unfolding as "*an object that is identically a structure and a mechanism*". He added that introducing such an innovative concept to architecture "*allows a controlled transfer of forces and motion within the system without the need for any secondary support systems"*(Hoberman, 2004) (Figure 3.2). This kind of architecture is also defined as: "Buildings and components of the building with inconstant mobility, location and/or geometry. Solutions of the Structure needs to be considered in equivalent both the methods and means for kinetic functional efficiency. The method in which a kinetic structural solution conducts may comprise, among others, folding, expanding, sliding, and transforming in both shape and size (Fotiadou, 2007). The foundation of each folding structural system is embodied in a minimum number of representative associated parts. Unfolding structures are created of a simple part with a simple relationship between them. Folding has become a technique for the morphogenetic investigation of program and space and to a minimum level, an inquiry of a structural skin (James, 2008).

**Figure 3.2: Unfolding movement of a door designed by Calatrava**

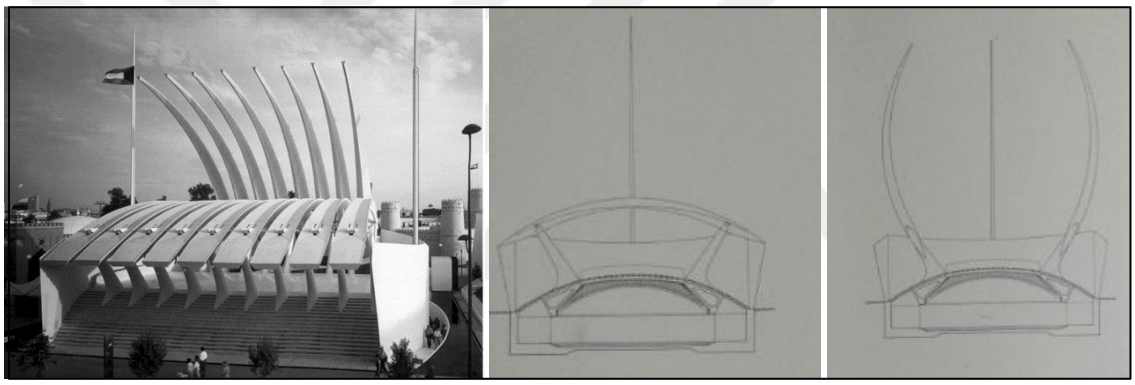
*Source:* (Tzonis, 2004)

The functional movement of the structural elements of the building can result in the spatial structure movement as a whole or only part of it. More specifically, Calatrava has produced design works with unfolding structures where their mobile parts are surfaces made up of "*repeated long and slender elements, or slats* " (Tischhauser and Sharp, 1996). Pivotal joints connect these slats together and the rest of the parts are considered as 'points of unfolding'.

**Rising**

Tzonis (1999 ) introduced rising of a structure as "*an architectural response to the particular changes in physical and pre-physical conditions*". It can be imagined the upstanding position of the structure, particularly from lying, kneeling, or sitting as shown in (Figure 3.3). The way the structure performs is created by two elements and connection between them, with the first element fixed in a specific position but the probability of rotating and the second moving along a certain linear path. However the first element is steadily fixed in a place and the second element is rotating along a hinge, not at the end of the body of the element where there can be a joint inside a point of the second element's body (Fotiadou, 2007)

**Figure 3.3: The rising movement of a roof designed by Calatrava**



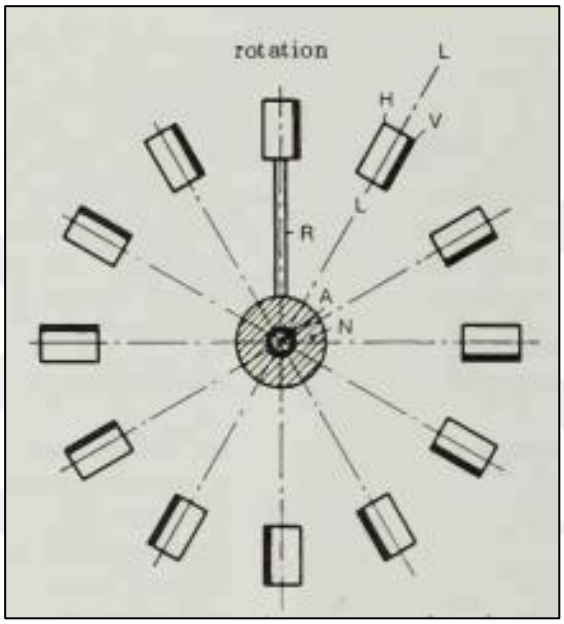
*Source:* (Tzonis, 2004)

New insight can be developed if the concept is utilized as an intellectual matter in architectural designs. Rising could also be utilized as a real activity in architectural designs and not only as being a symbolic value. Structures may rise or have rising parts to adjust for various physical states or to react to pre-physical changes (Emel, 2007). Calatrava has made use of this kind of movement in two ways the first one is connected and used in the building skin and covering the façade as he made it fold, rise, and extend in a way similar to the human limb (Tzonis, 1999). The second way is connected to the major structure of the building, which could be a roof, which can be accomplished by folding and rising of the structure.

**Revolving**

Heinrich Hertel (1996) in his book under the title of “Structure - Form – Movement“ distinguished two types of revolving actions. In the first type in (Figure 3.4 and 3.5), “the element that rotates hold its direction that relates to the center of the circle by rotating at the same time around its own center so that the same interior side of the particle is always seen from the center of the circle”

**Figure 3.4: Rotation**




*Source:* (Hertel, 1996)

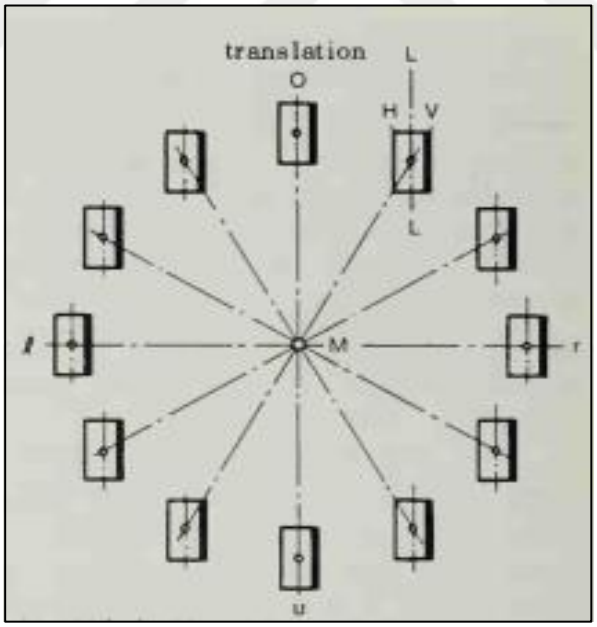
Hertel labels this action as “rotation, in this context, it can be compared to the movement of a wheel, as all constituent parts turn around a center with the equivalent angular velocity.

