BIO-INSPIRED DESIGN OF A KINETIC NODE FOR ADAPTABLE STRUCTURES

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Melodi Simay ACAR

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We approve the thesis of **Melodi Simay ACAR**

Assist. Prof. Dr. Koray KORKMAZ
Supervisor

Prof. Dr. Sc. Rasim ALİZADE
Committee Member

Prof. Dr. H. Çetin TÜRKÇÜ
Committee Member

01 March 2011

Assoc.Prof. Dr. Serdar KALE
Head of the Department of
Architecture

Prof. Dr. Durmuş Ali DEMİR
Dean of the Graduate School of
Engineering and Sciences

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“The real ethical question is not “to whom I responsible for?” but rather, “what sort of world do I want to live in”

Immanuel Kant

“All natural events, all natural rules are the same for the systems that coordinate in a systematically movable order.”

Albert Einstein

“The creation of living organisms through the morphogenetic process, the creation of matter, the creation of stars and galaxies from nuclear fire, the constant creation of particles by interaction with another. Therefore, the knowledge of order-creating processes is essentially important in the understanding of our world.”

Christopher Alexander

“If architects designed a building like body, it would have a system of bones and muscles and tendons and a brain that knows how to respond. If a building could change its posture, tighten its muscles and brace itself against the wind, its structural mass could literally be cut in half.”

Guy Nordenson,
Ove Arup and Partners

“It is possible since it exists.”

Melodi Simay Acar

ABSTRACT

BIO-INSPIRED DESIGN OF A KINETIC NODE FOR ADAPTABLE STRUCTURES

The architectural design should no longer consider just in terms of today's demands, but also the life cycle and the further requirements of the built environment. The design process should consider the adaptation to the changing conditions which can be in terms of the building usage, environmental factors or even in the changes of sociological demands.

Rapid change in activities of modern society and building technologies, has led to the need for adaptable spaces. Those spaces can be obtained by the adaptable structures which have potential for using our resources in efficient way and also for responding to the era's needs. This can be achieved with kinetic structural systems and learning adaptable structures from nature.

Nature has always inspired humanity by solving the basic needs with minimum material and sustainable solutions. Observation of nature enables architects and engineers familiar with highly developed structures and lead to the creation of new forms. The designs that are produced by learning from nature lead to practical engineering solutions in terms of sustainability.

The aim of this research is to propose a joint; kinetic node with multidisciplinary approach. This kinetic node is designed by inspiring from the minimum energy shape configurations and the structural orders in natural structures especially the cell membrane and analyzing the joining details of space truss structural systems and the geometric principles of Bricard linkage mechanism. This new kinetic node gives capability to construct variable static and dynamic structural systems while constructing in different structural orders.

ÖZET

UYARLANABİLİR STRÜKTÜRLER İÇİN DOĞADAN ESİNLENEREK TASARLANAN HAREKETLİ DÜĞÜM NOKTASI

Sürdürülebilir mimari tasarım sürecinde, sadece bugünün koşullarını değil, tüm üretim ve kullanım süresini ve ayrıca ileriye dönük ihtiyaçları düşünmek gerekmektedir. Bu nedenle, değişen koşullara uyum sağlayabilen tasarımlar günümüzde önem kazanmaya başlamıştır. Değişen koşullar, hem yapının kullanım amacı hem çevresel etmenler hem de sosyolojik değişimler olabilir. Bunlar bir bütün olarak ele alınmalıdır.

Strüktür canlı veya cansız her maddenin olmazsa olmazıdır. Bu nedenle değişime ayak uydurabilen strüktürler, hem sınırlı kaynakların verimli şekilde kullanımına, hem de dönemsel ihtiyaçlara cevap sağlayabilirler.

Doğabilimi birçok disipline olduğu gibi, mimariye de birçok alanda ilham kaynağı olmuştur. Doğadan öğrenerek oluşturulan tasarımlar, sürdürülebilirlik bağlamında etkin tasarımlar oluşturmaya imkan sağlar. Bugüne kadar doğadan esinlenerek tasarlanmış çoğu strüktürler mimariye yeni çözümler getirmiştir. Doğa, belirli bir dengeye gelinceye kadar strüktürünü minimum enerji kullanarak, değişen koşullara adapte eder. Bu en minik yapı taşı atomdan, ekolojik sistemlere kadar her düzeyde geçerlidir. Fakat günümüzde hızla değişen ihtiyaçlara ve gelişen teknolojilere mimari yapılardaki statik çözümler yeterli gelmemekte ve uyum sağlayabilen mekan arayışları ortaya çıkmıştır. Bu arayış, kinetik strüktür sistemleri ile daha etkin şekilde vücut bulmaya başlamıştır.

Bu araştırmanın amacı, değişen koşullara uyum sağlayabilen strüktürler için bir düğüm noktası tasarlamaktır. Bu hareketli düğüm noktası, çok disiplinli bir çalışma yaparak; doğanın minimum enerji kanunuyla oluşturduğu formlardan ve strüktürel düzenlerden ilham alarak, uzay kafes strüktürel sistemlerinin birleşim detaylarını analiz ederek, Bricard mekanizmasının gerektirdiği geometrik ilkeler sayesinde tasarlanmıştır. Sonuç olarak, bu düğüm noktasını farklı düzenlerde kullanarak çeşitli statik ve dinamik yapı sistemleri oluşturulmuştur.

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CHAPTER 1

INTRODUCTION

1.1. Definition of the Study

In the rapidly changing environmental conditions, holistic way of thinking in design process is a must in architecture. Many architects inspired from nature, such as Antonio Gaudi, Frank Lloyd Wright, Frei Otto, have studied the behaviour of the natural structures and generated new theories. The understanding of biological models can lead to more ecological designs and new efficient structural systems. For architects, the struggle of survival in nature can be taken as a design strategy. Charles Darwin emphasized that the surviving of the living organisms always depend on their ability to adapt to the changing environments. This theory can be applied to the main concept of kinetic architecture. Recent years, the need of adaptable forms in architectural applications is gaining their importance in respect of changing environmental conditions.

Respecting the environment in architectural design process is passing through a design concept which takes consideration of renewing the energy, the opportunity to reuse the land, the flexibility of recycling the building parts and the adaptation of space.

Jenaine Benyus declared in a conference that the biggest design challenge is finding the way how creatures did till today, without destroying the place that will take care of their offspring. Since, life sciences has already been the case for solving problems for humanity for centuries, yet recently used in technological development and in architecture. The designs that are concerned as bio-inspired are mostly mimicking partially but, deeper analysis provide benefits for more efficient solutions. A deeper analysis of the natural structures mostly leads to the main concept of bio-inspiration – to ecologic and sustainable design. Sustainable building conscious considers the whole life of the building from environmental quality to long term costs. In the light of sustainability, the architectural design should consider not only ecologic conscious approach to the design of the built environment but also the life cycle of the building which have capability to adapt to the changing conditions. It has always been a dilemma if form follows function or function follows form. Indeed, in nature, every element is in relation to the whole and the function and form correlation gives capability to adapt to the changing conditions. The structural orders in natural structures dynamically change and gain stability in respect of the function for the whole system. For this purpose, the design of the structure should be no longer static, but dynamic.

Structure is the main entity for a living or non-living object to exist. Despite the man-made structures are always searching for stability, adaptable structures can give more benefits to the changing conditions of life. Life itself is in motion from the basic natural building blocks, molecules, biological macromolecules, cells and the complex organisms. In nature, it is literally accepted that the form is a direct response to the pressures acting on the natural structures. From that view, we can say that for every organism, it is seen that their adaptation depends on their ability of motion.

Plants adapt to environment by the ability of their components. The plant need to response to the sunlight, gravity, presence of water and touching for their survival. Also for animals, the ability of their component movements is highly vital such as, the control of muscles by the neuron movement which results in a kinematic movement of bones. Free body movement is also for adapting to the need, for food fertilize, or protection. Briefly, Zuk and Clark (1970) emphasized that the form change is the main adaptive aspect and they pointed that the form change occurs in any period and any scale in nature. “Form may change very slowly by evolution, moderately fast by the process of growth and decay, and very fast by internal muscular, hydraulic or pneumatic action.”

Zuk and Clark created a schema for the set of pressures acting on the form basically which is shown by the illustration in Figure 1.1 and categorized in two categories; physical and non-physical pressures. Physical pressures are the physical activities - the usage of a space, man-made networks - the transportation networks and power systems, and environmental influences - energy, land, water and ecology. The non-physical pressures are the significant pressures which vary from the human response according to mental, physiological, sociological, economical conditions and cultural bases. The non-physical pressures affect the development of the physical form. Between the pressures and form, technology plays a huge role for supplying efficient responses to the pressures. Technology has given wide possibilities for solving the engineering problems and also the technological outcomes are developed from the physical and non-physical pressures directly.

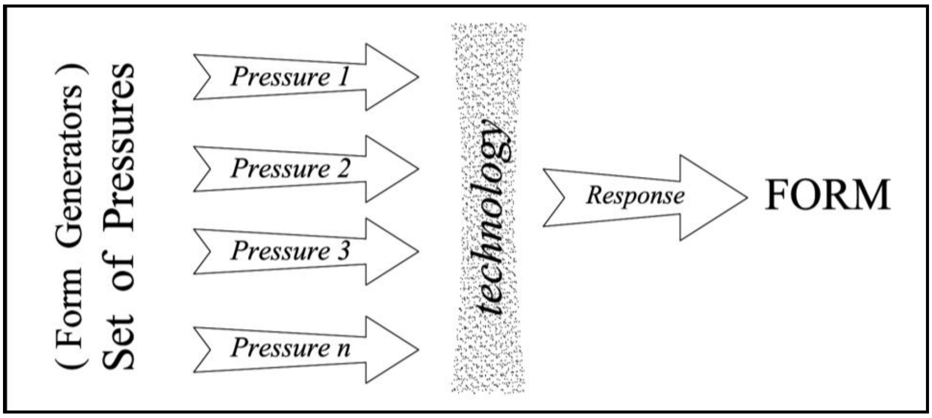


Figure 1.1. Set of pressures acting on the form
(Source: Zuk and Clark, 1970)

The function (physical and non-physical pressures) and form cannot be thought separately, they are interrelated. For architectural design, function, space, structure and form create the whole. Form is the reflection of the structure and the space that the structure generates serve for the function that is required (Senosiain, 2003).

In the dictionary of architecture and Landscape architecture by Curl (1999), kinetic architecture is defined as;

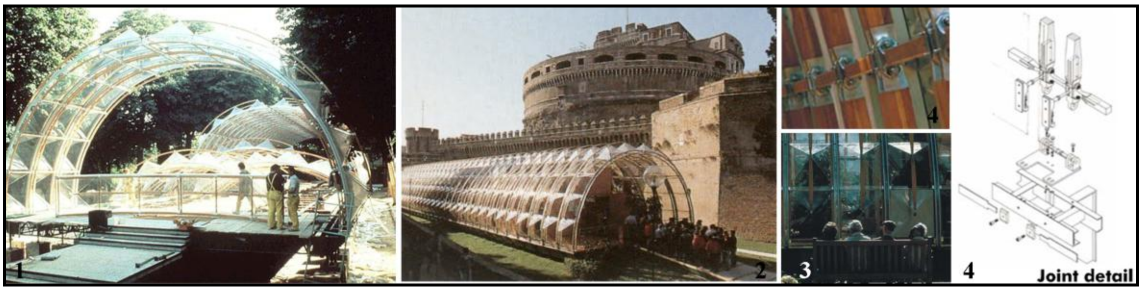
> Architecture evolved in the belief that the static, permanent forms of traditional architecture were no longer suitable for use in times of major change. Kinetic architecture is supposed to be dynamic, adaptable, and capable of being added or reduced, and even disposable.

This design concept corroborates with the main inspiration from nature; that every natural structures adapt to the changing conditions respect to their functions. The technological outcomes provide possibilities for developing new structural systems adapting to changing conditions and functions.

Motion in architecture is the basic and main need for adaptation; such as to relocate, growth, change and dispose. Zuk and Clark (1970) named the possible and applied applications in “Kinetic Architecture” as reversible architecture, incremental architecture, deformable architecture, mobile architecture and disposable architecture.

In reversible architecture, the structure can be erected at the same location or different locations in the same configurations without any damage to the structure. Reversible architecture had been applied to small-scale to large scale structures. Geomag, a magnetic construction toy, is given as an example for imaging the structural system in Figure 1.2. Also in Figure 1.3 the IBM Travelling Pavilion which travelled around Europe in 1980’s is designed by Renzo Piano Workshop group can be given as an example to reversible architecture.

Figure 1.2. Bars and spherical nodes of Geomag give multiple configurations.
(Source: Flickr, 2010; Morphocode, 2010; Kidestore, 2010)



1. Construction of Pavilion, 2. Pavilion in Milan, 3. Structure view 4. Joint details

Figure 1.3. IBM travelling pavilion in Europe tour, 1982-1984
(Source: Agisoft, 2011; Vestaldesign, 2011; Umd, 2011)

In incremental architecture, the possible variability of the system should be considered in advance for the future needs. The structural system is designed for adapting to the era’s needs by adding, subtracting or switching some parts. Increment also provides new spaces for new uses. The modular components which are designed by Peter Pearce can be given as an example for incremental architecture (Figure 1.4).

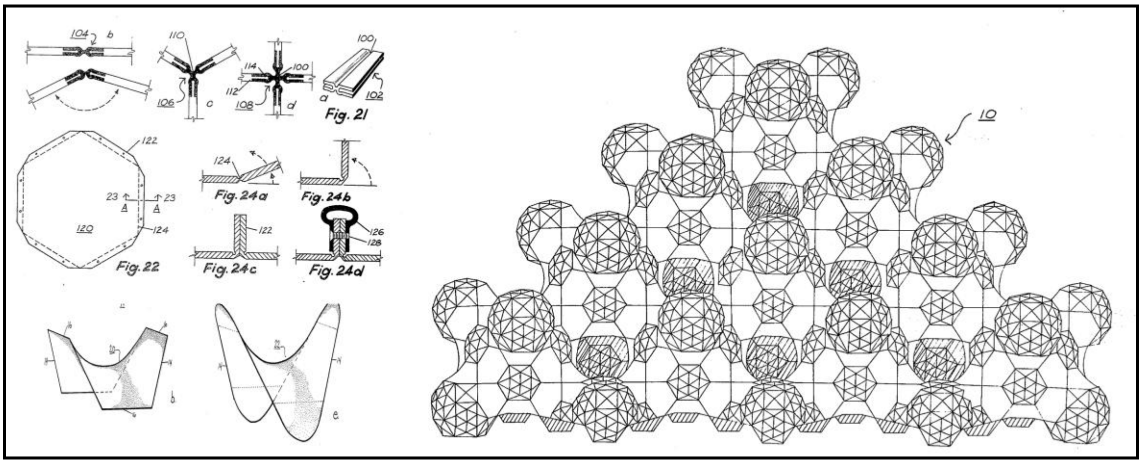


Figure 1.4. Peter Pearce patented for modular curved surface space structures
(Source: United State Patent No: 3931697)

Deformable means that the whole of the system has capability of change without any addition or subtraction. Pinero’s prototype (Figure 1.5) and Hoberman’s adaptive shading system in London (Figure 1.6) can be given as examples for deformable structures. The natural structures can be thought as deformable as they react to the pressures by their forms. Deployable structures, such as foldable, pneumatic and bar structures can be classified in this concept.

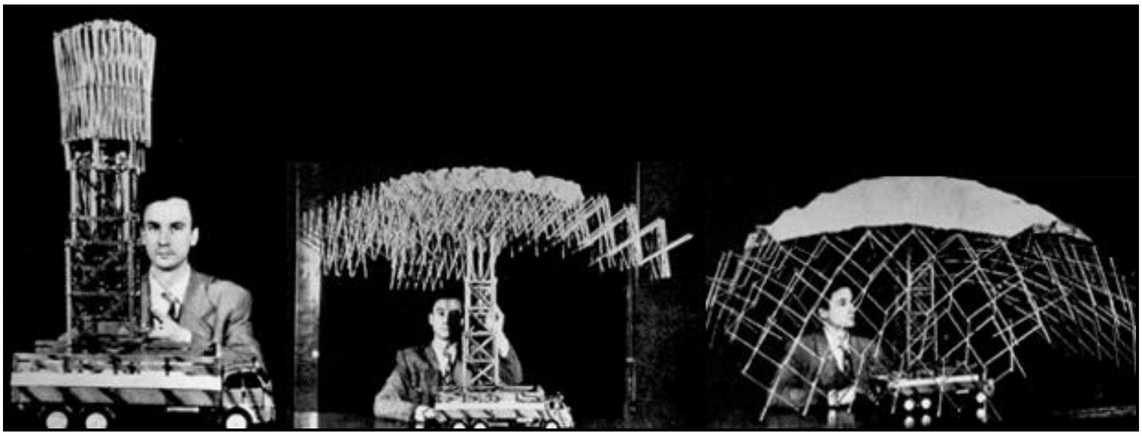


Figure 1.5. Pinero showing his prototype
(Source: Robbin, 1996)

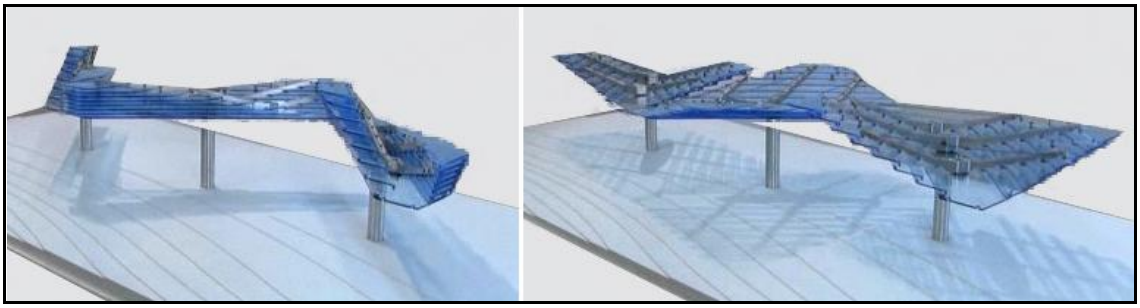


Figure 1.6. Adaptive shading Esplanada, in London, 2006
(Source: Hoberman, 2011)

Figure 1.7. Small capsule building for office usage
(Source: Arnewde, 2011)

Mobile means the total unit has possibility to relocate as given an example in Figure 1.7. Dmva- architecten designed a small capsule building for the office usage and since the size is like a caravan, it can move to any site.

Disposable architecture is short lived architecture such as igloos. The classes till now are defined for kinetic architecture as searching for a new form for adapting to the changing conditions, by adding, subtracting, transferring or deforming. But disposable architecture is for mainly dispose the components of the built architecture.

Architects and engineers mostly consider about space enclosing starting from the need of shelter. The development of technology, capability of researches and seeing through the systems more micro level lead to explore deeper than before. In any reversible, incremental, deformable, mobile architecture, the changes may be done by addition, subtraction and substitution of parts and with the deformation of the structural system. The structures which are seen as extraordinary in the recent era, are produced with the deeper analysis by asking “what, why and how” in the design process. For adaptable structures by asking how the nature adapts to the changing conditions, the structural order and minimum energy configurations lead to mechanical design process for a kinetic node design. The connectors of the structural systems - nodes present a special and critical considering point.

There are lots of ways while approaching to a solution for a defined problem. Bio-inspired design process as having the potential for leading to ecologic-conscious designs is one of the ways to approach to a solution for adaptable structures. Therefore, with the bio-inspired design process, the study will focus on the correlation of structure and function within the multidisciplinary approach of biology, geometry and mechanics for adaptable structures that can be applied in architectural field.

1.2. Aims of the Study

The holistic approach to design problems is maintaining its meaning by considering the whole besides its parts with a multidisciplinary method for efficient design solutions. The bio-inspired design process is a multidisciplinary research field for technological outcomes in many disciplines. This study focuses on a structural design solution for adaptable structures within the multidisciplinary approach of biology, geometry, mechanics and architecture.