**Figure 3.5: Puento de mujer bridge rotation**

*Source:* (Tzonis, 2004)

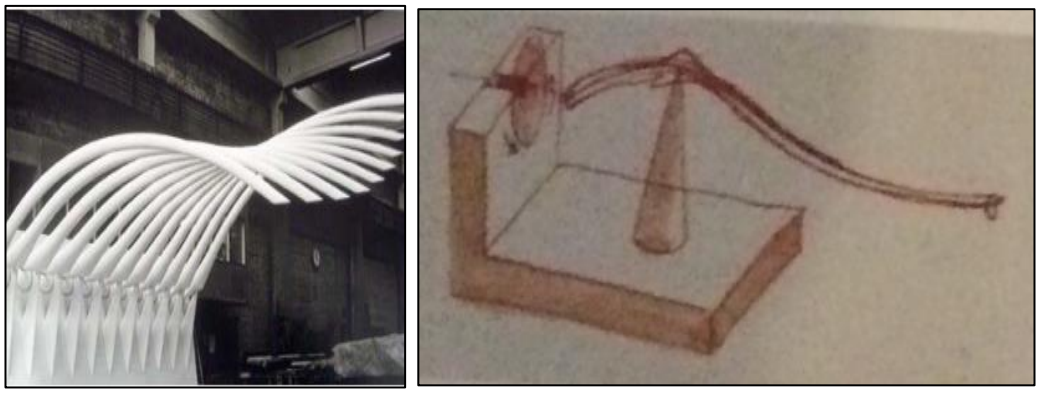
Conversely, the second action in (Figure 3.6 and 3.7) is “the body that rotates around a center without at the same time turning itself”. It is called as “translational rotation”. is similar to the movement of the foot in pedalling a bicycle, as the sole of the foot moves around a center though it always stays horizontal (Hertel, 1996).

**Figure 3.6:Translational rotation**




*Source:* (Hertel, 1996)

**Figure 3.7: Translational rotation of the Swissbau concrete pavilion**



*Source:* (Tzonis, 1999)

It can be stated that Calatrava has achieved functional movement through examining the movement of human and animal's skeleton in the following examples: the unfolding of the human's eyes; the rising of the human's fingers, and the rising of the bird's wings. Finally, Calatrava has used functional movements by analogy inspired by nature when he employed revolving based on the revolving of the human fingers.

### 3.3.2 Symbolic movement

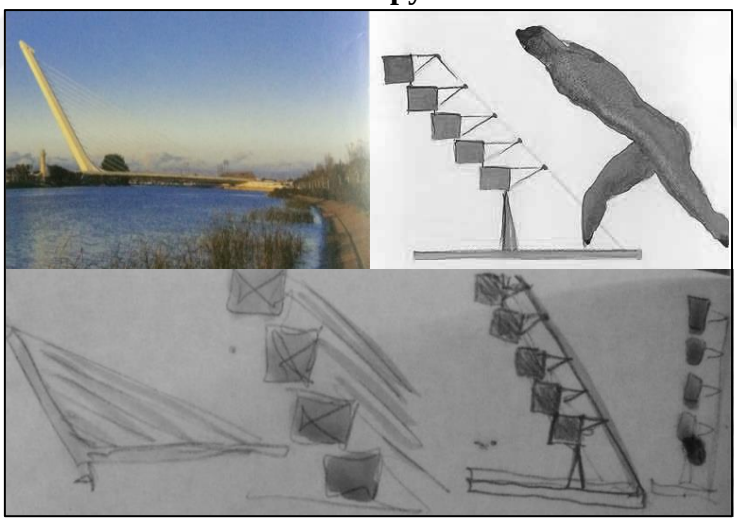
Symbolic movement is the method of planning structures that suggest the possibility of movement symbolically. One of the main characteristics of this type of movable movement is that its quality (as in a painting or sculpture) proposes or symbolic movement, which attributes to these types of movable structures. The structures prepared with 'symbolic movement' do not include any movable parts (Tzonis, 1999). Even by being completely fixed, symbolic moving structures seem as if they are in a state of movement. Calatrava's structures that use 'symbolic movement ' can be examined under three sub-categories as follows 'representation of nature', 'structural instability, and "figura serpentinata or S-form" (Tzonis, 1999). Looking at Calatrava's structures their aerobatic motions, their dancelike, falling, flying stances, create the impression that the structures have movement in them and that Calatrava other than the functional movement is aware of the symbolic movement of the natural forms and he is able to capture their abstract movement, A good number of Calatrava's works and designs are consented to suggest movement through their strange shapes or forms. This impression is fundamental because of the structures which are purposefully selected from configurations.

The symbolic movement includes the structural instability which is the body in a balanced configuration. And the S-form which is the twisted body in a balanced configuration.

**Structural instability**

Structural instability is a type of symbolic movement; it implies that the structure is in an unstable condition about to collapse due to its inefficiency, which in fact is stable. Calatrava refers to this idea, aiming toward "optimal" design, pushing his schemes to the outermost limit. Holding the designs within this frontier leads to inefficiency pushing them beyond this frontier, which is called " critical point" leading to collapse (Tzonis, 1999). Technically if a definite inconstant in design surpasses the "critical point" then the interatomic links, the ties between atoms of a structural member, will be broken, and the structure will fly in all directions at once. Figure 3.8 shows Alamillo bridge inspired by an inclined human body in a balanced configuration.

**Figure 3.8: Alamillo bridge designed by Calatrava with an inclined pylon**



*Source:* (Tzonis, 1999)

For achieving optimization, the narrow place between incompetence and collapse needs to be discovered. This ideal state , in fact , has been technically accomplished by Calatrava who at the same time was able to accomplish a very strong aesthetic state that has been called the "pregnant moment " which is a single moment of action that unites two distinct points of time by selecting configuration most suggestive of what has

occurred before and what is to follow (Tzonis, 1999). This is a very artistic idea that indicates a figure of a structure, or sculpture, or even painting, that infers movement. During the nineteenth century Gotthold Ephraim Lessing, in his well-known book “Laocoon”, put forward another driving force to the discussion about the portrayal of movement in human expressions in a given medium and space reality limitations.

Lessing obtained the term pregnant from British thinker and philosopher Shaftesbury so that he explains and clarify the exceptional difficulties of the visual arts in inferring time, event, and process (Tzonis, 2004). Talking about the human figure in art Lessing utilized the term pregnant to depict a structure suspended between past and future, inferring an earlier position and extrapolating a future one. Calatrava seems to push his structures to the ideal state between all-out success and failure. The "critical point" is that point between firm permanence and violent fading**.** When one looks at the structure it will look as if it moves and about to collapse but, in fact, it is completely firm and stable. The structure is suspended between the past and the future.

It can be stated that the structure in this condition is suspended between the past and the future by the concept of the pregnant moment. After the structure reaches the last point of the critical point which is the barrier between falling or collapsing of the structure and saving it. This idea is used in some of Calatrava's projects including towers and bridges, it also depends on the human body in any balanced configuration.

**Figure serpentine-S-Form**

The term figura- serpentine was introduced by Alexander Tzonis in which he tried to express an artistic notion that is employed to the human body in order to empower it with movement. The "counter position” of the limbs of the body was used in order to express a charming and graceful movement in a way that reflects artistic creativity (Tzonis, 1999).

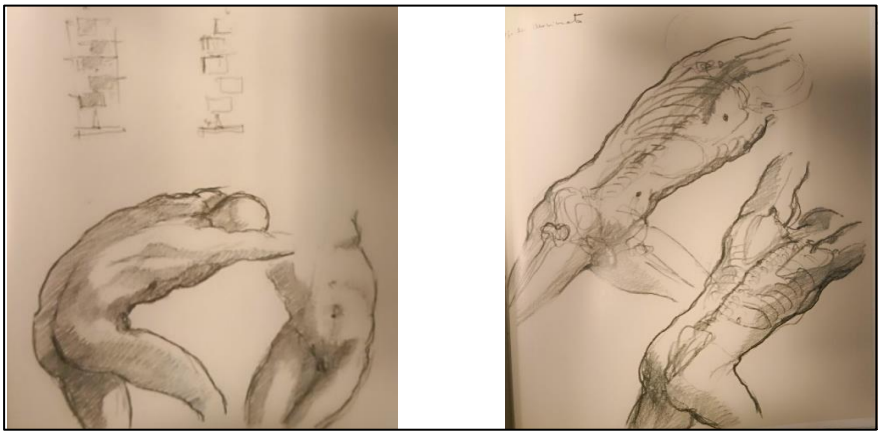
Polyclitus's sculptures are admired for the use of this movement (Figure 3.9). In addition to a formula for mimetic sculpture, the Canon made a theoretical system of tenets dependent on axes and a bunch of connections between them to catch the most valuable qualities of any sort of human body in balance while in motion.