The main aim of the study is proposing a kinetic node by studying the nature's building code and their possible integration with mechanical aspects, for defining variable volumes in the concept of adaptable architecture; reversible, incremental, deformable and mobile. This study also aims to highlight the importance of bio-inspiration in the design process. The proposed kinetic node which is inspired by the minimum energy shapes gives more challenges than it was expected by maintaining stability when composed in a sequence such as in the structural order of nature. The guidelines of the bio-inspired design of a proposed kinetic node have potential for interactive, responsive and smart building structures for future applications.

1.3. Methodology and Outline of the Study

Bio-inspired design process which is a multidisciplinary approach, supply efficient solutions when considered deeply. However, there is still no proper way of integrating engineering and nature into a design process. In this research, the bio-inspired design process is analyzed with the biomimetic map and synthesized from three disciplines.

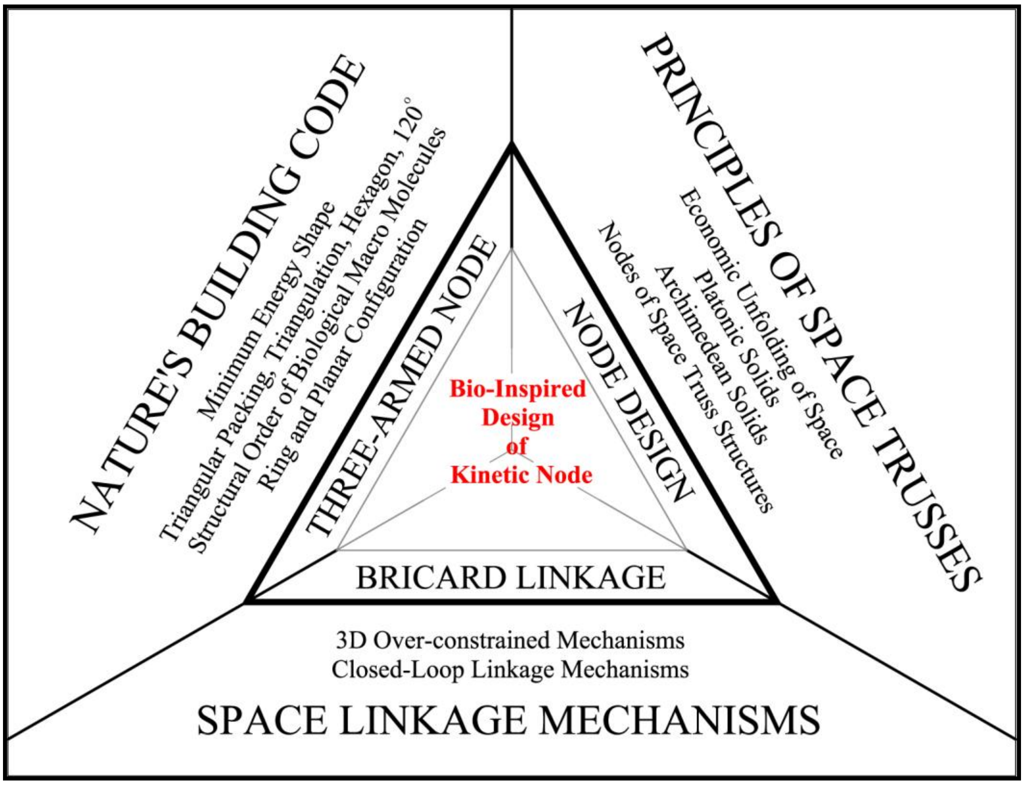


Figure 1.8. The bio-inspired design process of a kinetic node

Figure 1.8 shows the methodology for bio-inspired design of a kinetic node by the nature's building code from the discipline of biology, by the principles of space truss systems from the discipline of architecture and by space linkage mechanisms from the mechanism science.

In chapter 2, the importance of bio-inspiration and bio-inspired design processes for technological outcomes will be defined. The 'Biomimetic map' by J.F.V. Vincent will be discussed and developed for the aim of adaptable structures and their components.

In chapter 3, structural systems in architecture will be defined. Space truss systems will be analyzed deeply because of their lightweight and high strength properties obtained by three dimensional behaviour. From this perspective, the understanding of the components; nodes and axial members of space truss structures are emphasized for the design process through enclosing space.

In chapter 4, the minimum energy shapes and the structural order in the components of cell membrane will be analyzed. The outcomes from the analysis will be the inputs to biomimetic map for applying in to the manmade structures.

In chapter 5, the mechanism design process will be defined. For maintaining three dimensional behaviour, the Bricard Linkage mechanism from 3D over-constrained mechanisms will be analyzed. The mobility that the Bricard Linkage provides, gives possibilities of linking the units in different orders.

In chapter 6, the analysis from the minimal-energy configurations, the structural order in natural structures, the importance of nodes for space truss structures are integrated with trihedral case of Bricard linkage for the geometrical properties of the kinetic node for adaptable structures. Structural analysis of the codes that nature provides leads to a kinetic node which is a three-armed node intersecting at 120^o. Also, the structural order of the biological macro molecules inspires structural systems for stable and dynamic structures.

The illustrations of the figures are drawn by Autocad and the illustrations of mobile node and stabile-dynamic structures are modeled in Solidworks.

This thesis is highly inspired by the book 'Kinetic Architecture' by William Zuk and Roger Clark, the unlimited perspective of R. Buckminster Fuller and IL publications which are dedicated by Frei Otto, and the studies on bio-inspiration by Julian F.V. Vincent and predominantly the infinite knowledge of nature.

CHAPTER 2

THE BIO-INSPIRED DESIGN PROCESS

Bio-inspiration from nature to further technological outcomes - practical engineering solutions, has been named in many terminologies such as “Biomimetics”, “Biomimesis”, “Biomimicry” and “Bionics”. Biomimetics is a multidisciplinary approach by understanding, analyzing and abstracting for applying biological principles to human designs in a wide diversity of other domains like electronics, informatics, medicine, biology, chemistry, physics, mathematics, art, architecture and many others.

2.1. “Bio-inspiration” as a Scientific Term

From the historical standpoint, D’Arcy Wentworth Thompson wrote his most famous work “On Growth and Form” in 1917 in which he tried to illustrate the correlations between biology and mechanical forms by using mathematical formulas.

> An organism is so complex a thing and growth so complex a phenomenon that for growth to be so uniform and constant in all the parts as to keep the whole shape unchanged would indeed be an unlikely and an unusual circumstance. Rates vary, proportions change, and the whole configuration alters accordingly (Thompson, 1961).

This book as presenting a descriptive catalogue of natural forms and their geometric descriptions influenced many disciplines, mathematicians, biologists and architects.

Otto Schmitt, biophysicist, is the first person who coined biomimetics in 1950’s. Biomimetics is originally coming from bios-life and mimicry-imitating “The mimicry of life”. The answers to the problems that Otto found in natural world fascinated him deeply. By the potential of mimicking nature in the form of machines and processes can lead him to help humankind (Otto-schmitt, 2010).

After Otto Schmitt, the word bionic is coined by Jack Steele in 1958. Bios- life, ic- like, in the manner of “like life”. Ken Yeang (1995), in his book, ‘Designing with nature’ he finishes his words by the importance of bionics and its rich source for design inventions for ecologic design.

However, the first codification of Biomimicry as a field of research is from Jenaine Benyus. Biomimetics is a multidisciplinary approach by understanding, analyzing and abstracting for applying biological principles to human designs in a wide diversity of other domains like electronics, robotics, informatics, medicine, biology, chemistry, physics, mathematics, art and architecture and many others. Benyus (1997) declared that biology can be a model, measure and mentor for all disciplines.

Nature as Model: Nature serves as a bridge to engineering and natural sciences for solving the human needs by analyzing and taking inspiration or imitating from the natural models.

Nature as Measure: Nature provides a perspective of ecological standards for judging the rightness of the innovations. Nature has evolved for billions of years what works, what is appropriate and what lasts.

Nature as Mentor: Nature evolves holistically, depending on everything around. Viewing and valuing nature is not for mimicking but for learning from it.

As we see nature as the mentor, our relationship with our environment will change. Jenaine Benyus (1997) pointed in Biomimicry - Innovation Inspired by Nature - that our challenge is to take these time-tested ideas and echo them in to our lives. It is the point, when we come not to learn about nature but to learn from nature, by integrating with the ecosystem.

There are mainly three levels of inspiration while designing by mimicking from nature.

1. Mimicking of Natural Form: The first level is the natural form abstraction that means directly copying the form of a specified natural model by looking at external characteristics and it may or may not yield to something sustainable.

2. Mimicking Process: Deeper biomimicry adds a second level by analyzing how the natural process of the model is made and what it does.

3. Mimicking the Natural Ecosystem: If abstraction goes deeper by questioning what the model is for, it adds the third level. Since the model is a part of a larger system, by analyzing how each product fits in to that system, mimicking yield to something sustainable (Biomimicryinstitute, 2010).

While analyzing the natural ecosystems in which the model is a part of a sustaining biosphere, the inspiration begins to work to restore rather than deplete the earth and its community. The reason of bio-inspired design process is mainly for the similar goal for natural organisms and engineers, which is searching the possible cheapest way – even in terms of energy or in terms of money. Whenever we can manage to mimic all the three levels, the technological outcome will begin to be as the well-adapted organisms have already done, which is to create conditions conducive to life (Biomimicryinstitute, 2010). Also, Janine Benyus mentioned in a conference that the biggest design challenge is finding the way how creatures did till today, without destroying the place that will take care of their offspring (Ted, 2010).

Today, the significance of the environmental aspects comes ahead, but still the consideration points are wrong-headed for the technological outcomes and applications. Because of this, bio-inspired design process come into prominence even not figured out scientifically yet.

2.2. Bio-Inspired Design Processes

The fact that biology is chosen as an inspirational source for unlimited possible new innovations is because of the potential it offers to create a more ecologic built environment. For a sustainable development, biologically-inspired design, BID has gained its significance. The bio-inspired innovation design process of the technological outcome has been classified in two main categories. First one is to define a human need and design problem in the way how the organisms solve is "design looking to nature". The second is to identify a particular structure or function in an organism and translate it into human designs is "biology influencing design". Helms, Vattam and Goel (2009) classified the approaches as problem-driven approach and solution driven approach in their study on their cognitive study of BID. Even, there are few cognitive analyses about BID process, yet recently the productive BID process could not be figured out yet in scientific field. A growing international research is being done on biomimicry, despite the lack of a pure defined approach for bio-inspired design is still a huge barrier for productive solutions (Vincent et al., 2006). However, even the process is problem-driven or solution driven, the technological outcome's capability is vital in the biologically inspired design process.

The first approach, design-to-biology, which is called as direct approach in which the inventor identifies the core function and then searches for an appropriate answer from organisms. The second approach, biology-to-design, which is called as indirect approach is a biological phenomenon request a new way to solve a human design challenge.

2.2.1. Problem-Driven Approach: Design Looking to Nature

The Problem-Driven Approach, design looking to nature, is mainly seeks to define the human need and the nature of the design problem and the context of its creation and use in the way how the organisms solve. Direct approach starts with identifying the problem of the design, then finding a proper biologic model for technological outcome. The technological outcome's success depends on how deep the model was analyzed.

An example from industrial field is the bionic car as shown in Figure 2.1, designed by Daimler Crysler is one of the examples for direct approach. In order to obtain large volume, a highly aerodynamic fish, boxfish, is taken as a model for form abstraction by total mimicking. Also, the computer modelling method based upon how trees are able to grow in a way that minimizes stress concentrations is mimicked for the structure of the car. With these observations from natural models, because of the aerodynamics of the car, it consumes less fuel and also because of the efficient structural configuration, less amount of material is used to build up the car. On the other hand, the usage of car is not a new approach for transportation (Zari, 2007)

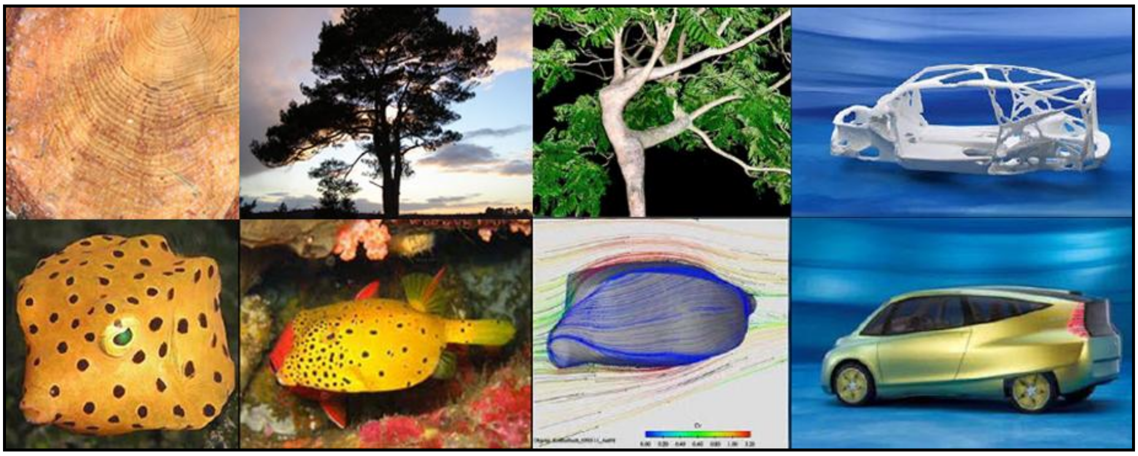


Figure 2.1. Daimler Crysler Bionic car inspired by box fish and tree growth (Source: Zari, 2007; Islandream, 2010; Whisperingcraneinstitute, 2010)

The other example is from textile field. In order to obtain less frictional swimwear, the shark skin detail is taken as the model as shown in Figure 2.2. An example for direct approach from the architectural field is the Beijing Olympic Stadium which is abstracted from bird's nest form. Even the bird nest is a seasonal and disposable model, only form is taken as the model in design process as shown in Figure 2.2.

Figure 2.2. Shark skin applied to swimwear and bird nest to the Olympic Stadium
(Source: Robinseab, 2009)

From these examples, we can identify that direct approach do not lead to sustainability as the biological model potentials are not well-analyzed since the basic need is pre-defined.

2.2.2. Solution-Driven Approach: Biology Influences Design

Solution-driven approach seeks to find solutions through defining the general principles of natural design and using those as guidelines for development progression. This approach leads to developments in the specified fields, as analyzing how the nature solves the problems; the designers begin to learn from nature, which is fundamental for bio-inspiration.

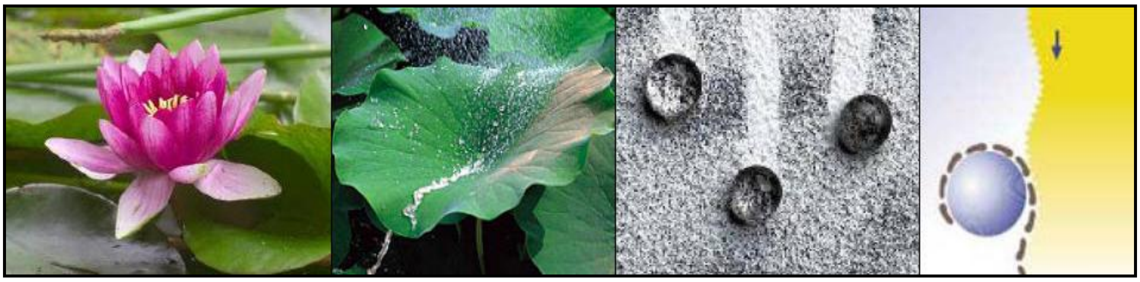
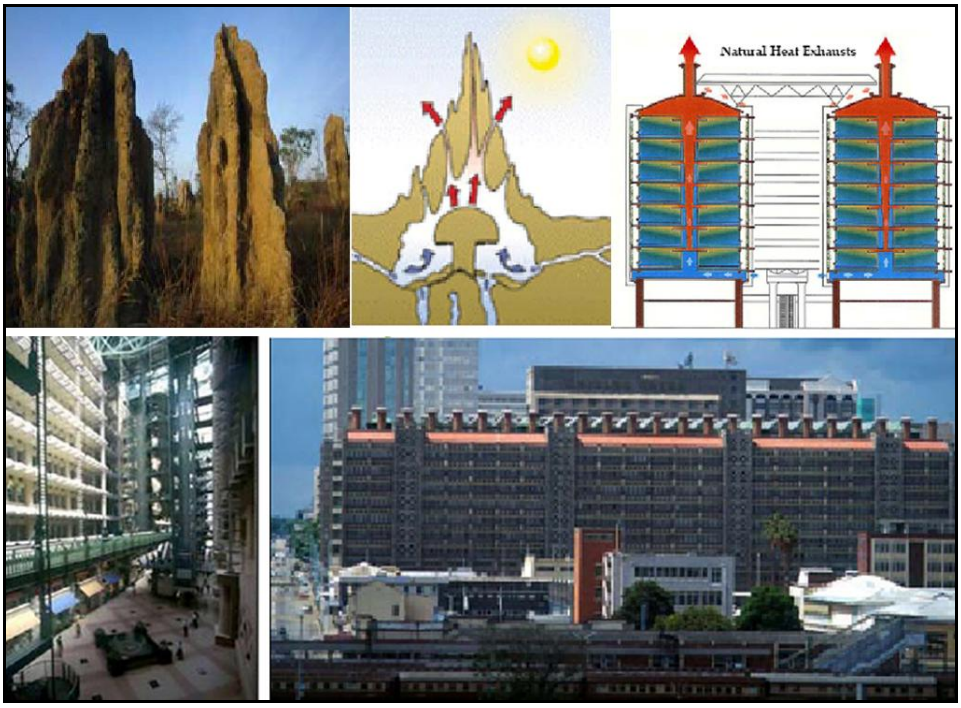


Figure 2.3. Self cleaning learnt from lotus
(Source: Zari, 2007)

An example from industrial field is the ‘Lotusan’ which is a self-cleaning paint. Whenever the self-cleaning properties of the lotus leaf are understood well enough, the notion of self-cleaning buildings begins to be questioned. In that respect, the ‘Lotusan’ paint come to life as an innovation for progression (Figure 2.3).

Figure 2.4. Learning From Chimpanzees How to Heal Ourselves
(Source: Biomimicryinstitute, 2010)

Another example is from medicine field. Mostly the medicines are derived from plants, and still lots of plants have not examined. In that case, watching the nature, as chimpanzees seek out trees from the Vernonia genus when they are ill, lead to find the chemical compounds promising medical applications as shown in Figure 2.4 (Biomimicryinstitute, 2010).



1-2 Termite Mound and its Ventilation system, 3. Building Ventilation Schema,
4-5. Eastgate Centre, Zimbabwe

Figure 2.5. Ventilation System learnt from Termites, The Eastgate Center
(Source: Robinseab, 2009)

An example from solution-driven approach to architectural field is The Eastgate Building, an office complex in Harare, Zimbabwe shown in Figure 2.5. Learning from termites’ mounds about how to create a sustainable building which has an air conditioning system such as in mounds that have self-cooling and maintain the temperature inside within one degree, day and night - while the temperatures outside change from 42 °C to 3 °C. By analyzing the ventilation system in mound, the building uses 90% percent less energy for ventilation than conventional buildings (Biomimicryinstitute, 2010).

Briefly, most of the indirect approach is a design process of choosing the biological model, structure, learning the specific ability of the model, and applying to the desired field. Since, this process starts with learning the biological model, the technological innovation depends on how deep the research analyze the model. Deeper analyzes lead to more ecologic solutions as the main concept of biomimicry.

2.3. Bio-inspiration for Technological Outcomes

It is hard to define the origins of bio-inspiration since men has looked and abstracted from nature for more than 3000 years. The artifacts are mostly abstract superficially the natural forms by just their visible characteristics, but analyzing the natural models deeply can lead to more sustainable innovations.

2.3.1. Biomimetic “Map”

Julian F.V. Vincent (2001) described biomimetics as the technological outcome of the act by using ideas from nature. Vincent who was a professor in Center for Biomimetic and Natural Technologies, Department of Mechanical Engineering at University of Bath developed a biomimetic map for describing the technological transfer from biology to engineering. There are databases from patent literature but the biological models can be more fruitful for technological innovations.

Vincent (2002) developed the map “the general concept is that the further down one can move from the origin (top left) the more general and therefore more powerful the concept will be.” Figure 2.6.a shows the general way and Figure 2.6. b shows more specific way relating to structure and materials.

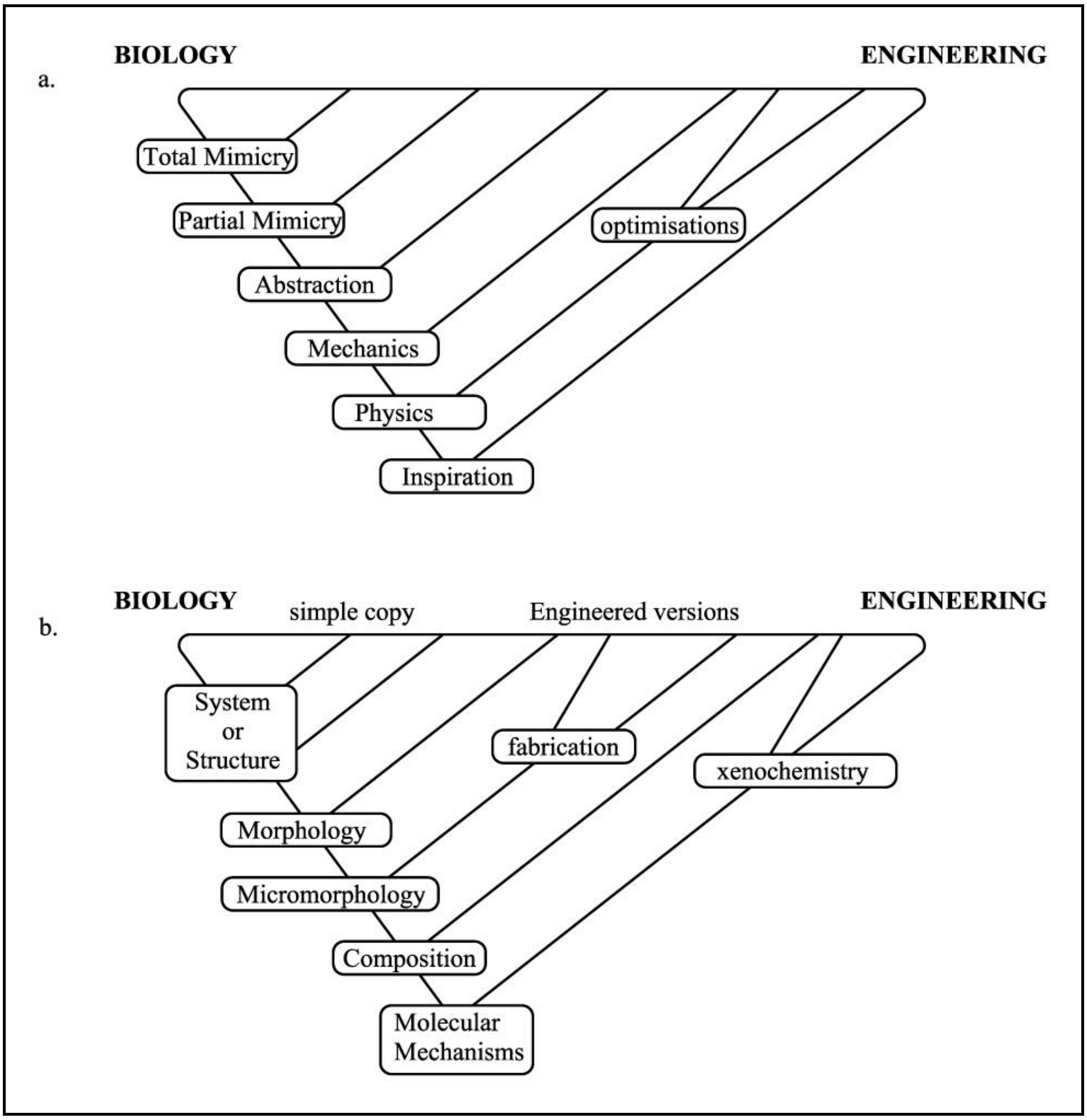


Figure 2.6. General concept of Biomimetic "map"
(Source: Vincent, 2002)

For illustrating the graph with applications from architectural and medicine field, Figure 2.8 shows, the deeper analysis adds new properties to the starting point. As in Figure 2.7, the folded structures have potential to apply for roof constructions and by analyzing deeper, with the potential of Miura-ori, origami structure can be seen in the convertible umbrellas and by adding the emergent properties of shape control and sensing mechanisms, the folded structures can be applied even for stents.

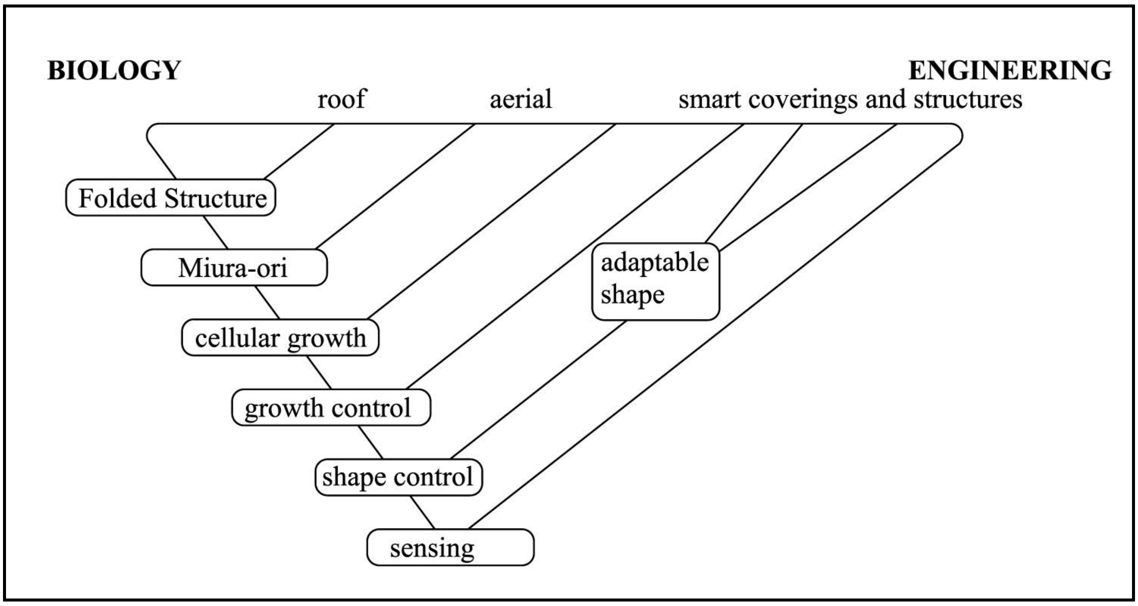
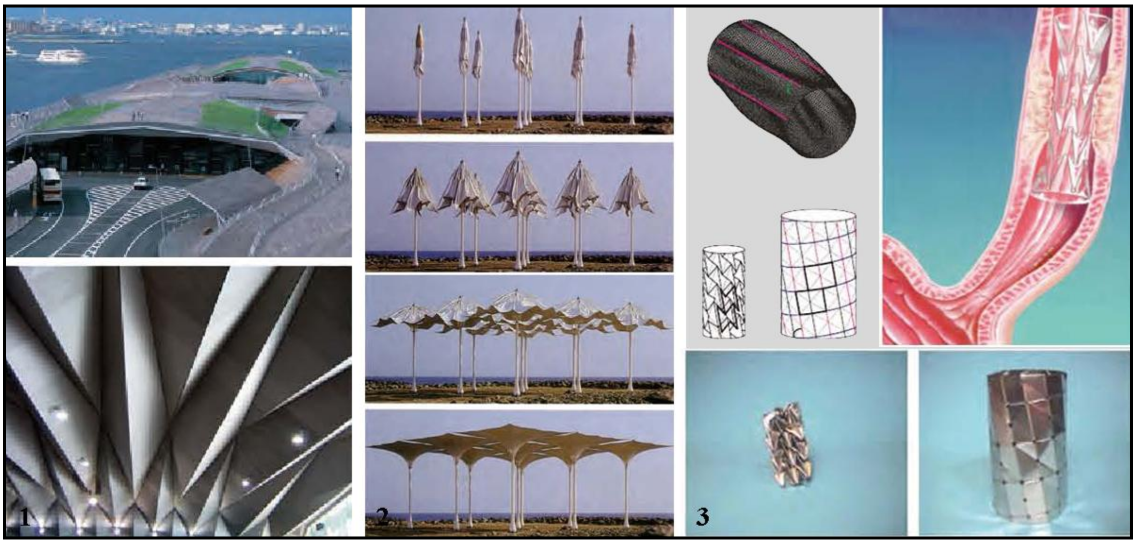


Figure 2.7. Biomimetic map of folding structure of leaves and flowers
(Source: Vincent, 2002)



1-Yokohama Port Terminal by FOA, 2-Convertible umbrellas by Frei Otto, 3- Expandable Stents

Figure 2.8. Folded structures applied in different disciplines
(Source: Sorguç et al., 2009)

As an example of analyzing the leaves of the flowers, the more that the research goes deeper, as understanding the mechanism of how the leaves folds besides morphologically, the more the innovation turn into powerful design for applying to the other fields such as graphed in Figure 2.7 and given examples in Figure 2.8. If this analysis can be applied to architectural field, the folded structure will have potential to response to the pressures and adapt to the changing conditions. In that case, this technological outcome turns into more powerful.

Vincent with these graphs, points that the more basic the abstraction, the more powerful its development. That means dealing more with the basic level, since in the entire world, the laws of physics are common to all living and non-living objects, this level generates the common ground for a powerful transfer of information between disciplines (Vincent, 1998). Besides, to understand the basic such as molecular configuration, the researcher should not look partially to the whole.

2.3.2. Bio-Inspired Design Process based on Biomimetic Map

Gattam, Helms and Goel pointed out that there is not a proper way of bio-inspired design process, it is mainly not forcing ourselves to understand deeper. Direct approach and indirect approach is defined in the literature but for an efficient design of bio-inspired technological outcome should be driven from both perspectives, as seen in all levels of biological organizations. In the rapidly changing environmental conditions, it begins to be important to have innovations in the light of ecologic conscious. From this perspective, biology is giving opportunities for development progression. The nature has a huge database for reaching ecologic solutions to the human needs. From the examples given above for direct and indirect approaches, the main difference is the analysis of a biological model learning process. However, the main objective for a sufficient technological outcome is the path to abstract from nature by learning deeply from it. As Vincent highlights the way for technological outcomes is by deeper analysis, the biomimetic map provides a way for design process.

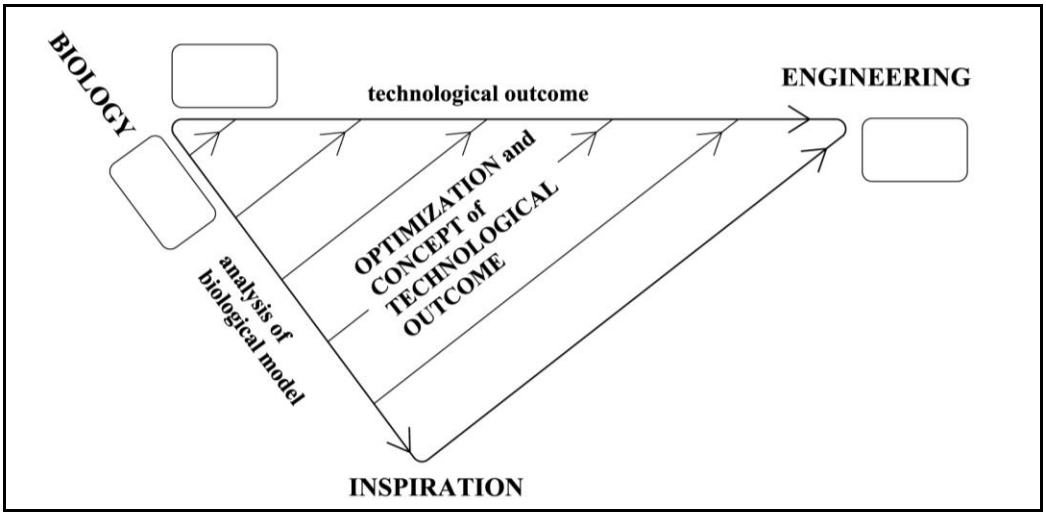


Figure 2.9. Biomimetic map for the BID Process of this study

Therefore, firstly defining the desired technological outcome and finding a conceptual biological model for that aim is really important as shown in Figure 2.9. Conceptual means not the physical properties or form but conceptually accommodate the idea for the engineering question. As starting the analysis of the biological model, the new hidden patterns and solutions will appear to apply or applied to the engineering solutions. When we limit it, it does not go deeper.

The above line, the technological outcomes for engineering solutions depends on the levels of analyzing the biological models. The more the analysis process highlights the path, new emergent properties occur.

Calladine (2000) pointed out that the natural structures in biology provide many subtleties that stimulate our creativity from all scales of the biological models- as a whole or under microscope. For an analogical example fish and boat can be taken. The fish swims in the water by flexing its body but the fish just arrange the rudder while on board. When the motive power is considered, the fish has a complex system- muscles, tendons and bones- than the combustion engine of the ship. Therefore, it cannot be wrong to say that the analogues can be wrong-headed. But the situation is different when we analyze deeper, such as the molecular or cellular level since the construction of a whole from parts is the central concept of a structure. The form depends on the function and when the function changes the form adapts to the changing conditions. Therefore, the molecular analysis can lead to understand the adaptation of structures if one’s aim is to build a structure that can adapt.

CHAPTER 3

PRINCIPLES OF SPACE TRUSS STRUCTURES

Structure is coming from Latin language, derived from the verb, struere- to construct. And by adding front of con- which means together, integrated, construction was derived.

Structure is defined as;

- Construction of something, such as a building.
- The way of arranging the parts or forming a whole in a particular way by putting the parts together.
- The arrangement or interrelation of parts in a complex entity.

Briefly, structure is the skeleton which carries the whole load and the main component for defining and erecting space with variable geometric forms. Moreover, structure is the way of emphasizing the organization and definition of the space. However, structure is more than resisting the loads and defining a space. The assembly of the materials and the way how the parts integrate shows a culture’s perspective and their relationship with the era. The changing needs of the social life developments in the building technology and economy embody the build structures.

The relationship between the components for defining the structure is termed as structural system. The components only gain its meaning and function in the whole organization of the system and the system loses its function without the components.

3.1. The Structural Systems Inspired by Nature in Architecture

Analyzing and learning from nature is rooted back to the main need of shelter (Türkçü, 2003). From the primitive ages, human beings are always concerned about the structural systems for protection from environmental conditions and other species and mostly the form of the biological models inspired the human-beings (Figure 3.1).

Figure 3.1. Some examples of form resemblance from nature
(Source: Selçuk and Sorguç, 2007)

Nature has always provided solutions for structural systems defined by Türkçü (2003), such as;

- Masonry systems: ants and termite mounds, the tunnels of rodents
- Framed Systems; anatomy of animal and human skeletons, some of bird nests
- Folded Plates; the wings of insects, leaves, bee’s honeycomb
- Shell System; Egg shell, turtle, mussel, abalone shells, and some fruit shells,
- Cable Systems; the spider webs
- Pneumatic Systems; Soap bubbles, blood veins, lungs
- Space Truss Systems; Crystals, the economic unfolding of the atoms,
- Geodesic Domes; Diatoms and radiolarians.

The shape resembling and the structural resembling should be analyzed separately. In the applications that just the shape resemble does not mean that the structure will also resemble. But in the structural analysis and applications of the natural structures, the shape also resembles and gain more advantages than copying the shapes (Türkçü, 2003). It cannot be wrong to say that, from these inspired structures, the more analyzing the micro level, the more efficient - to maintain more advantage with less material – the design of the structural systems.

One of the most important architects is the Barcelona architect, Antonio Gaudi who was famous for his biomorphic forms in 19th century. Gaudi observed and interpreted nature in his design process. It is clear that he observed the construction techniques of the nature by analyzing the anatomy of the skeleton and bones which appear in his buildings as shown in Figure 3.2.

Figure 3.2. Antonio Gaudi's inspirations from the anatomy of skeleton
(Source: Selçuk and Sorguç, 2007)

The other important architect in 20th century who pointed to design in harmony with nature is Frank Lloyd Wright. He declared in his writings that he inspired by the branching of the trees and the mushrooms as seen in Figure 3.3 for the columns and consoles.

Figure 3.3. Fallingwater, Johnson Wax Building inspired from the mushroom.
(Sources: Wikipedia, 2010; time4time, 2010; Thelensflare, 2010)

Mies van der Rohe expressed the architects' will in structural systems by this sentence; "We took all the unnecessary weight of the buildings to make them as light as possible. It is often taught that heaviness is synonymous with strength, in my opinion it is just the opposite" (Margolius, 2002). Mies in 1920's, read biology and had a book collection of the botanist Raoul Francé. Raoul Francé's approach to living things is that they are the prototypes for human technology. At that era, the idea that comes to front is that the form is not a priori and occurred as the result of the process. Mertins (2007) adds that “This statement opens the door to question of what kind of processes are being involved in the making of form”. Mies analyzed the organic structures as not from functional point of view, but he questioned optimization, rule of the minimum and harmony.

Buckminster Fuller and Frei Otto are among the leaders who tried to analyze the process of the natural forms in the perspective of lightweight structures to apply in large span with less material.

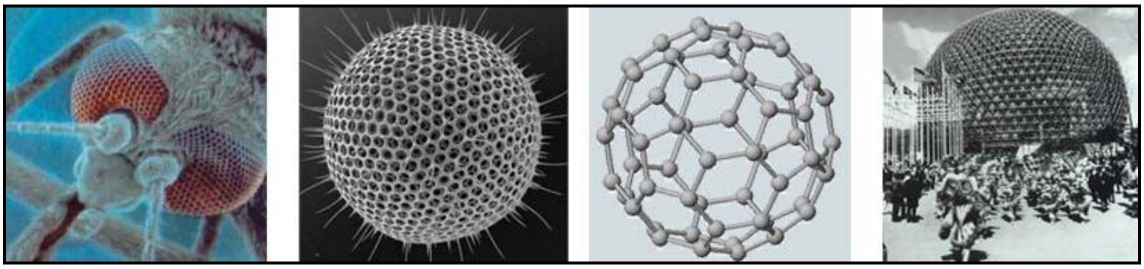


Figure 3.4. Bee eye, radiolaria, the molecule of Carbon 60 and Geodesic Dome
(Source: Selçuk and Sorguç, 2007)

Buckminster Fuller highlighted the internal properties of nature with its dynamic, functional and lightweight structural configurations. Geodesic dome is an important architectural application from which the molecule of Carbon60 - discovered after Geodesic Dome - is named Fullerenes because of his deep analysis of the natural forms. In Figure 3.4, it is seen that the formation of geodesic dome can be found in nature from the bee eye, radiolarian and the smallest Carbon 60.

Frei Otto (1995), who is the leader of the Institute for Lightweight Structures, described architecture as the man’s oldest skill in his struggle for survival in nature, he deals with the principles of natural form generation. He used biomorphic forms not only for inspiration but also for learning the construction techniques (Figure 3.5).