**Figure 3.9: Polyclitus sculpture of a twisted body**

*Source:* (Neer, 2010)

The term “counter position" was used for the first time in the Renaissance to refer to Polyclitus designs who set the structure of the human body as laying on one leg, driven a little to the back, with the other leg twisted at the knee and applying less weight. The chest as it is leaned in reverse is also somehow twisted. Furthermore, the head is inclined to the side of the other way of the chest. The movement was seen as portrayed in a perfect way in this counterposing of the organs of the body, or contrapposto (Tzonis, 2004). Figure 3.10 shows sketches of a twisted human body drawn b Calatrava.

**Figure 3.10: Sketches of twisted human body drawn by Calatrava**



*Source:* (Calatrava and Zardini, 1996)

In picking this term, the Renaissance designs’ intellectuals, were engaged with the concept of movement ,to include it in both arts and literature of that time in order to

show that this connection can also be incorporated in structure and movement rather than it is simply a change of position, and to express a progressively widespread principle of poetics (Tzonis ,1999 ). The Figura serpentine or S-structure is another sort by a list of structures whose harmony guarantees that for each force that undermines to bring it down there is a similarly opposing force. The S - structure that is dominant in Calatrava's designs in its entire architectural implications has immense value in the way that it depicts movement throughout the history of visual culture (Tzonis, 2004). Figure 3.11 shows a twisted tower designed by Calatrava .

**Figure 3.11: The design of a tower inspired by a twisted human body**

*Source*: https://www.archute.com/the-turning-torso/, [Accessed 18 July 2019]

It can be stated that Calatrava has achieved symbolic movement through the S-form by a turning body or the spine of the skeleton. It is a structure whose balance guarantees that each force that undermines to collapse will be similarly resisted by a resistant force. Furthermore, the term counter position is the process of describing a body suspended between the past and the future. It can include two types of symbolic movement, which are the structural instability and S-form because both ideas depend on the human body. The only difference is in structural instability the human body in any balanced

configuration is captured while in the S-form only the idea of the twisted body in a balanced configuration is captured.

To conclude this chapter the kinds of movements are utilized as motivational and inspirational sources for producing forms that are functional and symbolic by which architects use to highlight the two principles they derived and inspired from nature. The first principle is the possiblity of learning from natural forms and inspiring from their forms visually or functionally ; the second is watching their movement in such a manner Calatrava uses in his works where the body of a living being is destroyed and then brought together to make a creature that seems as though relates to the landscape..

# 4. CASE STUDY ANALYSIS

Four of Calatrava's projects are selected to be analyzed. Each of the projects is inspired by a different element and concept from nature. The selected case studies are Planetarium of the city of arts and sciences in Spain, Milwaukee art museum in the USA, Malmo tower in Sweden, and finally Shadow machine in the USA. The analysis of case studies consists of two phases the first one is to analyse the projects according to four criteria. Tables 1,2,3,4 show the four criteria in which the case studies have been analyzed. The second phase is to convert the criteria to step by step process of generating the form of each case study.The process of generating the form of each case study is shown by a model. The criteria in which the case studies will be analyzed in term are as follow:

**a. Source of inspiration**

Calatrava's works can be considered as an aesthetic aspect and a technological invention (sharp, 1998). The existence of these features has been confirmed in the architect's statements. Calatrava clarifies many times that the primary source of his inspiration that brings aesthetic choices and technological applications is "nature"; thus, nature becomes a notion offered by Calatrava as a generator for his works and creative inspiration. He gives much interest in human and animal bodies.

**b. The elements of design inspired by nature**

All the natural structures, whether animate or inanimate consist of some elements that help to create or to form a natural form. Calatrava's structures, like the body of an organism, have been destroyed and reassembled to convert the elements of the natural form to the building. *'Calatrava's projects recall the way the body of a complex living organism is put together this is one of the reasons his bridges, observation towers, and building complexes fit and enhance the landscape like enormous organism growing out of it or living with it'* (Tzonis, 1999). The aim of this criteria is to find out the elements that the architect imitates from the human and animal body such as Ribs, Fingers, Spine, Skull, Eye, Wings.

**c. The types of biological analogy**

The analogy is defined as a cognitive process for describing the shared features between two objects. This criterion aims to find out the types of biological analogy in Calatrava's structure.

**d. The movement**

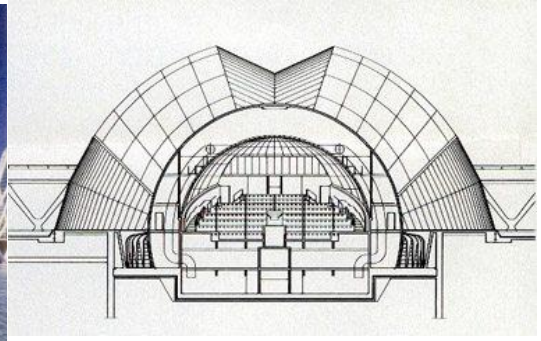
This principle is considered as the essential source of inspiration. The movement has interested Calatrava and became an inspiration source for most of his structures. He explores movement as an essential feature of the architecture, emphasizing that a building is not only a visual image built of various volumes and textured surfaces but a dynamic object (McQuaid, 1993). Calatrava's works also illustrate great interest with the capacity that natural creatures have to alter, grow, move and adjust (Tischhauser and Von Moos, 1998). The aim of this criteria is to find out the types of movement in Calatrava's projects.

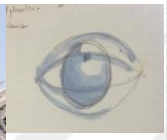
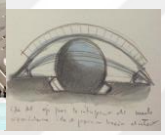
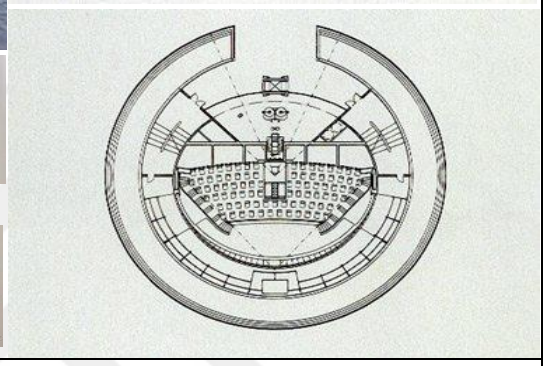
## 4.1 THE PLANETARIUM OF THE CITY OF ARTS AND SCIENCES

The first case study in (Table: 4.1) is the Planetarium of the city of science art and in Valencia in Spain. The planetarium, with a hemisphere dome with a movable sunshade structure, covers an area of 2,600 square meters is designed in 1998. Looking at the idea of the project and how it is developed. By analyzing Calatrava's sketches it can be seen that the concept is inspired by the visual analogy of the human eye, to become Calatrava's most clear reference to the human eye. Moreover, the type of movement which is applied to the project is the functional movement by unfolding which was employed in the ribbed eyelid that covers the project which is inspired by the analogy of the human eyelid. The eyelid structure by the aid of slats on both sides helps functional moving of the eyelid by unfolding. The steel structural elements that have been used in the project are developed by rhythm, recurrence and symmetry, which are common principles that exist in nature.

**Table 4.1: Analysis of the planetarium of the city of arts and sciences**

## 1.PLANETARIUM OF THE CITY OF ARTS AND SCIENCES -SPAIN



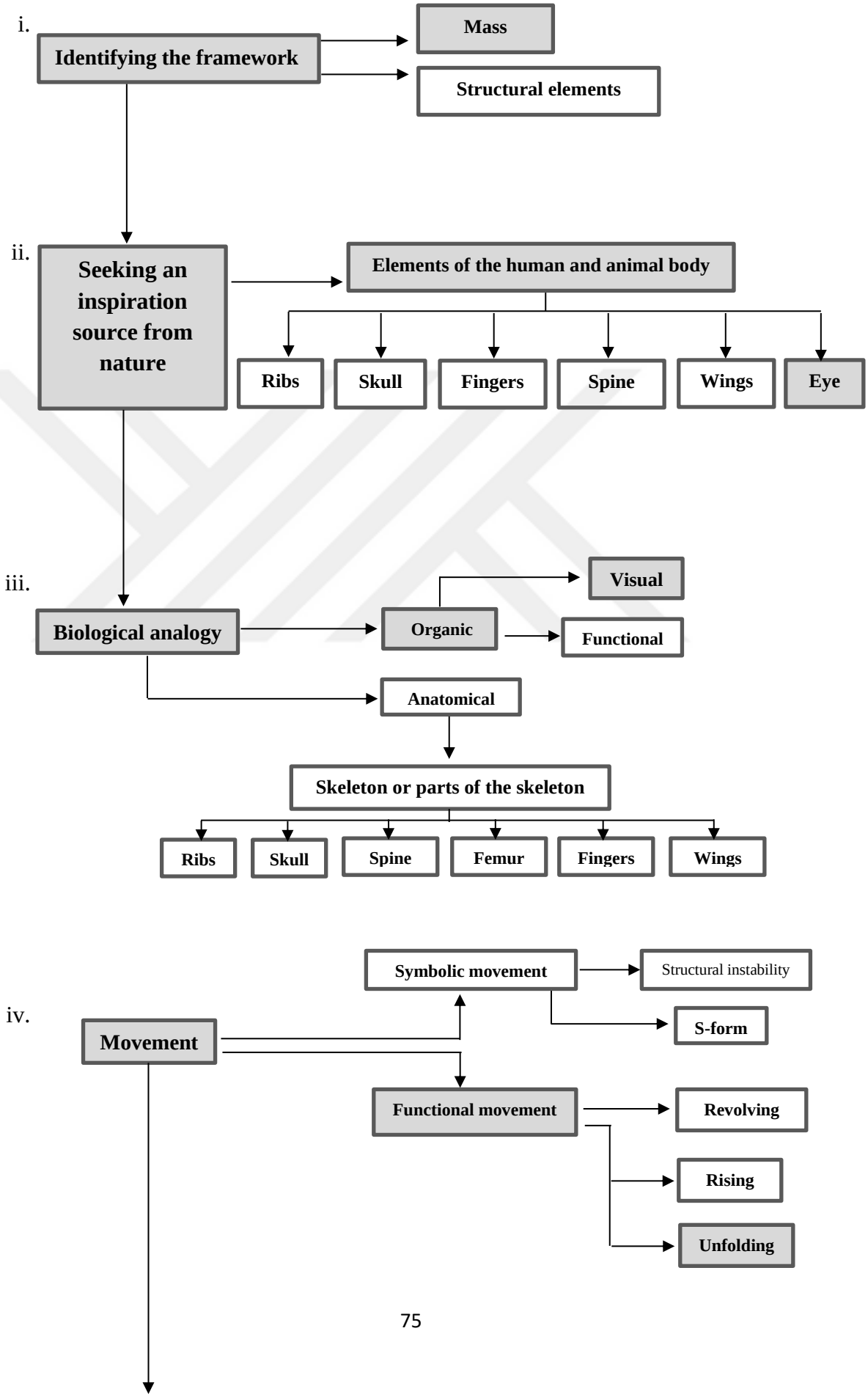
**1.The source and element of inspiration:** The Planetarium of the Valencia City of Sciences may be Calatrava's most explicit reference to the human eye.

**2**. **Type of the biological analogy:** The project is inspired by the visual analogy of the human eyelid.

**3.Type of the movement:** The form and mechanism of the mobile structure that open and closes seem as the eyelid that covers and uncover the eye. In the Planetarium, the functional movement is achieved by Calatrava by unfolding.

| The Project | Source of inspiration | | The elements of the inspired source | | | | | | Types of biological analogy | | | | | Types of movement | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | Functional | | | Symbolic | |
| | | | | | | | | | Organic analogy | | | | | | | | | |
| | Human | Animal | Ribs | Skull | Finger | Spine | Eye | Wings | Visual | Functional | Anatomical | Ecological | Darwinian | Unfolding | Rising | Revolving | Structural instability | S-Form |
| **1.Planetarium** | ● | | | | | | ● | | ● | | | | | ● | | | | |

Figure 4.1:The steps of designing the Planetarium of the city of arts and science



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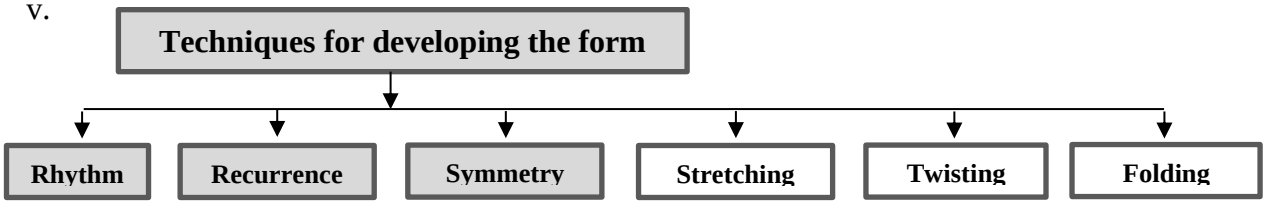
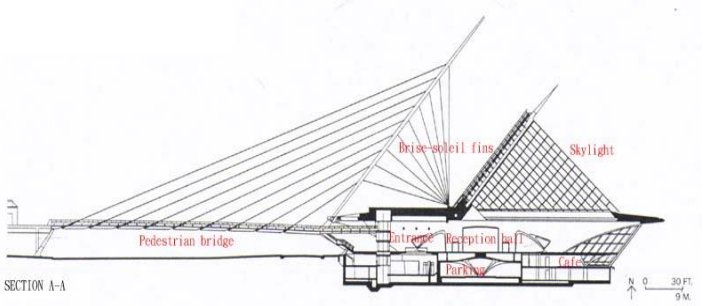


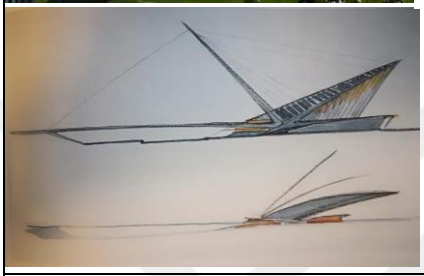

## 4.2 MILWAUKEE ART MUSEUM

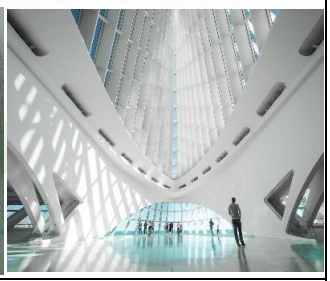
The second case study in (Table:4.2) is Milwaukee art museum which is located in New York in the USA. Designed by Calatrava overlooking lake Michigan as a War Memorial. Calatrava designed the project after participating in a competition in 1994, to redefine the museum identity through the creation of a new image to become a new orientation for the visitors. The concept of the project is inspired by the wings of the bird. The concept of the project is inspired by the anatomical analogy of the shape of a bird in a flying position, especially when the "wings" are open. It is the comparison of the skeleton of the wings of the bird to the form of the wings of the building and the idea of how the wings work in nature to be applied to the wings. Inside the building specifically in corridors, there are structures inspired by the ribs.The project consists of a 27-meter-high glass and steel reception hall shaded by a moveable sunscreen. Made of steel plates welded and stiffened inside. The moveable sunscreen structure is comprised of two equal wing elements, each one formed by 36 ribs whose lengths range between eight meters and 32 meters. A computerized system is installed to automatically override the manual movement of the structure when wind speed surpasses 40 miles per hour. Furthermore, the movement in this project is achieved by functional rising up and down of the wings, which are connected to a central inclined pylon that recalls the spine of the bird. By closing the wings, it become a surface that covers the conical structure. In their open location, the facades of the structure become exposed. Finally, for the development of the initial form the techniques such as rhythm, recurrence and symmetry have been used which are the most employed techniques in Calatrava's projects which can be seen in almost all of his projects that are inspired by nature.