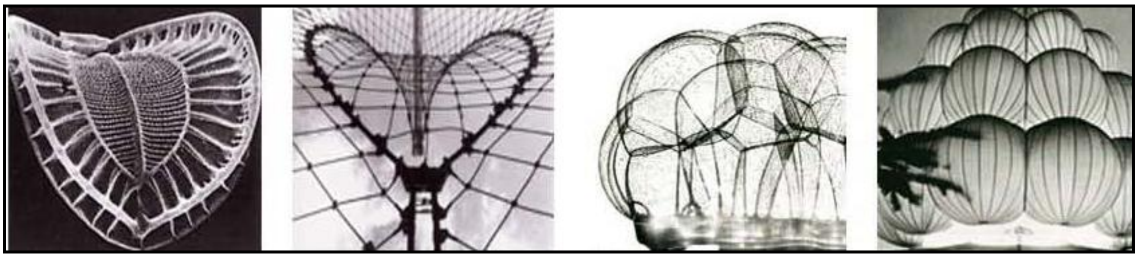


Figure 3.5. Structure analyzes and applications by Frei Otto
(Source: Selçuk and Sorguç, 2007)

The demand for long span structures force the engineers and architects' aim for the minimum to build especially with the industrial revolution and developments of the modern world (Margolius, 2002). Architects who possess engineering institution will endeavour for efficient structure inspiring by the natural structures.

Bio-inspiration design process can also be found in the landmarks which are vital for community life. The way the organization of the space usage provided by architectural point of view affect the society deeply. Eden Project by Nicholas Grimshaw (Figure 3.6) and Water Cube, 'National Swimming Centre Beijing Olympics 2008' by the Australian architectural firm of PTW and China State Construction and Engineering Corporation (CSCEC) and Arup are some of the architectural applications based on analyzing natural forms (Figure 3.7).

Eden Project is a Millennium Project for the public in UK. The main purpose for this project is to build a research and education for public and highlight the importance of sustainability, instead of touristic place. The need for grand spans forces the architect to find a design solution by inspiring from nature, honeycombs and the structural possibilities of Geodesic Domes.

The National Aquatics Center, Water Cube is designed for the competition for the Olympics 2008 in Beijing. After the Olympics, it served for special events such as Ballets Theater and sound-light shows besides its touristic visits.

These two landmarks are also important for being classified as green buildings. Construction techniques concerned about the energy consumption and used technological developments for environmental-conscious design.

Due to the weight and danger potential of the glass, UV-transparent ETFE film is used which act as a thermal blanket to the structure. Besides of the material and lightweight structure, both of these landmarks have environmental aspects, maintained by the technological developments such as heat and water efficient use.

Figure 3.6. Eden Project by Nicholas Grimshaw
(Source: Stach, 2005; Davelicene, 2010; Blogspot, 2010)

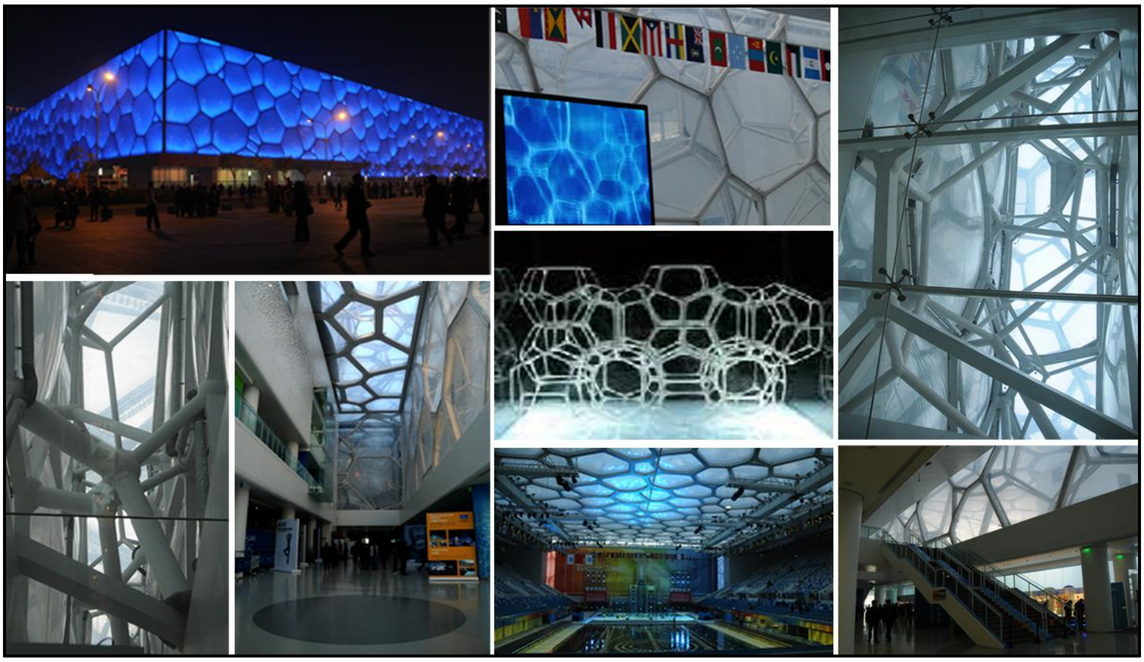


Figure 3.7. Water Cube, 'National Swimming Centre Beijing Olympics 2008'
(Source: Author, 2008; Stach, 2005)

By the development in technological applications on computer-based calculations and system analysis, the space truss structures and geodesic dome have increased in building systems. The space truss structural systems are the most successful structural systems because of combining high strength, light-weight, minimum material usage, and three-dimensional behaviour. Since space truss structural systems are inspired by the principles of economic unfolding of atoms and crystals, their tendency is to use minimum materials to gain maximum structural advantage. In that case, understanding of the space truss structures is significant in the design process for the aim of adaptable structures.

3.2. Development of Space Truss Structures

The space truss structures are the structural systems resisting only tension and compression. Moore (1999), in "Understanding Structures" defined as "Truss systems, are assemblies of ties (acting in tension) and struts (acting in compression) arranged in pin-connected triangles so that all internal forces are axial." Triangle is the only hinged polygon which is stable even with flexible joints. The other polygons, such as square, are unstable as shown in Figure 3.8.

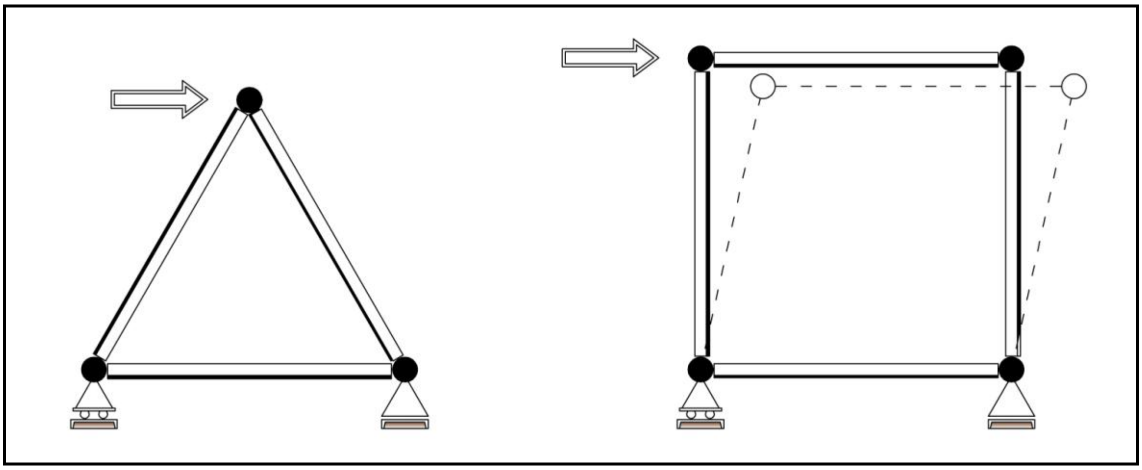


Figure 3.8. Triangle is the only polygon that has inherently stability

The railroad truss bridges in the 19th century caused the development of truss systems. This development led to a significant point of analysis the vector-based structures' structural behaviour and the understanding of the significance of the nodes.

The usage of steel in structures is also give rise to analysis of truss structures. Crystal Palace in London at 1851 and Eiffel Tower in Paris at 1897 are the important examples that certify the development of truss systems (Türkçü, 2003; Chilton, 2000).

Although it is mostly written that Alexander Graham Bell is the first person who invented space truss systems, the first stability analysis of space truss structures and published the first treatise 'Theorie des Fachwerks' is by August Föppl in 1880 (Bradshaw et al., 2002). He put forth for consideration about truss structures that the most stable polygon is triangle and the most stable polyhedral which defines volume is tetrahedron for space truss structures.

Graham Bell, as shown in Figure 3.9, used the efficiency of the tetrahedral units for his creations from kites to viewing deck and he mentioned this with an article in National Geographic Magazine in 1903;

> Of course, the use of a tetrahedral cell is not limited to the construction of a framework for kites and flying-machines. It is applicable to any kind of structure whatever in which it is desirable to combine the qualities of strength and lightness. Just as we can build houses of all kinds out of bricks, so we can build structures of all sorts out of tetrahedral frames and the structures can be so formed as to possess the same qualities of strength and lightness which are characteristic of the individual cells (Chilton, 2000).

The applications by Alexander Graham Bell are the first developments on space truss structures. Bell evaluated the importance of space truss structural systems and three dimensional tetrahedral forms by the properties of high strength and light-weight.

However, the first major development was the invention of Unistrut systems by Attwood in 1939, and followed by Dr. Ing. Max Mengeringhausen's MERO systems in 1940's. The invention of the nodes affects the development of space truss structures.

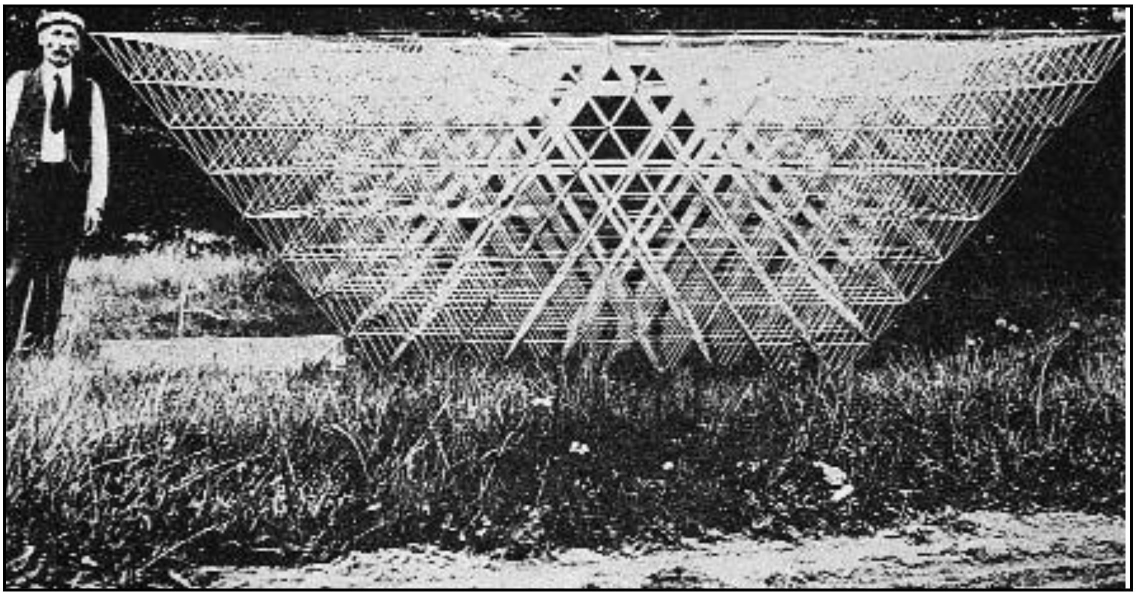


Figure 3.9. Early experimental space truss developed by Alexander Graham Bell
(Source: Chilton, 2000)

Space truss structure components have been a great interest among engineers and architects and developed new systems for the construction markets. Since then, after 1940's space truss structures have been using in many applications from exhibition halls to swimming pools and world's fair pavilions, etc. The main reason is the advantages that the space truss structures provide such as;

- The structural behaviour is three dimensional
- The structural system is light and efficient as using materials optimally
- The assembly and construction is easy as the factory made components and unskilled labour is adequate.
- Construction time is short.
- Give freedom to architects and engineers in planning different geometric patterns
- It is possible to cover an area or volume by large column free spaces with variable applications.
- Provide opportunity for reusability
- Easiness of transportation

3.3. Classification of Space Truss Structures

Space truss structures are originated from truss development and knowledge. In literature, the space structures are named as space grids, space frames or space truss structures. Handbook of Structural Engineering the chapter of space frame structures by Tien T. Lan gave a brief explanations that the space frame structures are the systems assembled by linear elements and their load carrying mechanisms are three dimensional which can be put in practice for covering a space by flat or curved surfaces (Chen and Lui, 2005). However, in ‘Space Grid Structures’ John Chilton defined the differences of space frame and space truss by the connection types and the load carrying properties of the structural systems.

Space frame structures are generally not triangulated, and applied by fully rigid nodes. They are usually constructed from pre-fabricated, three dimensional modules or by welding the fabricated elements in the site. The system resists the loads by a combination of bending, shear and axial forces in elements when applied in one point (Chilton, 2000).

Space truss structures are commonly constructed by pin-ended bars or members connected with nodes. The structural system is obtained by triangulation of the structure, and when load is applied to the node in the system, the space grid has mostly axial tension or compression forces.

In general, Engel described Space Grid Structures as the assembly of linear elements in 3D system (Mirmiran et al., 2002).

The components of the structural system of space truss structures are the rods (linear and diagonal) and the connectors. In the design process of the space truss structures, as the rods are always axial, the node qualifies the structural system.

Türkçü (2003) has explained the space truss structures as in two classifications by their geometric properties such as flat-surfaced space truss structures and curved-surfaced space truss structures. Even, the curved-surface space truss structures can be single or double layered, the flat- surfaced space truss should be applied in bi-layer or at least two layers.

3.3.1. Flat- Surfaced Space Truss Structures

The flat-surfaced space truss structures can be defined as three-dimensional truss systems and composed of lower and upper layers. Most of the flat- surfaced structures are constructed by minimum amount of identical units repeating in an order and give possibilities for variety of configurations, including walls and roofs. Even, mostly tetrahedron and half-octahedron is used for space truss structures, the geometry of space trusses are quiet diverse. The derivation methods of space grid layers seems complex, however, geometric aspects help the designers for efficient solutions. The main consideration point for derivation is obtaining a structural system with minimum amount of identical members.

In ‘Contemporary Structural Systems’ Türkçü (2003) explained two derivation methods for flat-surface d space truss systems. The first one is the commonly used derivation method by using the polyhedrons. There are five regular polyhedrons which are called Platonic Solids, and thirteen semi-regular polyhedrons, Archimedean Solids, defining a sphere. These solids are used as a whole or the usable parts of them.

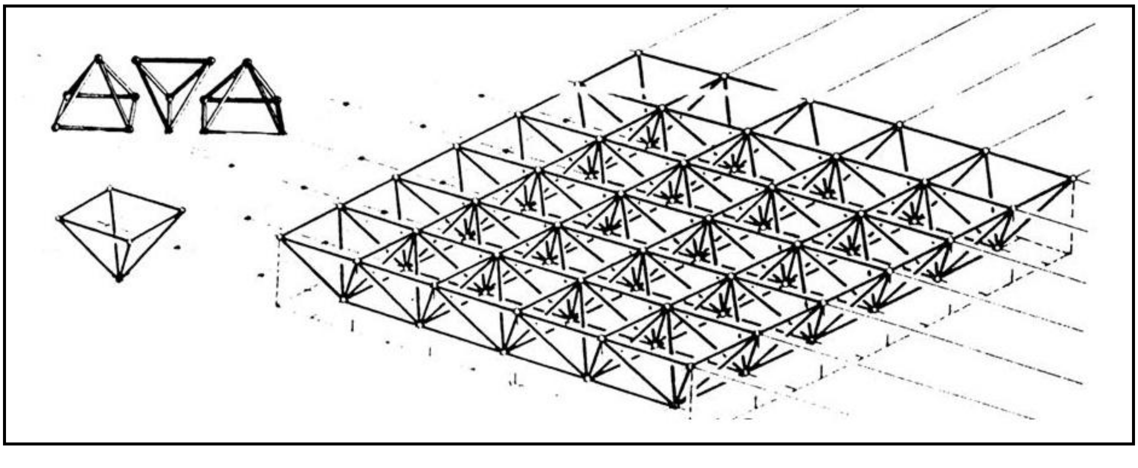


Figure 3.10. Derivation method by using the polyhedrons
(Source: Türkçü, 2003)

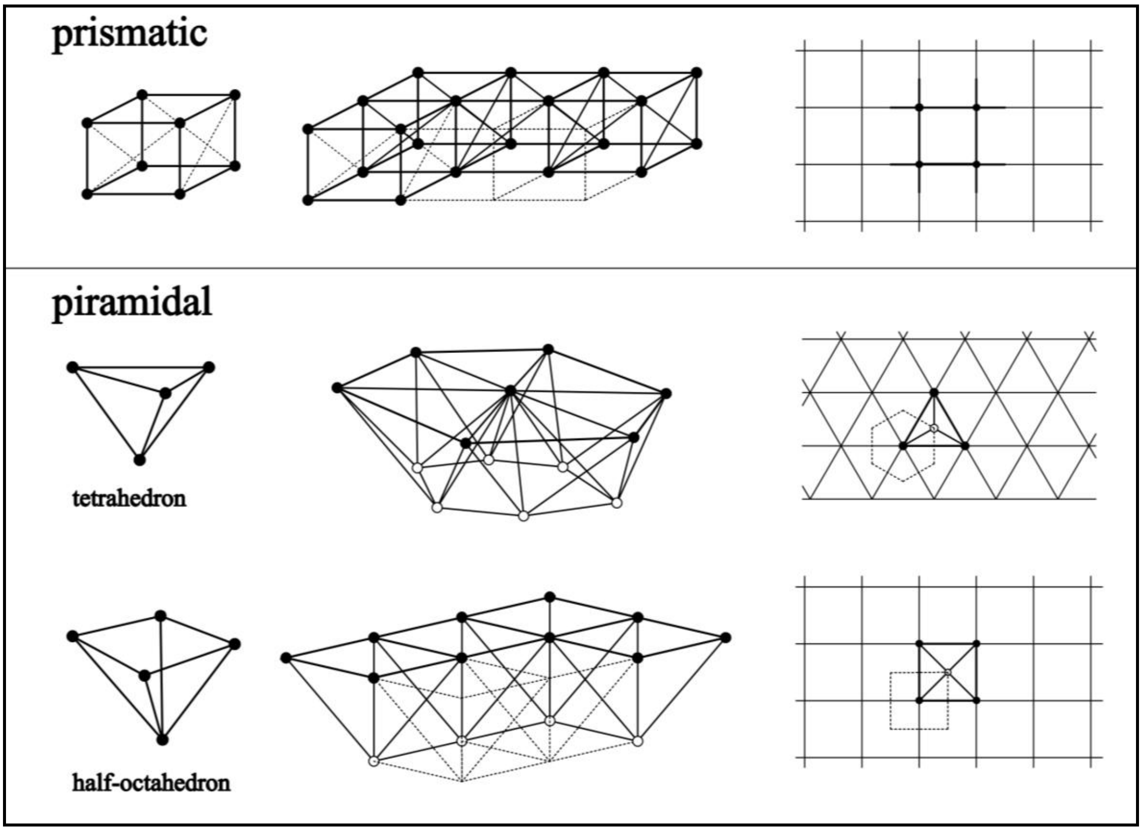
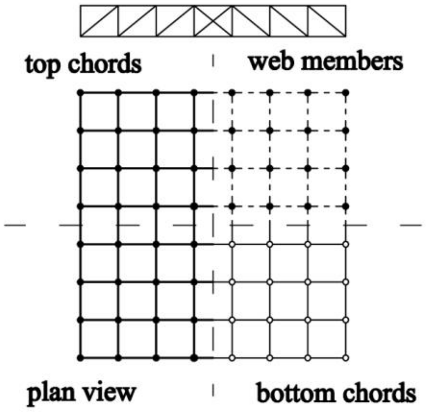
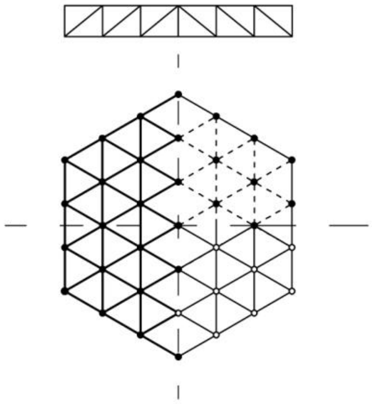
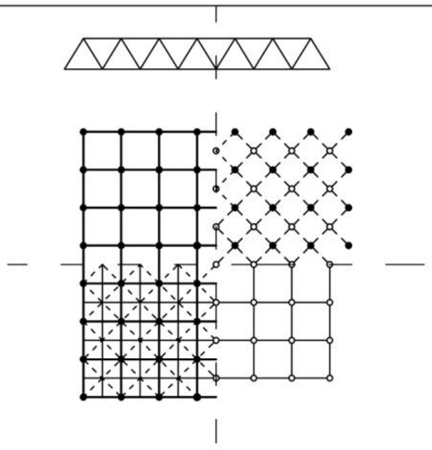
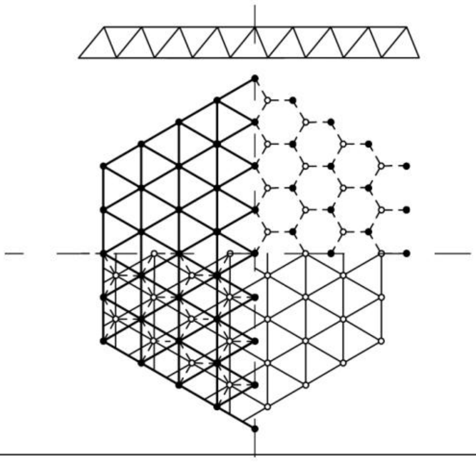
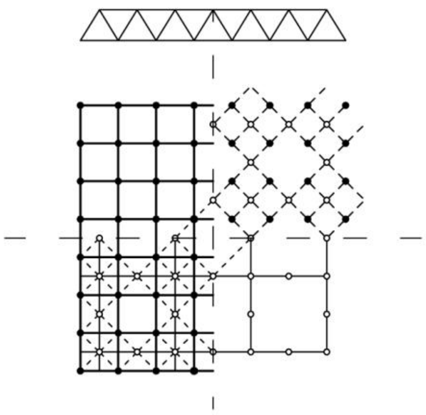
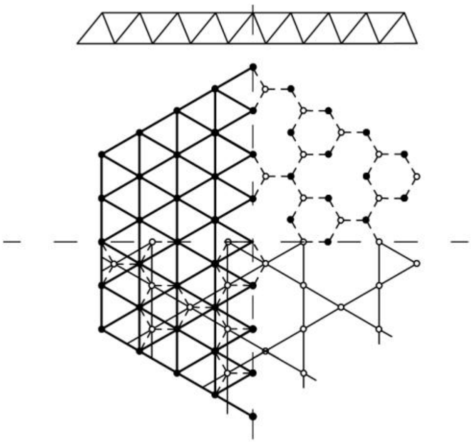