**Table 4.2: Analysis of Milwaukee art museum-Spain**

## 2.MILWAUKEE ART MUSEUM -USA





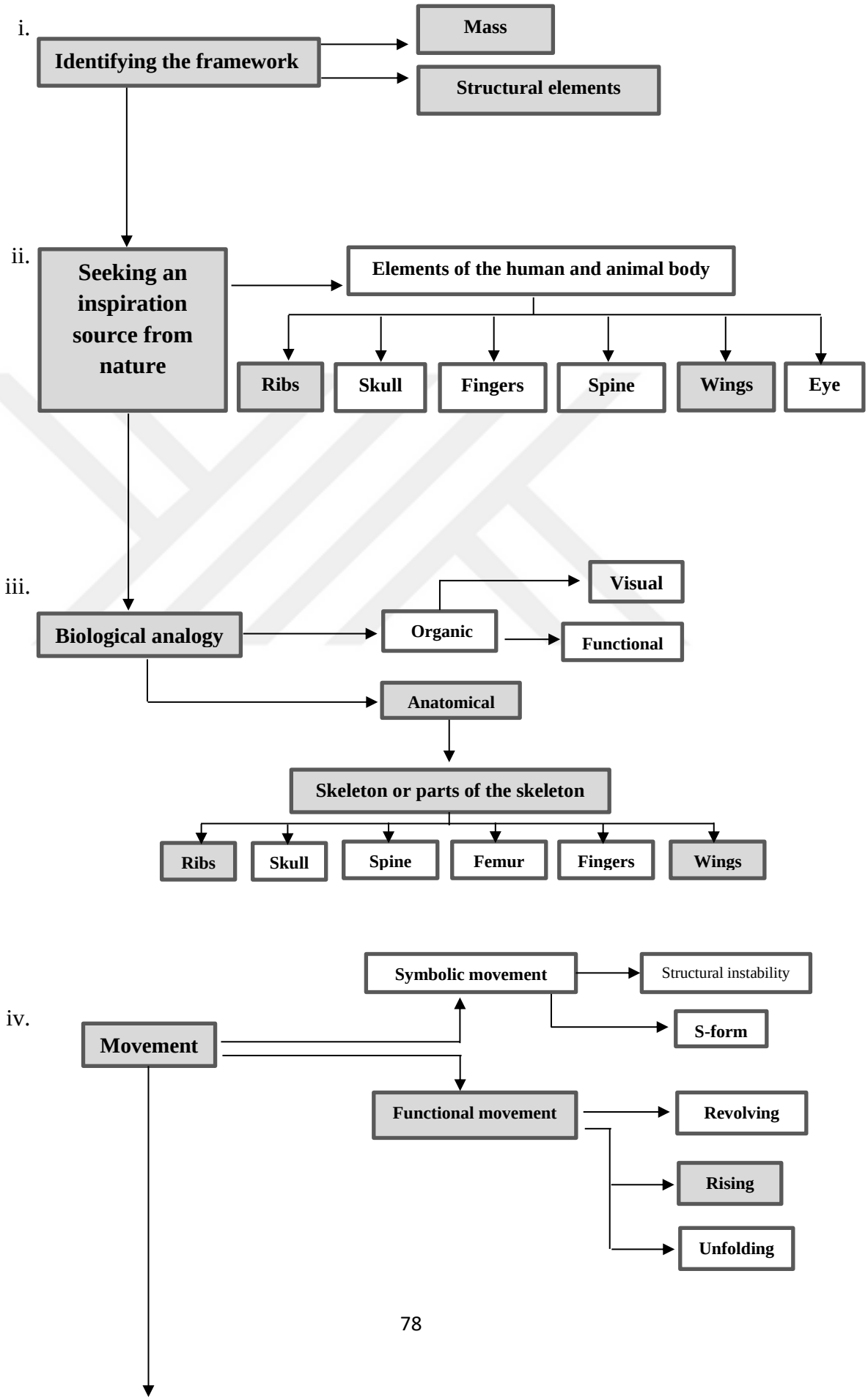
**1.The source and element of inspiration:** The concept of the project is inspired by the shape of a bird in a flying position especially when the "wings" are open.

**2. Type of biological analogy:** The project is inspired by the anatomical analogy of the wings of a bird.

**3. Type of movement:** Movement in Milwaukee Art Museum is achieved by functional rising up and down of the wings and the second one is achieved by symbolic the giant bird is trying to take off or move toward the lake to implicate the representation of movement.

| The Project | Source of inspiration | | The elements of the inspired source | | | | | | Types of biological analogy | | | | | Types of movement | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | Functional | | | Symbolic | |
| | | | | | | | | | Organic analogy | | | | | | | | | |
| | Human | Animal | Ribs | Skull | Finger | Spine | Eye | Wings | Visual | Functional | Anatomical | Ecological | Darwinian | Unfolding | Rising | Revolving | Structural instability | S-Form |
| **2.Milwaukee art museum** | | ● | | | | | | ● | | | ● | | | | ● | | | |

Figure 4.2: The Steps of designing the Milwaukee art museum



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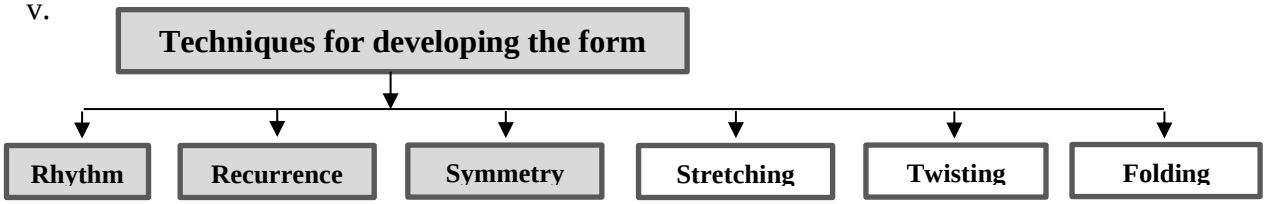
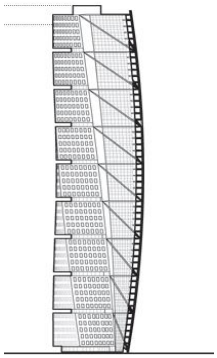


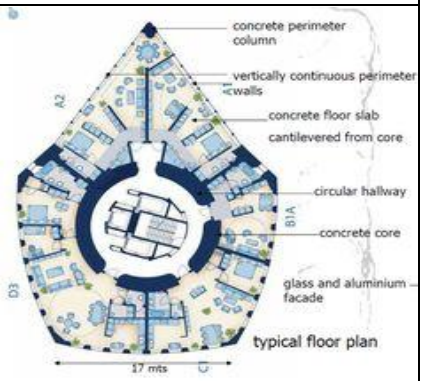

## 4.3 MALMO TOWER

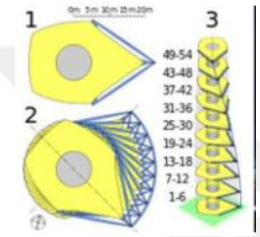
The third case study in (Table:4.3) is Malmo tower -Turning torso. Turning Torso is one of Calatrava's projects designed in Malmo, Sweden 2004. The concept of this project is inspired by the analogy of a twisted human body in a balanced configuration. So the concept of the project is inspired by the anatomical analogy of the human body. The concept of balance in the human body is related to the human skeleton, particularly spine, which is the main reason why the human body stands up. In this project, the structure of the vertebral column is connected by flexible wires to the tensioned spinal cord with its rigid vertebrae. This project first started with a sculpture created by the architect that reflects his intense interest in sculptures and the study of the statics. Calatrava's sculpture consists of seven cubes placed around steel support to create a spiral form that resembles a twisted spine. Calatrava replaced the cubes of the original sculpture by sub-buildings which accommodate from one to five of approximately 2.200 square meters residence units. The symbolic movement in this project is achieved by structural instability and S-form of the twisted body. This is achieved by the balance of the posture that was captured through a stance of motion. The tower seems twisted trying to return to the original point this effect is endless.

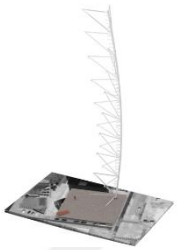
**Table 4.3: Analysis of Malmo tower -Sweden**

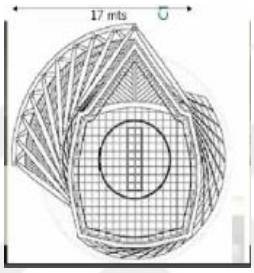
# 3.MALMO TOWER-TURNING TORSO-SWEDEN

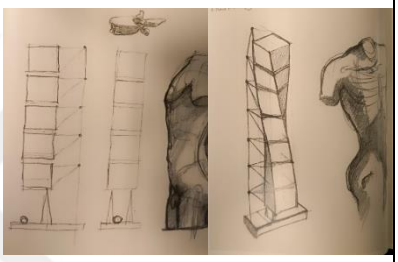






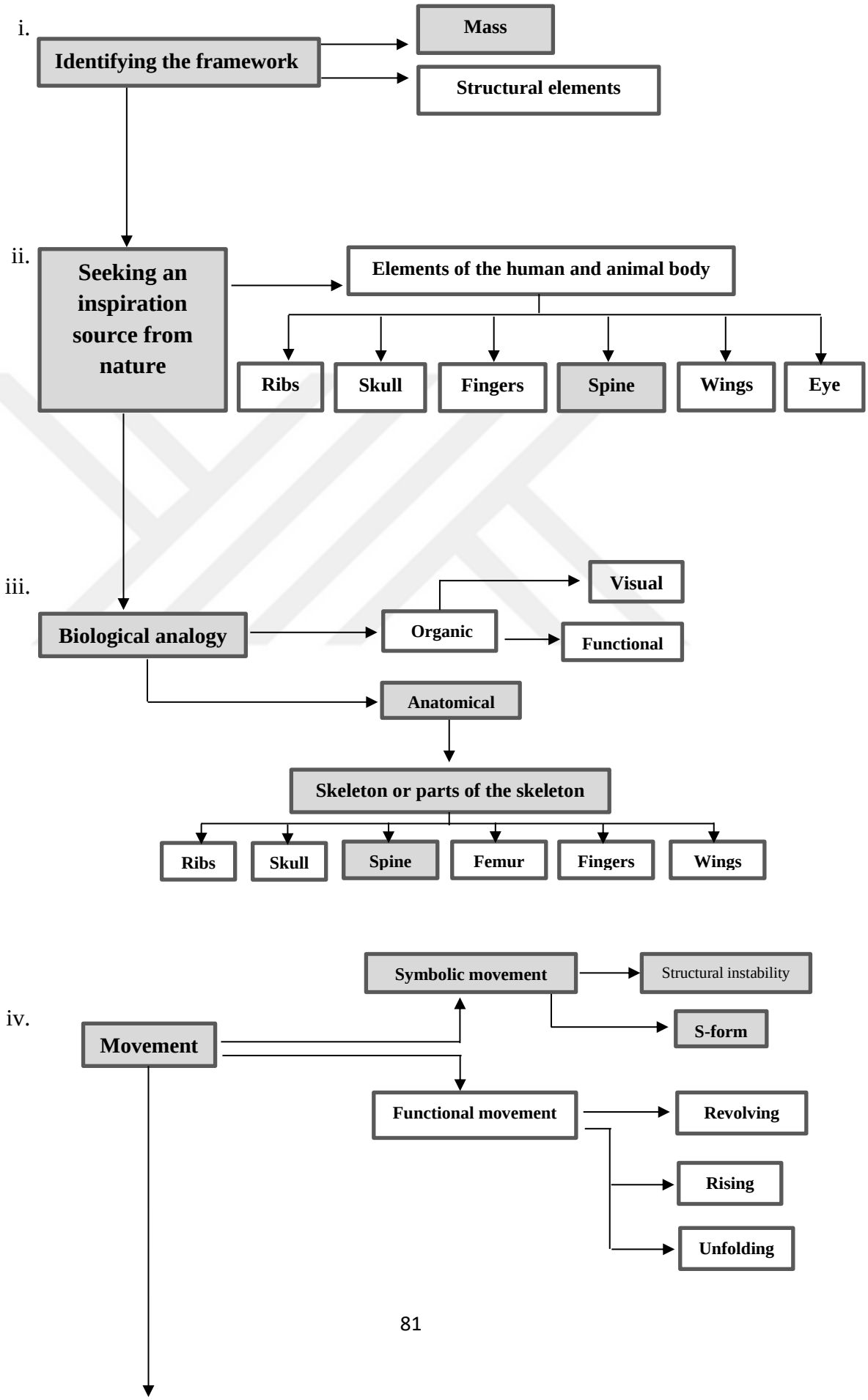
**1.The source and element of inspiration:** the concept of this project is inspired by the analogy of a twisted human body in a balanced configuration. The concept of balance in the human body is related to the human spine which is the main reason why the human body stands up

**2.Type of biological analogy:** The concept of the project is inspired by the anatomical analogy of the human body the twisted body is trying to stay in a balanced configuration.

**3.Type of movement:** The symbolic movement is achieved by two ways which are structural instability and S-form.

| The Project | Source of inspiration | | The elements of the inspired source | | | | | | Types of biological analogy | | | | | Types of movement | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Organic analogy | | | | | Functional | | | Symbolic | |
| | Human | Animal | Ribs | Skull | Finger | Spine | Eye | Wings | Visual | Functional | Anatomical | Ecological | Darwinian | Unfolding | Rising | Revolving | Structural instability | S-Form |
| **3.Malmo tower** | ● | | | | | ● | | | | | ● | | | | | | ● | ● |