Figure 3.11. Prismatic and pyramidal derivation of space truss systems

The second derivation method is by combining the grid layers. Türkçü (2003) described two methods for combining the grids, so the structural system turned into prismatic or pyramidal space truss structural systems. First method is by using the same grid for two layers which turn into prismatic structural system. But for prismatic derivation, additional members are used for stability and then obtained space truss structures. Also, the second method is by using the dual of the first layer for the second layer (Figure 3.11, Table 3.1).

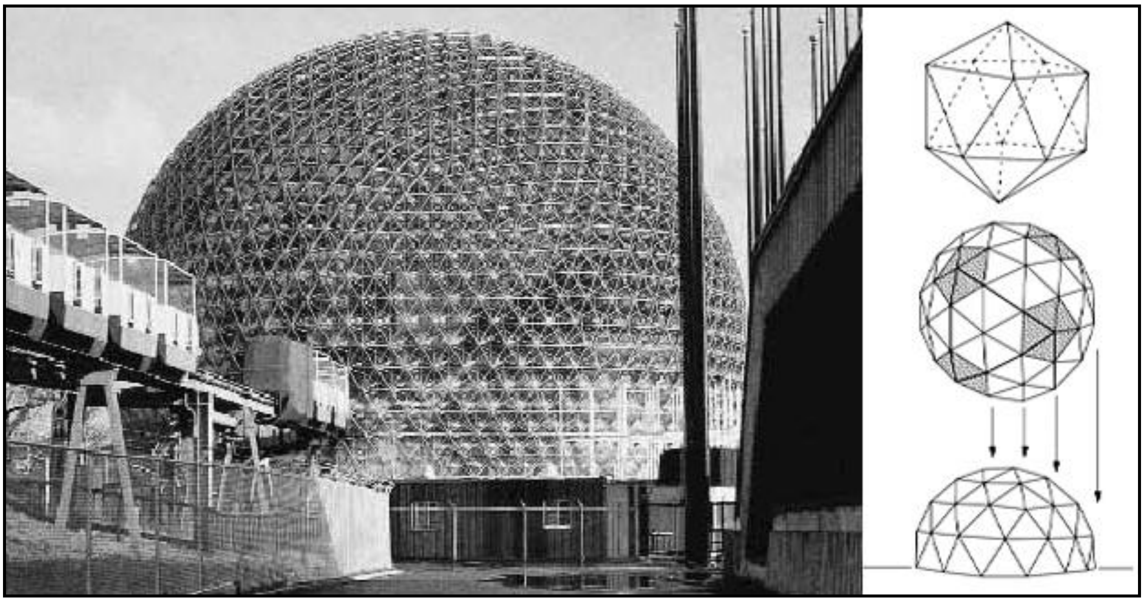
Dual of one pattern is obtained by intersecting the centre points of adjacent polygons. Lan, also added that the differential grids, with different grids - regular and semi-regular grids - but generating a regular pattern is also used, especially for obtaining openings (Chen and Lui, 2005). Some examples are given in Table 3.1, the hollow circles are bottom chord's nodes and the solid circles are representing the upper chord's nodes.

Table 3.1. Derivation method of grid layers in triangular and square packing

	Square Packing	**Triangle Packing**
Same Grids		
Dual Grids		
Differential Grids		

3.3.2. Curved-Surface Space Truss Structures

Türkçü (2003) classified the curved-surface space truss structures in two categories; single curved- surface and double curved-surfaces. The single-curved surface structures are braced barrel vaults. Barrel vaults are obtained mainly by cylinders, even their geometry is simple, and their stability is not qualified as double curved surface structures. Double curved-surface structures have two types, as the curves are in the same direction, such as braced domes and geodesic domes, and the curves having different directions such as hyperbolic paraboloids. In space truss structures, the easiness of application really depends on the amount of the unit types such as web members, chord members and nodes; components for building up the structure. Geodesic Domes are the only application that minimize the amount of the materials and maintain the maximum efficiency of space truss structure. In that case, Geodesic Domes will be analyzed.



76 m diameter geodesic dome for the US pavilion at Expo'67 in Montreal

Figure 3.12. R. Buckminster Fuller's geodesic dome and its derivation method (Source: Chilton, 2000; Moore, 1999)

Geodesic Dome is firstly patented by R. Buckminster Fuller in 1954. He analyzed mainly the sphere which encloses the most volume with minimum surface and tetrahedron which encloses the least volume with maximum surface (Fuller, 1975). He tried to find a structural system pattern for this two regular solids and obtained geodesics as shown in Figure 3.12. Fuller developed the intrinsic mathematics of the geodesic dome during his studies in 1949 at Black Mountain College with a group of professors and students although it was invented by Dr. Walther Bauersfeld 30 years before patented by Fuller.

Geodesic dome is obtained in the geodesic pattern which is obtained by connecting two points with the shortest arcs on a sphere. The nodes are situated in the curves and the rods connect the nodes. Since icosahedron is the closest regular solid to the sphere and as obtained by triangles like tetrahedron Fuller analyzed the geometry of icosahedrons. Geodesic Domes are obtained by dividing the triangles into smaller triangles which is called frequency. In Figure 3.13, it is shown that the more the frequency increases, the structure of the dome gets smoother.

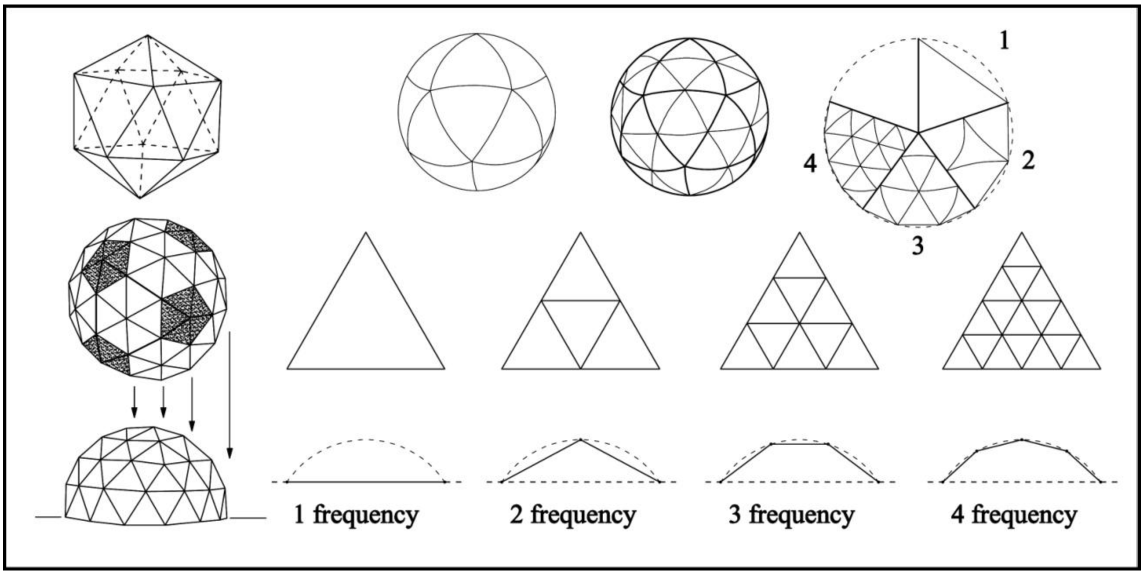


Figure 3.13. Icosahedron and its usage to obtain geodesic dome

Truss depth of the geodesic domes is significant for restraining to the loads acting on the structural system. However, as the frequency increases, the truss depth loses its structural efficiency. For increasing the truss depth for long-span structures, constructing a double layer is a solution in geodesic domes as shown in Figure 3.14.

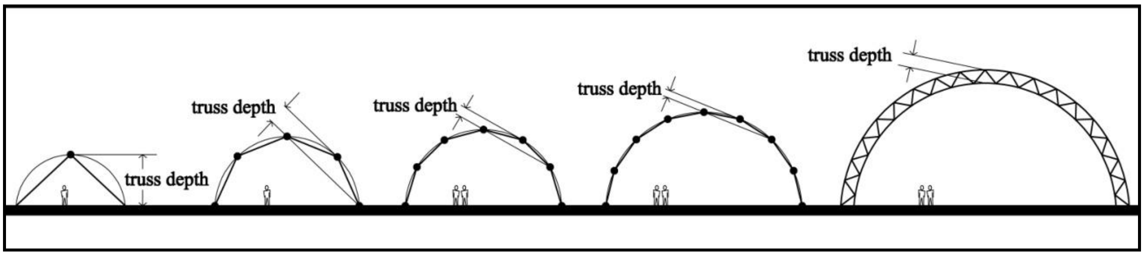


Figure 3.14. Truss depth is significant for resistance to loads.

From the development of space truss structures, the most important consideration points are the geometrical configurations and the nodes. The nodes are the components that provide the final commercial success with their efficient and simple design. Therefore, understanding the geometrical configurations of the solids and the nodes are significant in the design process.

3.4. Geometrical Configurations

Space truss structures are derived from mostly regular solids (platonic solids) and also from the Archimedean solids and their useful parts (Türkçü, 2003). That's the main reason; it is advantageous to study simple, regular, polyhedral shapes for understanding the structural behaviour of the geometrical configurations (Chilton, 2000). The formation of the regular polyhedral shapes has always been a research field in mathematics, physics, chemistry, mechanics, architecture and engineering.

Platonic solids are the basis for space truss structures. The most important reason that the platonic solids are chosen for space-filling is that they are composed of same size rods, same size plates and identical nodes. The other specific reason is the most economic unfolding of space.

3.4.1. The Economic Unfolding of Space

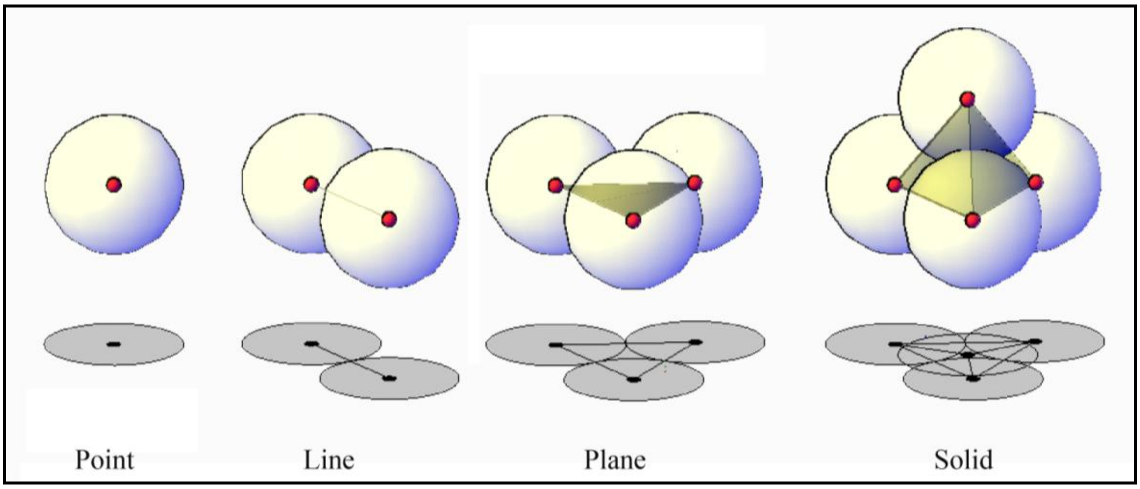


Figure 3.15. Presenting the economic unfolding of the dimensions of space

Basically, point is the origin for defining a plane or a solid. Point describes unlimited possibilities of axis for defining line, plane and solid. The economic unfolding of the dimensions of space starts firstly by defining a point in the space. Positioning the second point limits one of the axes spreading from one point and defines a line. Then, by adding the third point on the same axis with the first and second point defines the plane. Lastly, by adding the forth point on the axis of the other three points, the plane turns into solid, tetrahedron (Critchlow, 1969). This approach as visualized in Figure 3.15 shows the importance of nodal points for defining the space by the economic unfolding of the space.

3.4.2. Platonic Solids

Plato was one of the people who attempted to describe the geometry in natural structures. While analyzing the natural structures, he explored the basic geometric shapes, five regular polyhedrons (Figure 3.16). These are called Platonic solids, which are the only three dimensional figure defined by a closed set of same polygon faces, defining a sphere. Briefly, polyhedron is a volume which occurs from plane surfaces in which all vertices are equal (Pearce, 1978).

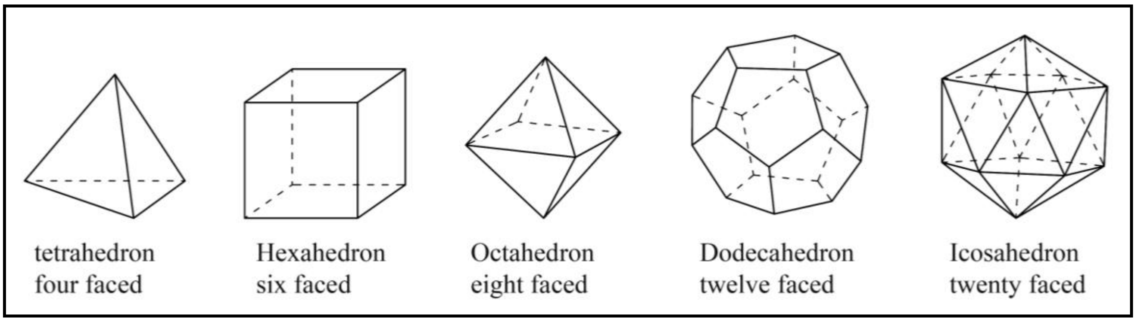
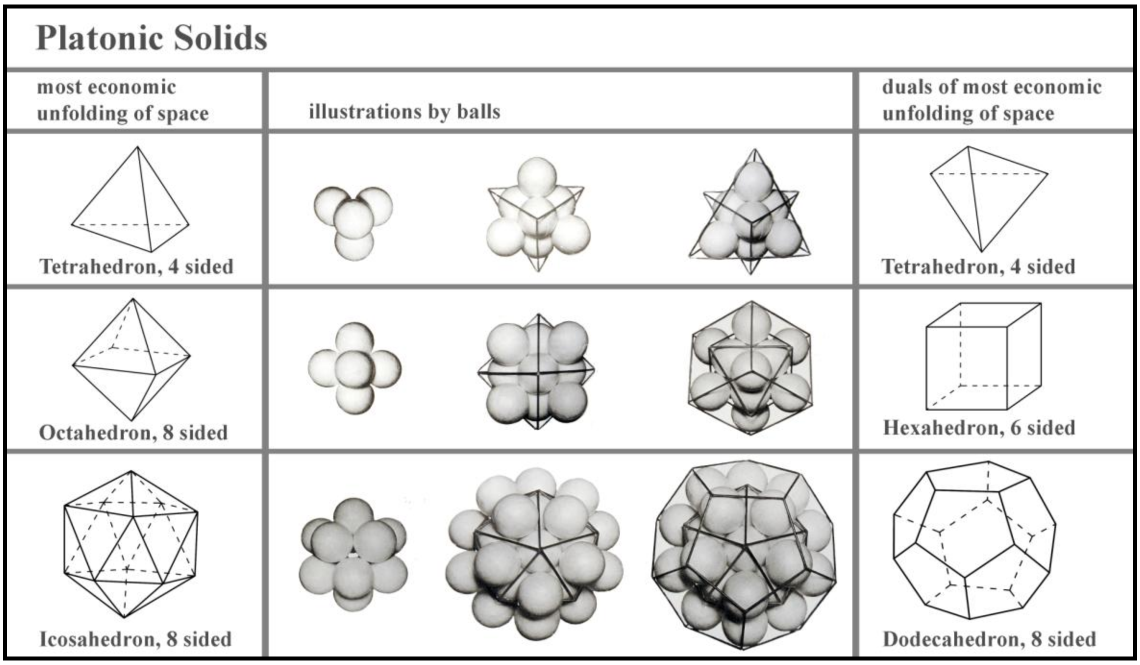


Figure 3.16. The Platonic Solids

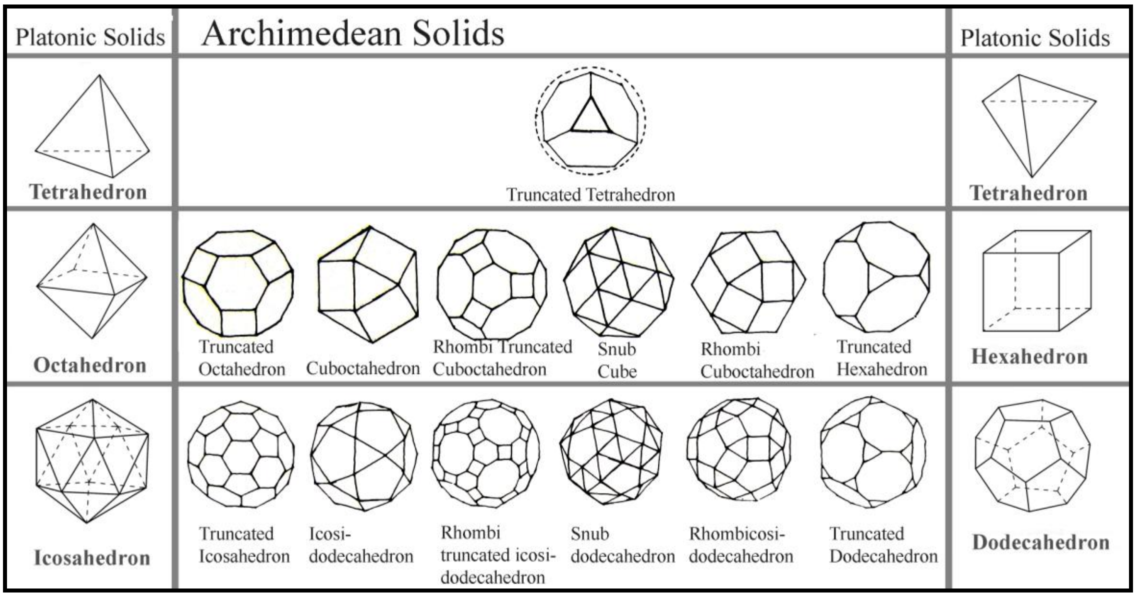
Of all regular polyhedrons, the sphere encloses the most volume with the least surface, and the tetrahedron encloses the least volume with the most surface (Fuller 1975). As defined before, tetrahedron is the prime solid, which is the first and most economic unfolding of space. After tetrahedron, the next most economic regular grouping of spheres is octahedron. The icosahedron is the third regular grouping of sphere which is in triangulated configuration. These solids are the triangulated platonic solids (Critchlow, 1969). Dual of the solids can be obtained by connecting the central points of each plane, or as shown in Table 3.2 by adding balls to each intersection points. As it is seen from the table, the tetrahedron is its own dual, the hexahedron is the dual of the octahedron and dodecahedron is the dual of icosahedron.

Table 3.2. The Platonic solids and their illustrations by balls
(Figure Source: Critchlow, 1969)



3.4.3. Archimedean Solids

Table 3.3. The Archimedean Solids derived from Platonic Solids



The Archimedean solids are obtained by the platonic solids by truncation on the edges and they are also used for derivation in space frames. Table 3.3 shows the graph of the Archimedean solids from the platonic solids towards their duals. As all the vertices are the same, it is understood that the configurations appear in 3, 4 and 5 nodes at their intersections.

3.4.4. Construction of Platonic Solids

However, when these five solids are constructed by bars, the cube and dodecahedron will collapse as not being triangulated at their nodal points, differently from the other three, tetrahedron, octahedron and icosahedron. As shown in the Figure 3.17, triangulation gives strength to the structures even before the physics of materials is taken into account.

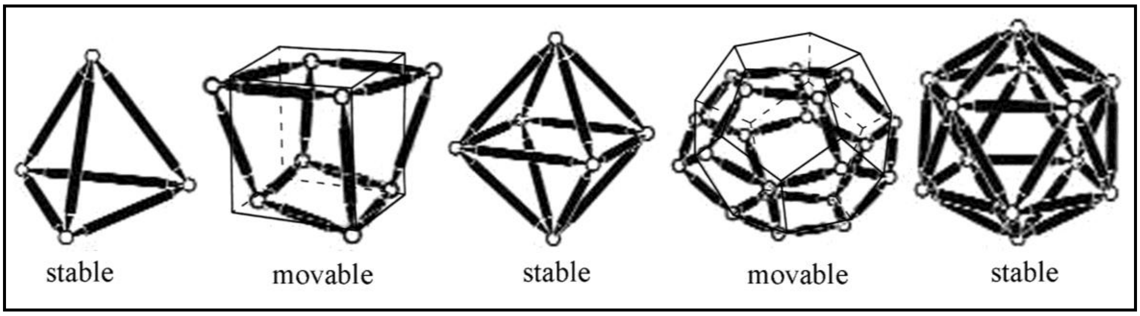


Figure 3.17. The stable and movable bar structures of platonic solids
(Source: Chilton, 2000)

In space truss structures, the bar structures are especially used. The type of the node used for construction qualifies the identity of the structure (Clinton, 2003). On the other hand, the complexity of the junction points is one of the merits of triangulated systems (Pearce, 1978).

3.5. The Nodes of Space Truss Structures

The nodal points of the space truss structures are the transmitting points of the forces affecting on the structure in three dimensions. The nodes are the main components for generating the form by integrating the bars. That is the reason, in the study of space truss structures, the main focus points of the engineers and architects are mostly the nodal points. Some applications of the nodes are shown in Figure 3.18.

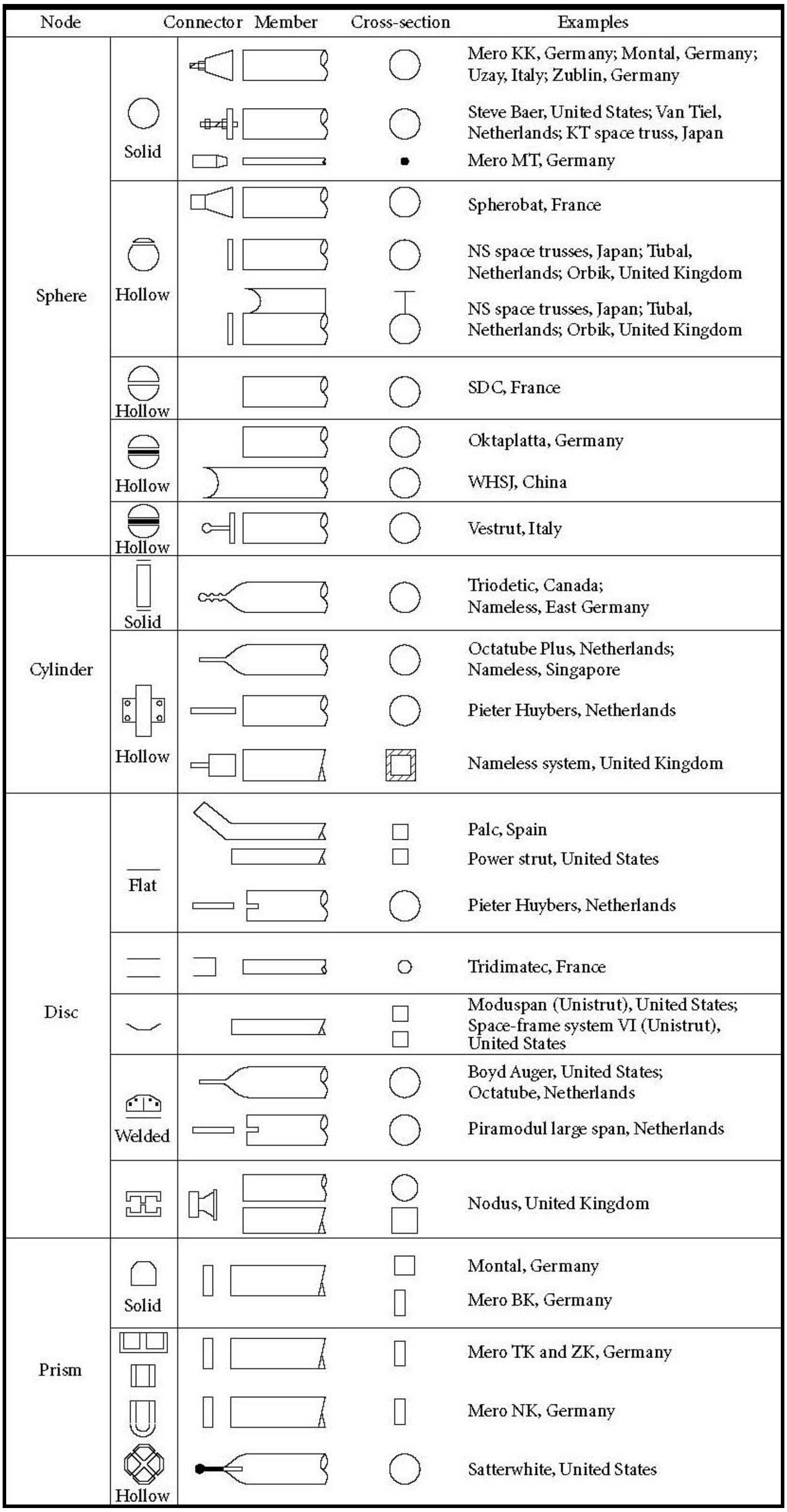
1-2. Standart Mero KK, used in stadium, Split
3-4. Harley/Conder Harley nodeless joint, used in Eagle Center Market in Derby
5-6. CUBIC Space Frame modules applied in Int. Convention Center, Burmingham

Figure 3.18. The nodes that has been applied in several space truss structures
(Source: Chilton, 2000)

Since the first invention of the connections, literally hundreds of different space structure systems have been developed over fifty years. Also, in each year new systems are developed for the market. There are over 250 different nodes around the world applied till today. However, some of them gain its importance in the construction field. A detailed study of Joop Gerrits of TU Delft; classifies the nodes as shown in the tables and classifies the connection types as; (Chen and Lui, 2005).

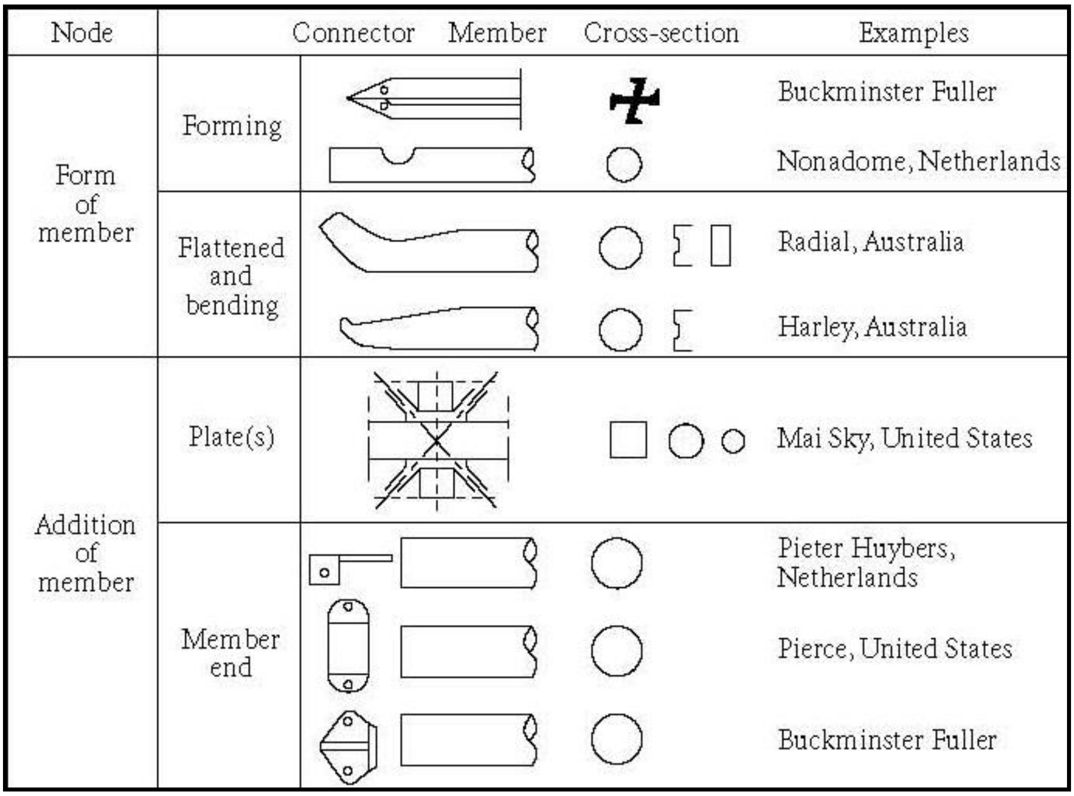
- The connection types with nodes as shown in Table 3.4.
- The connection types without nodes as shown in Table 3.5
- The connection types with prefabricated units as shown in Table 3.6

Table 3.4. The connection types with node
(Source: Chen and Lui, 2005)



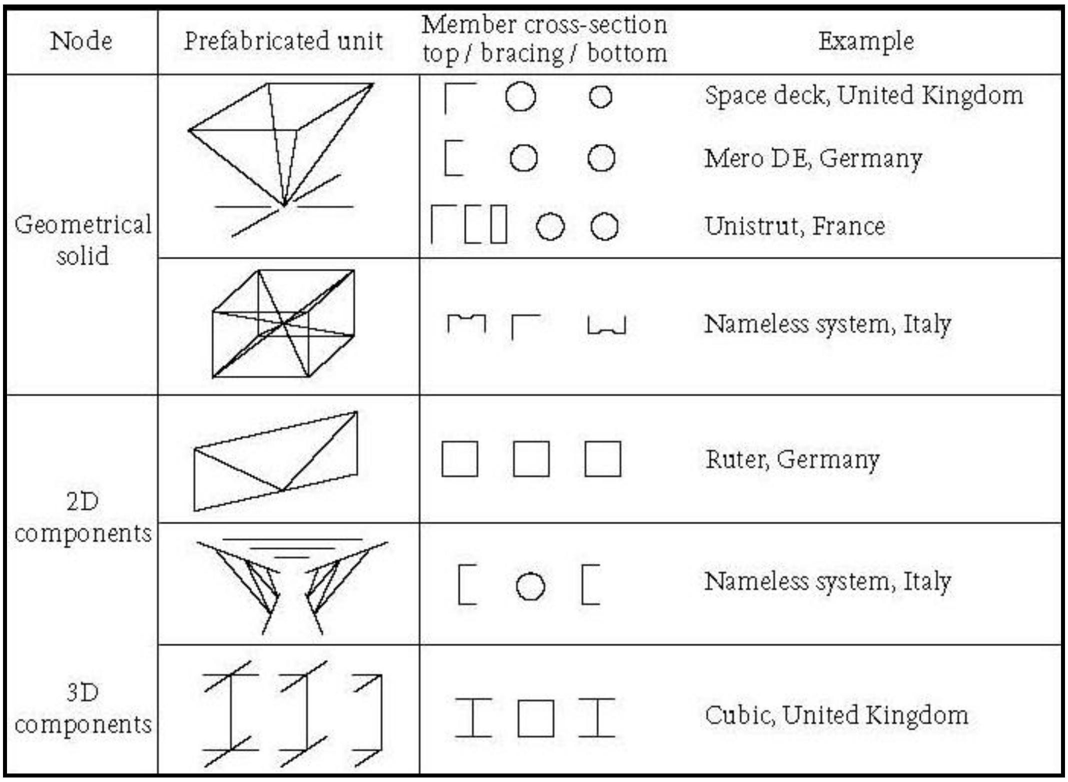
Node	Connector	Member	Cross-section	Examples
Sphere	Solid			Mero KK, Germany; Montal, Germany; Uzay, Italy; Zublin, Germany
				Steve Baer, United States; Van Tiel, Netherlands; KT space truss, Japan
				Mero MT, Germany
	Hollow			Spherobat, France
				NS space trusses, Japan; Tubal, Netherlands; Orbik, United Kingdom
				NS space trusses, Japan; Tubal, Netherlands; Orbik, United Kingdom
	Hollow			SDC, France
	Hollow			Oktaplatta, Germany
				WHSJ, China
	Hollow			Vestrut, Italy
Cylinder	Solid			Triodetic, Canada; Nameless, East Germany
	Hollow			Octatube Plus, Netherlands; Nameless, Singapore
				Pieter Huybers, Netherlands
				Nameless system, United Kingdom
Disc	Flat			Palc, Spain
				Power strut, United States
				Pieter Huybers, Netherlands
				Tridimatec, France
				Moduspan (Unistrut), United States; Space-frame system VI (Unistrut), United States
	Welded			Boyd Auger, United States; Octatube, Netherlands
				Piramodul large span, Netherlands
				Nodus, United Kingdom
Prism	Solid			Montal, Germany
				Mero BK, Germany
	Hollow			Mero TK and ZK, Germany
				Mero NK, Germany
				Satterwhite, United States

Table 3.5. Connection types without node
(Source: Chen and Lui, 2005)



Node	Connector	Member	Cross-section	Examples
Form of member	Forming			Buckminster Fuller
				Nonadome, Netherlands
	Flattened and bending			Radial, Australia
				Harley, Australia
Addition of member	Plate(s)			Mai Sky, United States
	Member end			Pieter Huybers, Netherlands
				Pierce, United States
				Buckminster Fuller

Table 3.6. Connection types with prefabricated units.
(Source: Chen and Lui, 2005)



Node	Prefabricated unit	Member cross-section top / bracing / bottom	Example
Geometrical solid			Space deck, United Kingdom
			Mero DE, Germany
			Unistrut, France
			Nameless system, Italy
2D components			Ruter, Germany
			Nameless system, Italy
3D components			Cubic, United Kingdom

Although, there have been wide applications considering the nodes, some of them such as Mero, Triodetic, Oktaplatte, Unibat, Nodus, NS and Space Deck are commonly used as proprietary systems. The connections types with node will be defined in the respect of Gerrits classification, spherical, cylindrical, disc and prism nodes.

3.5.1. Spherical Nodes

Spherical nodes are grouped in two categories, solid spherical nodes such and hollow spherical nodes.

Mero

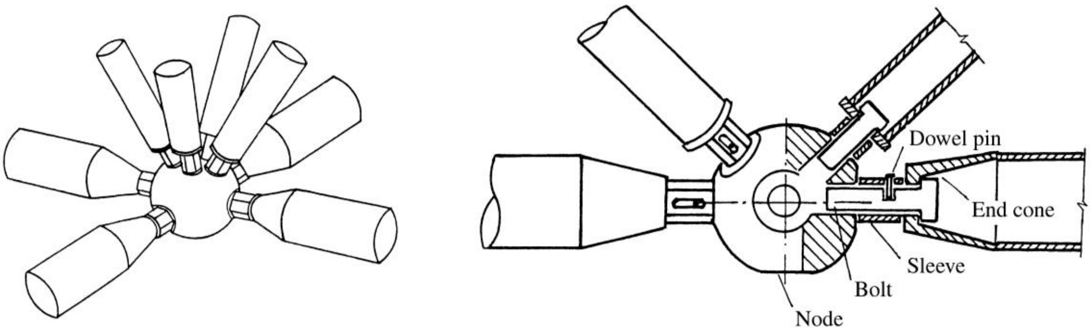


Figure 3.19. Mero KK
(Source: Chen and Lui, 2005)

Mero KK is a solid spherical node and its jointing system is introduced by Mengeringhausen Rohrbauweise in 1942 and used for many applications from industrial buildings, churches to halls and domes. Mero joint is firstly considered for pin-connected structures. However, with the need of different applications other types of Mero connectors developed (Makowski, 2002). Mero KK, the original Mero connector is considered as the most effective solution for space grid structures. Mero KK is investigated by the studies on natural structures strength derivation of wheat stalks and bamboo stems (Chilton, 2000).

Mero KK was originally developed for double-layer grids and obtained by spherical hot pressed steel with flat faces and holes on it. The faces let up to 18 members to connect to the node with no eccentricity which eliminates the loads on the joints. The axial members are connected dowel pins as shown in Figure 3.19. The nodes can be applied in different sizes and with angles of 45°, 60 °, 90°, relative to each other and also fabricated with determined specific angles.