**Figure 4.3: The steps of designing Malmo tower**



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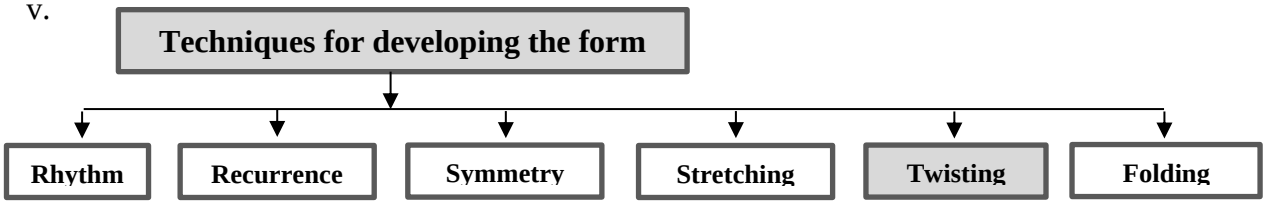
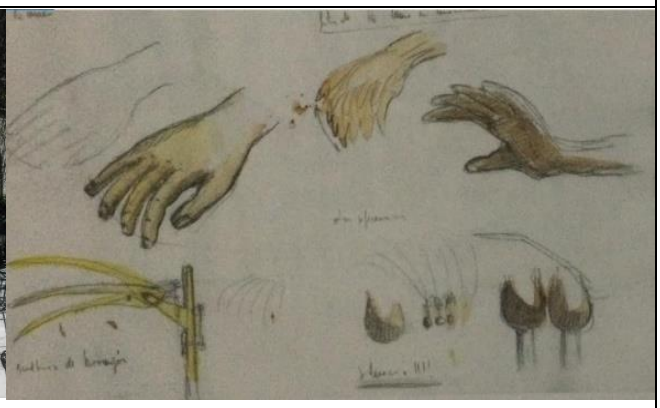



## 4.4 SHADOW MACHINE

The fourth case study is Shadow machine in (Table: 4.4). It is a sculpture designed by Calatrava located in New York designed in 1998. The concept of the project is inspired by the anatomical analogy of the human fingers. The white colour of the fingers and rhythm that has been applied to the structure emphasizes the inspiration of the bones of the fingers. Each finger weighs 6oo kilograms with eight meters long. Each of the twelve fingers is connected to the base, which is 30- ton, fixed supporters protruding from the base which fingers rest on. Since the fingers do not move in a uniform manner the sculpture produces an ununiformed shadow. The movement is achieved by the revolving of the fingers that move independently like the movement of the foot on pedalling bicycle so the rotation occurs at the base without turning the finger around itself this is called the translational rotation.

**Table 4.4: Analysis of Shadow machine -USA**

# 4.SHADOW MACHINE-USA



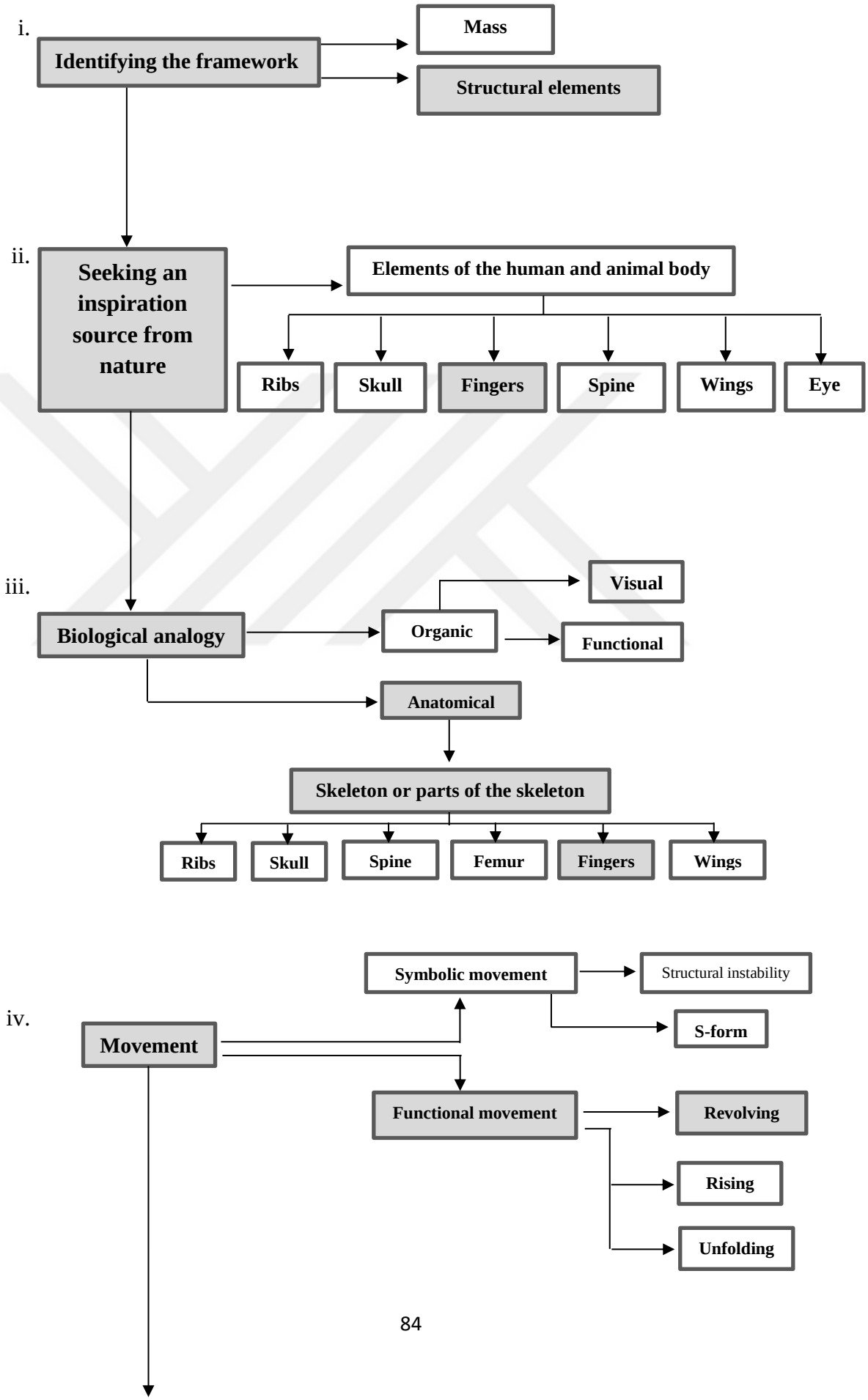
**1. The source and element of inspiration:** The concept of the project is inspired by the analogy of the human fingers.

**2. Type of the biological analogy:** The machine is inspired by the anatomical analogy of the human fingers.

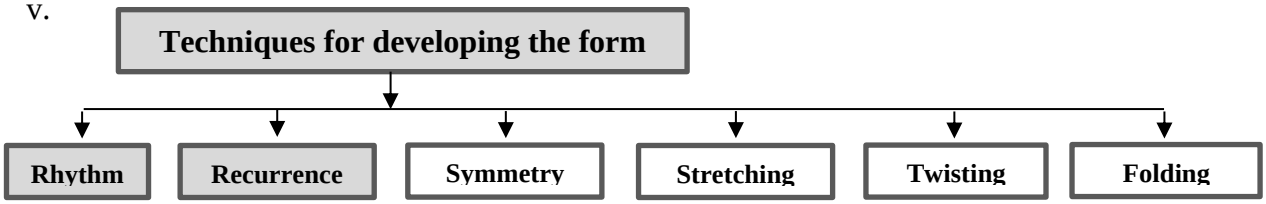
**3. Type of the movement**: The movement is achieved by functionally revolving which is called translational rotation.

| The Project | Source of inspiration | | The elements of the inspired source | | | | | | Types of biological analogy | | | | | Types of movement | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | Functional | | | Symbolic | |
| | | | | | | | | | Organic analogy | | | | | | | | | |
| | Human | Animal | Ribs | Skull | Finger | Spine | Eye | Wings | Visual | Functional | Anatomical | Ecological | Darwinian | Unfolding | Rising | Revolving | Structural instability | S-Form |
| **4.SHADOW MACHINE** | ● | | | | ● | | | | | | ● | | | | | ● | | |

**Figure 4.4: The steps of designing Shadow machine**



V.


Techniques for developing the form
Rhythm
Recurrence
Symmetry
Stretching
Twisting
Folding

# 5. DISCUSSION AND FINAL REMARKS

## 5.1 DISCUSSION

From the selected case studies, one project is inspired by organic analogy and three projects are inspired by the anatomical analogy. The Planetarium of the city of science and art in Spain is inspired by the organic analogy of the human eye. In the planetarium, the eye is used most explicitly as a form and the function of the eyelid.

The other project is inspired by the form of the bird, which is Milwaukee art museum in the USA. The project is inspired by the anatomical analogy of the wings of the bird,the structure which has been used for the corridors of the building is inspired by the ribs.The movement is functional by rising up and down of the wings.

Malmo tower is inspired by the anatomical analogy, it is inspired by the form of twisted human body in a balanced configuration. The architect in this project abstracted the twisted spine of the human body and converted it to sculpture then to a building so he deals with the internal part of the body. The movement in Malmo tower is achieved by the structural instability and the S- form and representation of nature. The last project is Shadow machine in the USA it is inspired by the anatomical analogy of the human fingers. The idea of this project can be seen in the Swissbau concrete pavilion, which is a sculpture for producing shadow. Both projects have the same principles the only difference is in shadow machine the fingers are longer and the movement in both projects is achieved by translational rotation.

Looking at the way Calatrava deals with the selected projects and the way he generates the forms in nature, he employes the form in nature in two ways.The first way is to imitate the visual characters of the human and animal body including movement of the elements of the body.The second way is to imitate the deepest principle in the skeleton which is the idea of stability and how the body stand up and how all parts of the skeleton are supporting each other in nature to prevent the body from falling the same idea is employed by Calatrava in his projects.

## 5.2 FINAL REMARKS

This thesis explored the form generation process in architecture; it discussed some approaches of form generation;and how architects have dealt with each method. For achieving the aim of the thesis, a comprehensive study conducted on the form generation methods. It is found out that the origin of all processes and the main source of inspiration for creating a form since the ancient times is nature starting from the platonic solids which are originated from nature by Plato to the most complicated forms that cannot be generated without the digital software. The geometry relies on the concept of proportion such as the golden ratio so the forms that are inspired by the geometry can be considered as the forms of beauty. Some architects combined between the geometry approach and context, so they employed simple geometric forms as for the main form and the context of the surroundings such as the historical principles such as materials, textures and ornaments for the elevation. It is found out that architects such as Antoni Gaudi, Frei Otto, had created and discovered very sophisticated approaches before the existence of the digital tools they most were depending on physical hanging models to see the flow of forces in the vertical elements such as columns and ribs. Shukov was the first architect who depended on the hyperboloid forms that depends on the stacked sections of hyperboloid to help to gather the entire gravity load at the top of the structure. So, the idea of inspiration by performance depends on the form that has been designed and to which degree it resists the tension and compression forces. This approach is complicated but can be done by more simple materials such as physical models. Moreover, the form generation by nature was explored there is a difference between bio-biomimicry and bio-morphism what makes these two concepts different is that bio-morphism inspires the forms as symbolic it employs the exterior form of the natural creature while biomimetic is the process of employing the form and behavior of nature. In addition, morphogenesis is the idea of creating forms from nature by structure so it starts from structure to create the form. it is concerned with the shapes of tissues, organs and whole organisms in biology .Some of the complex form generation approaches were discussed which some of them have been discovered after the invention of digital techniques such as folding which is also called origami or the folding of paper .this method is used to reduce the load on the form also to create deployable and for aesthetical purposes. By integrating folding with graphical tools, it will increase the design process remarkably. Fluidity is a

sophisticated form generation technique that has been seen in baroque architecture. The fluid forms are more connected to some shapes of digital tectonics.Moreove, topology is defined as the study of specific forms that are not affected by variations in size or shape. It continues in a stable condition through the constant transformation of flexible alteration, such as stretching or twisting. It is found out that Non-Uniform Rational B-Splines or NURBS; can be used as a very effective technique for generating forms that contain topology of curves in architecture. Its curvature can be controlled by manipulating the location of its control points, weights and knots to generate diverse curves and surfaces. Algorithmic form generation as based on parameters is a clear series of orders which received data as input, processes them and provides its answer in output. In algorithmic architecture, it is endeavoured to make the parameters to influence the physical behavior of the building such as structure and materials. The parametric technique can be said is based on parametric design principles where the architectural form is generated and characterized throughout mathematical parameters and equations. In parametric design, the parameters of a specific design are proclaimed instead of the shape. By conveying various values to the parameters, diverse forms or configurations can be easily generated. Furthermore, form generation by analogy is another way of creating form regardless of the source of inspiration, whether from nature or any other sources. The concept of analogy and its types and the role of analogy in architecture were discussed. An analogy can be used as a technique in architectural design, especially at the first phase of the design process, which involves the concept, form generation, and structural issues of design ideas. Furthermore, analogy is the idea of transferring an idea from a known source to create a new form or solve a specific problem. Biological analogy was also discussed in chapter two it is found out that the organic analogy and anatomical analogy are the most preferable and used by architects the organic analogy consists of visual and functional analogy but both are interrelated in nature due to the responsibilities that each one has.in nature the visual analogy is the interpretation of the visual characteristics of the organism and the functional is the main reason why the organic form exists, for example, the relationship of the legs with the body. The function of the legs is to support and provide movement to the body, so if one of them detached, the other becomes useless. However, in architecture, the most used between visual and functional is visual analogy which can be said is bio-morphism.It is possible to employ the functional

part of the organism in architecture by the biomimicry approach because the function is the behavior as it is mentioned in chapter two the idea of bio car form was inspired by the fish box and structure was inspired by the growth of tree patterns. The anatomical analogy is the most used by the architects and engineers for the ideas of statics and the weight by comparing the skeleton of the living creatures to the structure of the buildings. And the idea how the skeleton holds up the body of the organism and how the building stands up so both visual and anatomical analogy is employed in architecture. Also, the structures in nature and architecture are mentioned briefly, which are tree-like structure, shell-like structure, web-like structure, pneumatic structures and skeleton-like structure. It is found out that the structure in nature whether organic or inorganic, animate or inanimate has been changed since its creation due to the physical forces; that affect the generative process of every form in nature. They also affect the efficiency of the form in terms of their use of materials, lightness, rigidity, and stability. It is also found out that any structure or form in nature with its aesthetic, functional, and structural concepts can be used as a model for architectural innovations by transferring concepts from the discipline of nature to the architectural discipline by abstracting the forms. In chapter three the architectural production of Santiago Calatrava is discussed in terms of the types of movement that are inspired by the form of the human and animal. Furthermore, the types of movements are utilized as motivational and inspirational sources for producing forms which are functional and symbolic. Functional movement can be achieved by observing the movement in the human and animal body such as unfolding, rising, revolving. on the other hand, symbolic movement can be achieved in two ways, which are, structural instability, and S-form. It is possible to achieve structural instability and s-form together because both ideas depend on balance. Furthermore, the term counter position which is the process of describing a body suspended between the past and the future can include two types of symbolic movement which are the structural instability and S-form. Both ideas depend on the human body the only difference is in structural instability the human body in any balanced configuration is captured while in the S-form only the idea of the twisted body in a balanced configuration is captured.

Within the aim of this thesis the following topics are suggested to be explored for the future studies:

-Developing a method for form generation for the students of architecture.

-Analysis of more strctures of Calatrava and proposing a designed strategy based on his architecture for the students of architecture.

-Analysis of other architect's works and converting their architecture to a design strategy.

Finally, nature as a constant source of knowledge with the aid of the technology can be used to solve the structural and form in architectural. The natural forms are unique because they have been created and affected through millions of years by the physical forces that have affected their form, efficiency, and stability.By observing the secrets that exist in nature, the form and structure can be generated through a specific strategy.

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