Oktaplatte

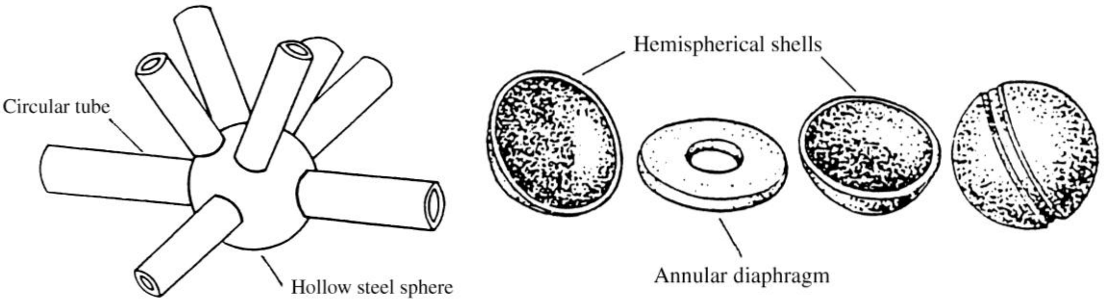


Figure 3.20. Oktaplatte
(Source: Chen and Lui, 2005)

Oktaplatte is a hollow spherical node and its jointing system is especially popular when the space truss structures were developed. This node is composed of hollow steel hemispheres and steel plates. The circular tube axial members are welded to the connector as shown in Figure 3.20. Oktaplatte is useful for long-span structures and also applied to single layer latticed structures (Chen and Lui, 2005).

NS Space Truss

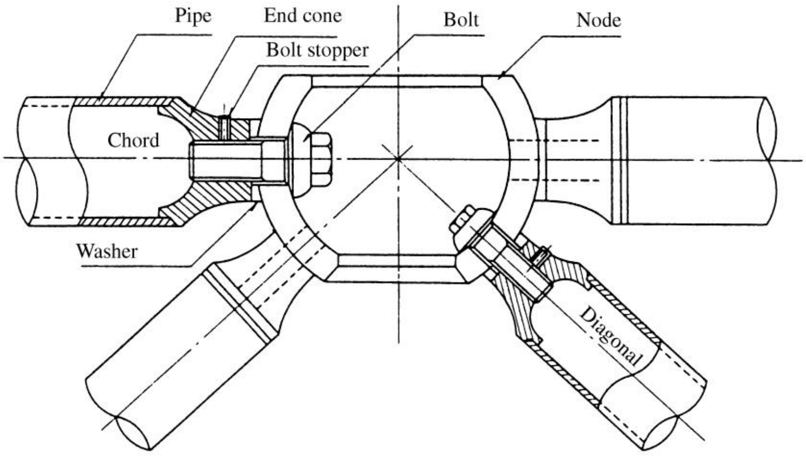


Figure 3.21. NS Space Truss
(Source: Chen and Lui, 2005)

NS Space Truss is a hollow spherical node and its jointing system is developed by Nippon Steel Cooperation in 1970's and applied to many large-span double and triple layer grids and domes. This connector is composed of thick spherical steel shells with an opening at the bottom for inserting bolts for welding the axial members as shown in Figure 3.21. The axial members are connected to the node without any eccentricity of internal forces (Chen and Lui, 2005).

3.5.2. Cylindrical Nodes

Triodetic

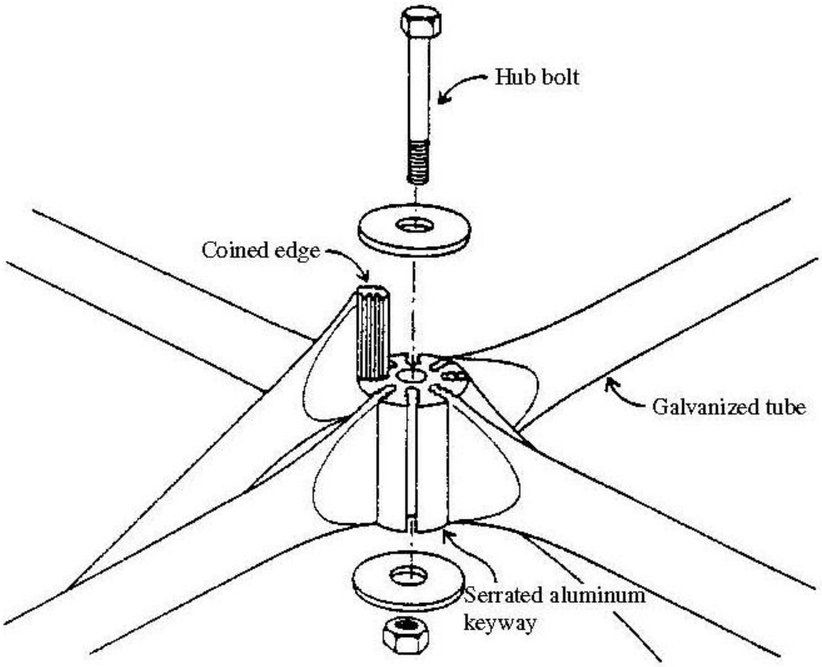


Figure 3.22. Triodetic
(Source: Chen and Lui, 2005)

The Triodetic jointing system is developed by Fentiman Bros. in 1950's in Canada by a totally different concept for the connecting method. The connector is composed of aluminium hub and flattened the ends of the axial members for connecting in to the hub's keyways as shown in Figure 3.22 (Chilton, 2000; Chen and Lui, 2005). They are capable for applications of any type of three-dimensional space truss structures (Makowski, 2002).

3.5.3. Disc Nodes

Moduspan/ Unistrut

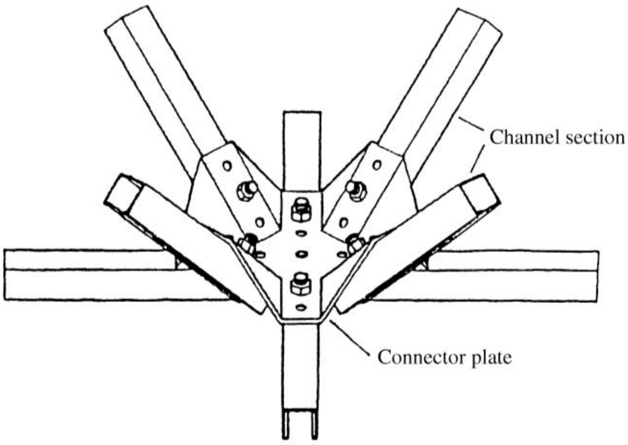


Figure 3.23. Unistrut
(Source: Chen and Lui, 2005)

Unistrut jointing system is developed in United States by Charles W. Attwood in 1950's. The connectors for both layers in bi-layer system is identical, therefore, Unistrut system is composed of four members, the plate connector , the strut, high-tensile bolt and the nut as shown in Figure 3.23 (Makowski, 2002).

Nodus

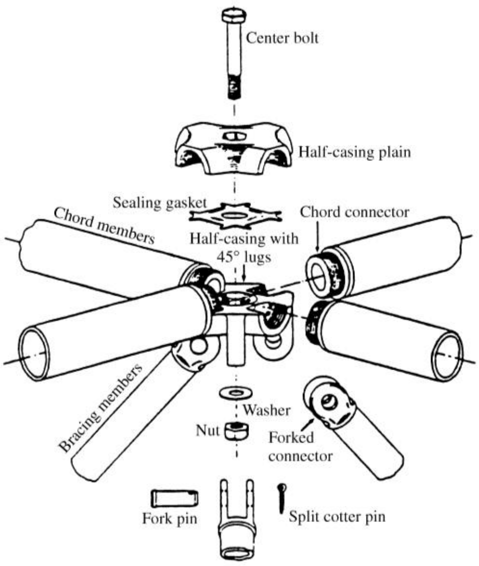


Figure 3.24. Nodus
(Source: Chen and Lui, 2005)

Nodus jointing system is developed in England in 1970’s by Tubes Division of British Steel Corporation. This system is especially used in bi-layer horizontal grids, besides it can be applied to variety of applications. The joint has two half-casting connected by a bolt inserted in a hexagonal recess as shown in Figure 3.24 (Makowski, 2002). The axial members are connected to the joint with eccentricity which produces some amount of bending on the members (Chen and Lui, 2005).

3.5.4. Prism Nodes

Mero TK, Mero ZK

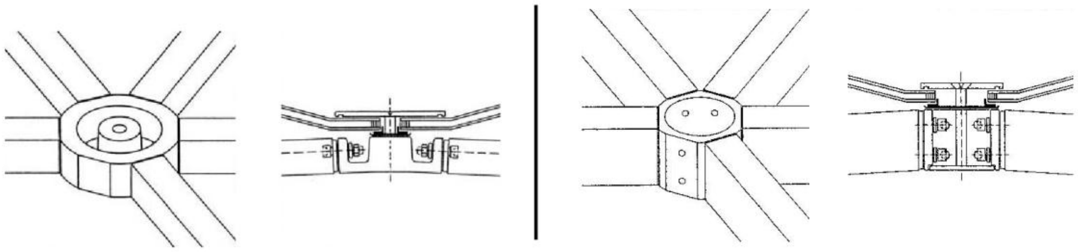


Figure 3.25. Mero TK and Mero ZK
(Source: Chen and Lui, 2005)

Due to increasing use of non-planar roof forms new type of jointing system called Mero Plus System was developed to use in curved structure applications. Disk node, Mero TK and cylinder node, Mero ZK type were developed which can connect 5 to 10 square or rectangular members with bolts as shown in Figure 3.25 (Chen and Lui, 2005).

3.6. Conclusion

The space truss structural systems are the most successful structural systems because of combining high strength, light-weight, minimum material usage, and three-dimensional behaviour. The space truss systems enable the architects and engineers design wide diversity in new forms and flexibility. The three dimensional behaviour in space truss structures, the nodes are the main consideration parts of the structural system. The node of a structure determines the area of the plane and further the volume of the space. Yet, the nodes are mainly solute by rigid components which limit the application diversity or the nodes become complex because of triangulation at the nodal points for gaining stability. In general, rigidity and no internal mobility are accepted in the components of a structure. Although, the structures are mostly designed by rigid connections, alternate structures which are capable of geometrical transformation also exist. This geometrical transformation can provide new structural systems for adaptable structures.

Space truss structural systems are inspired by the principles of economic unfolding of space and their tendency is to use minimum materials to gain maximum structural advantage. Even, space truss structural systems have inner potential for adaptable structures, after building the construction, the system lost its potential. Especially in natural structures from molecules to high levels of order have a capability of changing their forms from one rigid phase to another in minimum energy configurations. In that case, analyzing the nature’s building code is a significant field to be explored in the design process.

CHAPTER 4

THE NATURE'S BUILDING CODE

All forms in nature are structured by the interaction of inner and external forces. Fuller (1995) describes the structure as system of dynamic stability occurring by self-stabilizing energy-event complex. Structure cannot be considered apart from a profound respect to natural laws. From this perspective, analyzing the natural structures, the process and their behaviour in respect to the natural laws will light up the design process for the technological innovations. Non-living and living organic structures are under the influence of the same laws of physics. These physical attributes provides a common ground for interdisciplinary studies.

4.1. The Significance of Understanding the Natural Structures

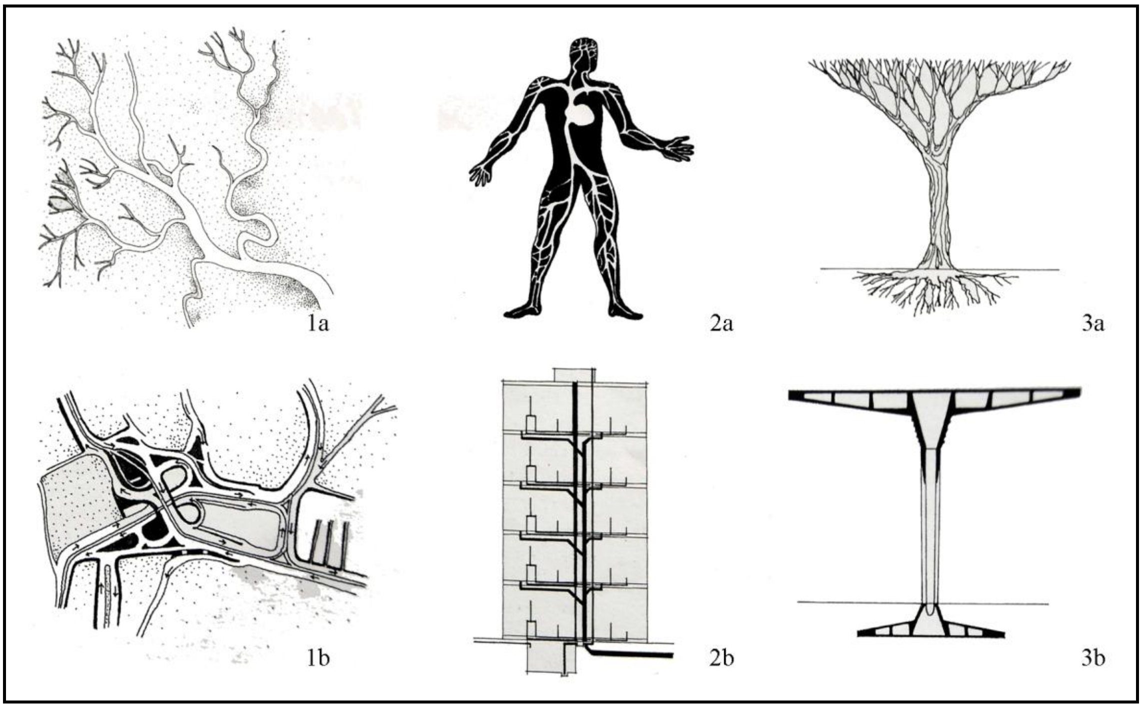


Figure 4.1. Looking to nature and providing solutions
(Source: Senosiain, 2003)

Natural structures have always provided a further understanding of the structural systems for maintaining logical solutions. The basic principles of continuity and fluidity of the structures in nature such as the branching of the rivers and the circularity system of the veins can bring further understanding for the city planning and for dwelling systems designing by angularity in their connections. The city planning is as vital as the circularity, because the life depends on this system basically. The analysis of the branching of trees provide a further understanding of cantilever structures for more efficient design solutions to infrastructures such as shown in Figure 4.1(Senosiain, 2003).

Ingber (1998) pointed out that organic structures are composed by a universal set of building rules. The rules that nature applied recurrently can be found at every scales from simple molecules such as certain patterns, spirals and triangulations. These patterns can be seen in simple crystals to highly complex organic structures such as biological macromolecules (proteins, nucleic acids), cells and tissues. These basic principles guide the organizations of organic structures.

The organic structures are always tending to be in the state of minimal energy configurations. The structures that nature configures are occurred for maintaining the energy efficiency which is one of the main key for understanding the complex organic structures, sustaining structures, from each level from atom to the whole universe.

4.2. Natural Structures in Minimal Energy Configurations

Christopher Alexander expressed in Nature of Order, Book 1 (1980), “When we understand the art of building from the point of order, it not only changes our understanding of the building process, but also has the capacity to change our cosmology.” He mentioned the word order, as a concept of life which inheres in space itself as in biological structures. However, it can be understood as a general system of mathematical aspect that occurs because of the nature of space. He emphasized “It is the way to look to see what worked, studied it, try to distill out the essentials and wrote them down for maintaining the pattern language.”

The pattern language distilled out from the minimal energy shapes will be by analyzing the close-packing in nature, the connections in natural structures and the minimum energy configurations in nature while gaining dynamic stability. The outcome of these analyses will be in geometrical definitions as geometry is the language based on shapes for describing the things we analyze from our environment.

4.2.1. Close-packing for Minimal Energy Shape

Close-packing is one of the main problems that nature seems to solve by parting the limited area in the most efficient way. Close-packing is related to the proposition between the boundary and the area, or between the surface to volume.

The circle encloses the largest area within the minimum boundary, however as putted together to tile an area, gaps left in between. Although the square and triangle is more efficient for tiling a specified area, the proportions of the area to the boundary are not capable as circle (Pearce, 1978; Gaß et al., 1990).

Triangular packing is the sufficient way as fewer gaps appear and 7% more circles can be placed as shown in Figure 4.2. On the other hand, for the structural efficiency, triangulated systems are very stable, even with flexible nodes. In the aspect of efficient space filling of the circle and stability of the triangle, hexagon is playing the key role for tiling a space and gaining support at their junctions by three-arm node as each balance the stresses (Figure 4.3).

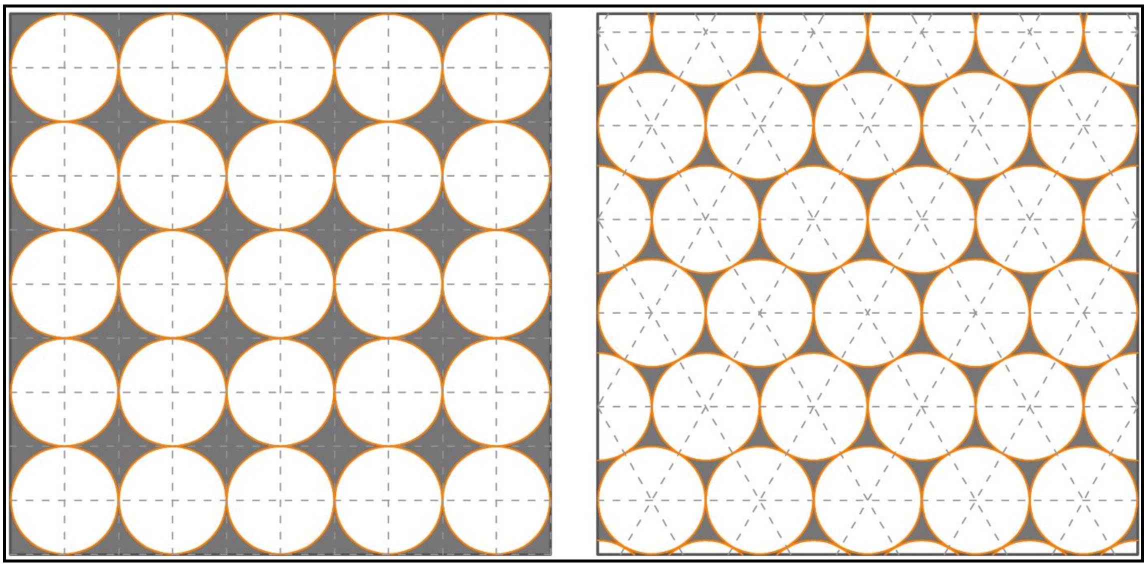


Figure 4.2. Square and triangular packing of equal circles in same sized area

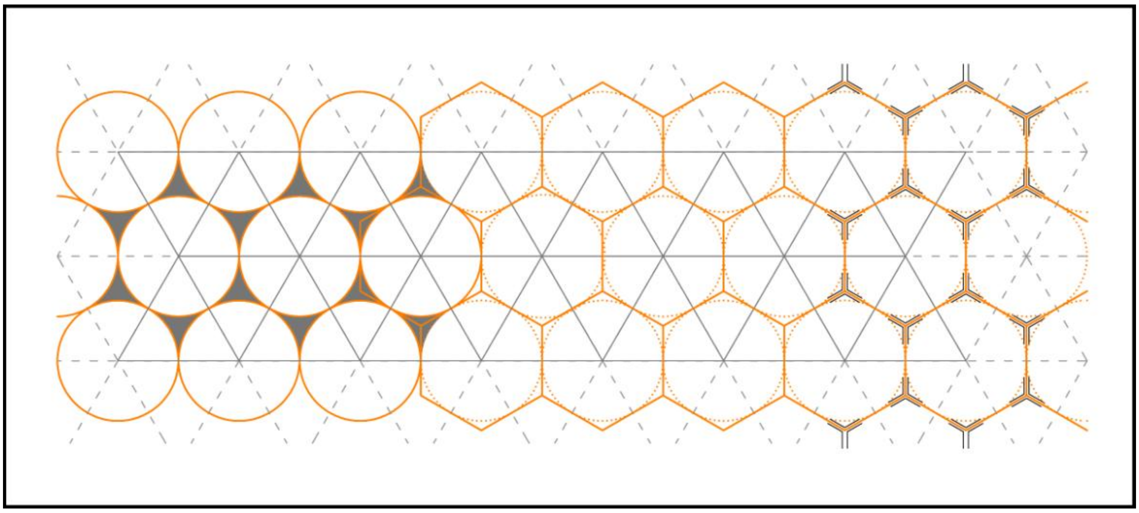
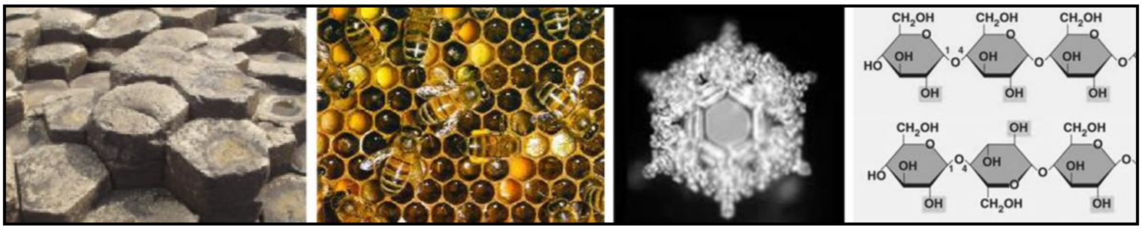


Figure 4.3. Hexagon is filling the space the most efficient way

The repeated or iterated pattern of hexagons is widespread in nature and seen in every scale, from unaided eye to micro-scale, as it is related to close packing in natural structures such as in Figure 4.4.



1)Basalt blocks on the Giants Causeway 2)Honeycombs 3)Snow Flake 4)Glucose monomers

Figure 4.4. Some examples of hexagons in natural structures
(Source: Scarr, 2009; Buzlu, 2010; Emoto, 2004; Campbell and Reece, 2008)

However, hexagons need to be triangulated for gaining stability in the physical and geometrical aspects. But, as seen in natural structures, they are in the triangular packing order with hexagonal shapes which requires less effort to maintain and more space to use efficiently. The junction points balance the hexagons in the most efficient way. So it is possible to synthesis the patterns of closest packing by the three armed node and hexagons as illustrated in Figure 4.3.

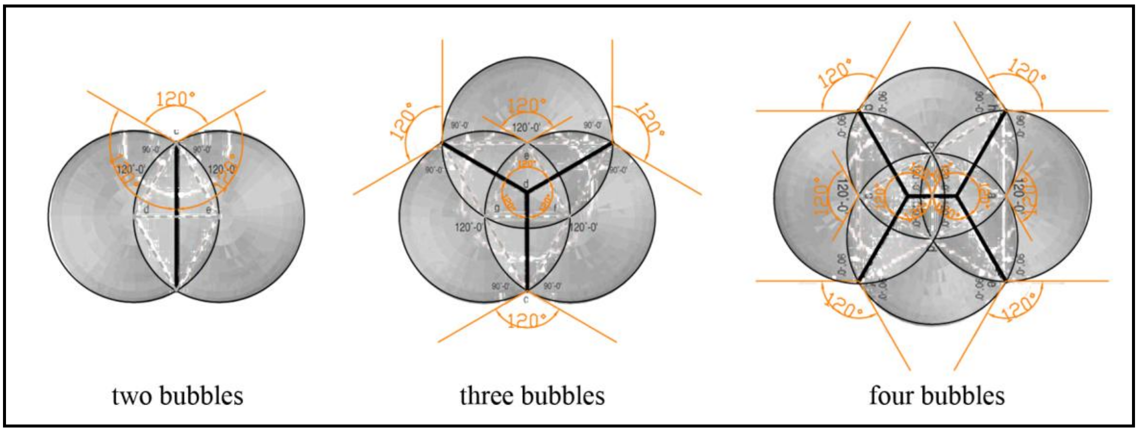
4.2.2. Three-arm Node

Some architects and engineers have made researches on the natural structures for building up lighter structures with the help of the technological advances. The development of lightweight structures can be counted as one of the greatest achievements in architecture (Senosiain, 2003). Frei Otto and his design theme is one of the researches that made some researches for seeking resistant and rational structures and published IL Series on natural structures and their possible applications in engineering.

Frei Otto (1995) declared the structural system of life as pneus. All living creatures form in pneu while come into being. The liquid filled envelopes grow, divide and reproduce by their internal pressures while interacting with the environment. The pneu formed as it is the most effective protection with its strong envelope. D’Arcy Thompson who spends a great deal on liquid dynamics also pointed out that cells behave like bubbles.

The bubble foam is used for experiments in many disciplines on analyzing the geometrical principles for minimal energy shape configurations. A single soap bubble which floats in space freely is in the form of a sphere. All forms in nature are occurred by the interaction of the forces. That is the reason that the soap bubble configures the sphere as it is the state of minimum potential energy.

When the main bubble associates with other equal size bubbles, the minimum energy shape configurations occur. When two or three bubble foams get together, the three angles are all equal, 120^{o} (Thompson, 1961). When the forth bubble is added in the plane, they configure also in triangulation and 120^{o}. The bubbles tend to form triangle as their tendency is to arrange themselves in triangulation for minimum energy shape (Pearce, 1978; Gaß et al., 1990; Stach, 2005; Scarr, 2009). The characteristic feature of all minimal way systems is the three arm node with the constant angle of 120^{o} as shown in Figure 4.5.



two bubbles three bubbles four bubbles

Figure 4.5. Two, three and four equal sized bubbles joining with 120^{o} angle

Briefly, the invisible forces which form the three arm node in 120^{o} appear when the bubbles get together. Three-arm node, consists of three arms and one nodal point, is the main simplest order in the formation of minimal energy shapes.

Most structures in nature can be regarded as three dimensional nets with variable sizes. The most flexible nets are the ones with three-armed nodes. In manmade structures, as five-six to eighteen armed structures exist, in natural world three-armed or four armed nodes are predominant (Gaß et al., 1990; Otto, 1995).

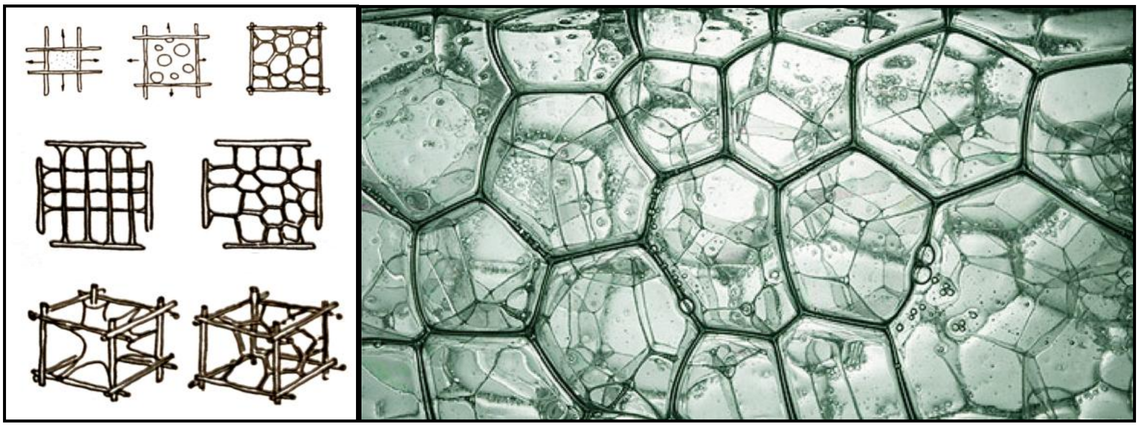


Figure 4.6. The bubbles form three armed nodes
(Source: Otto, 1995; Rit, 2010)

The nets form in two or three dimensions. These nets reform themselves by small displacements of the nodal points. This shows that the four legged nodes can turn into a three-legged node net. The net structure as being in a state of flow, can easily change and show a tendency to form in hexagonal pattern by shorten or lengthen the lengths of the links . The meshes can be shaped in pentagonal or heptagonal, but always in the configuration of three-arm nodes as shown in Figure 4.6 (Otto, 1995).

4.2.3. Platonic Solids in Nature

Two and three bubbles are located on a surface, the bubbles integrate with a constant angle 120^{o}. One bubble have potential to relocate and also two and three bubbles are in the same fluidity. After forth bubble is added to the three bubbles on a glass surface, the forth bubble directly locates on top of them forming tetrahedron (Stach, 2005). The state of flux is turned into a stable form, tetrahedron and it no longer can move and immobilized at the forth situation as shown in Figure 4.7 (Fuller, 1975).

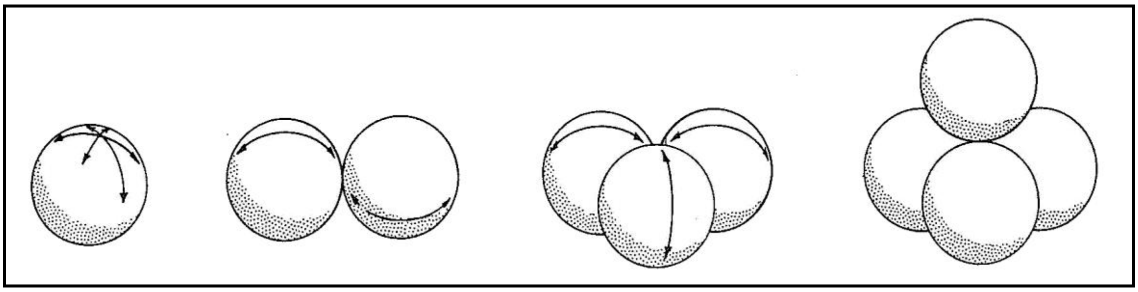
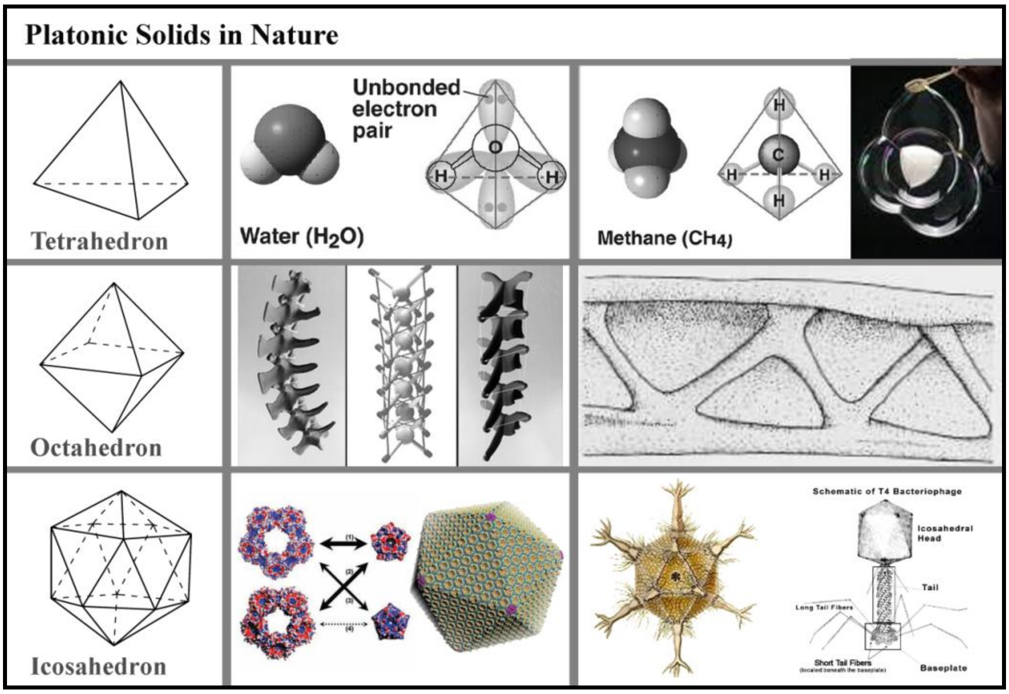


Figure 4.7. The state of bubbles turned into mobile or immobile situation
(Source: Fuller, 1975)

As defined before, tetrahedron is the prime solid, which is the first and most economical configuration. The tetrahedral shape is a repeating motif in molecules such as in water molecules and methane molecules, as the molecules form in most efficient bonding. In nature, even in the early embryo the four cells arrange as tetrahedron. After tetrahedron, the next most economic regular grouping of spheres is octahedron which is possible to be seen in the bones of birds as shown in Table 4.1.

The icosahedron is the third regular grouping of sphere which is in triangulated configuration and can be seen in varies forms in nature from proteins to virus heads. These solids are the triangulated platonic solids and provide stability.

Table 4.1. Platonic solids can be seen in natural structures
(Source: Thompson, 1961; Tanaka et al., 2008; Intensiondesigns, 2010; Nsf,2010)



- *Water and methane molecules configure and derive in tetrahedron. Bubbles form tetrahedron.*
- *The tetrahedron octahedron tensegrity of bones, The bone of the bird*
- *The icosahedrons the bacterial carboxysome shell, radialians and virus form in icosahedron*

4.3. Structure and Function of Biological Molecules

One of the main themes of biology is “Form and Function correlation”. The molecules gains stability in the defined function of the structure, however, they modify their structural form as the function changes. So the molecules are in dynamic stability, gains its structure by the function and when the function needs another configuration, the structure changes to another stabile form as shown in Figure 4.8.

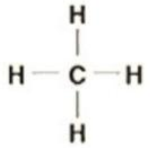
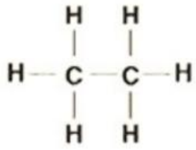
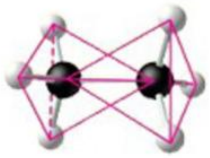
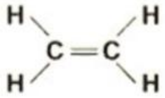
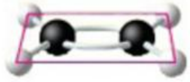
Name	Molecular Formula	Structural Formula	Ball and Stick Model	Space Filling Model
Methane	CH_4			
Ethane	C_2H_6			
Ethene	C_2H_4			

Figure 4.8. The molecular structures change respect to the functions.
(Source: Campbell and Reece, 2008)

The orderly arrangement of the atoms provides unique emergent properties to the biological molecules and macromolecules. The architecture of a large biological molecule helps us to understand how that molecule works. In that case, we will examine the structural hierarchy in respect of physical hierarchy in the non-living and living organisms and the systematic in providing the cell membrane considering the structural configurations.

4.3.1. Physical Hierarchy

In the entire world, structures exist at levels of biological organizations ranging hierarchically from non-living units; atoms, molecules and molecular compounds, biological macro molecules, to living units; cells, tissues, organs, organisms and further ecosystem level. The higher levels are composed of the copies of the lower-level structures in a defined rule of organization.

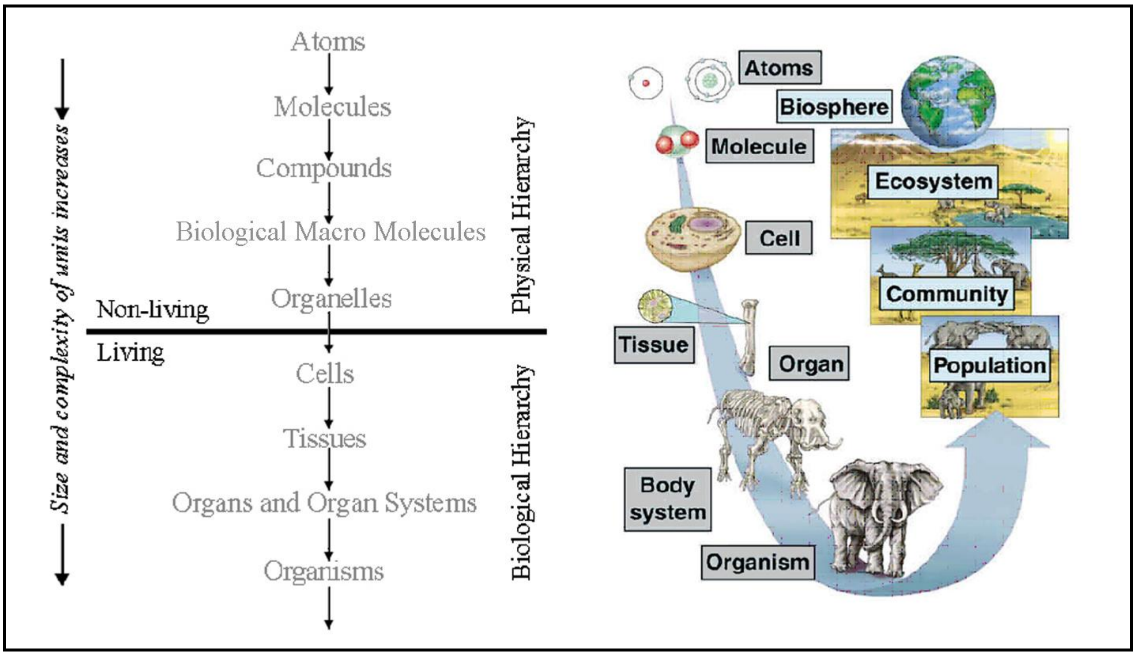


Figure 4.9. Physical Hierarchy of levels in the organisation of organic structures (Source: Uxl, 2010; Tutorvista, 2010)

Campbell and Reece (2008) defined seven unifying themes that connect the concepts of biology.

- New properties emerge at each level in the biological hierarchy.
- Organisms interact with their environments, exchanging matter and energy.
- Structure and function are correlated at all levels of biological organization
- Cells are the life’s fundamental units of structure and function.
- The continuity of life is based on the heritable information in the form of DNA.
- Feedback mechanisms regulate biological systems.
- Evolution accounts for the unity and diversity of life.

Components interact to each other for obtaining larger organic structures by exchanging matter and energy. Every level emerges in different properties that cannot be predicted by the characters of the parts that compose the upper level. The size and complexity increases at each level of physical and biological hierarchy as shown in Figure 4.9.

Cells are the life's fundamental units in the means of structure and function. In the process of forming cells the non-living units have a structural hierarchy. In that case, it is vital to understand the components.

- Atoms; the smallest units for both non-living and living are protons, neutrons and electrons which combine atoms in a specific manner. The main atoms are carbon, hydrogen, oxygen, nitrogen and phosphate and sulfur. Atoms are the elements such as H, O, C.
- Molecules; a group of same atoms held together by energy in a stable association such as H_2, O_2.
- Compounds; a molecule contains atoms more than one element such as H_2O. The molecules form in chains to maintain the compounds. When the chain molecules have a carbon skeleton, they are called biological macromolecules.
- Organelles; they are also called as structures. The molecular compounds are in an architectural order to build up the organelles. But they are not classified as living units.
- Cell; the organism's basic units of structural organization in an organism. Cell requires a boundary (membrane) and functional organelles.

Building up is the process as complexity starts even in the molecular level, not down. That's the reason analyzing from the molecular level is vital for understanding the building code.

4.3.2. Systematics in the Components of Cells

The systematic in cell is mostly demand on minimal structural configuration of the components. The chemical and structural configurations mostly resemble from one cell to another. These similarities tempted the scientists to search for a systematic in their structural order. The components that build up the cells are mobile in contrast to man-made structures, such as concrete and steel buildings. For understanding the systematic of cells, the physical attributes of the components is a deep well to consider

In the design of the simplest cells, the molecules arrange in a defined manner to build up the upper fibrils and molecular filaments and further the cell boundary, the cell membrane such as shown in Figure 4.10 and Figure 4.11. The cell membrane usually forms in spherical configuration. David Boal (2002) explains the logic behind the shape is for enclosing a given area with minimal energy configuration just like building a minimal town wall for a defined field is by a circular wall.

As explained, in the beginning of this chapter, minimal-energy configurations are the nature's main principle for building up the organic structures level by level.

Boal pointed out that, by their research, they found that the designs that uses the available materials effectively generates structural elements that work cooperatively in order to function. Boal concludes his enthusiasm for the research on the mechanics of the cell by these words; "As we better understand the nature's building code, we will discover subtle features that may have application beyond the cellular world."

There are many routes to the understanding of complex systems in nature. Even in the cellulose and muscles arrangement, there is a structural order in the process of making up the upper levels as shown in Figure 4.10 and Figure 4.11. The lower levels build in the minimum energy configurations to build up the upper levels. The whole of a structural group became a part of the upper levels structural group.

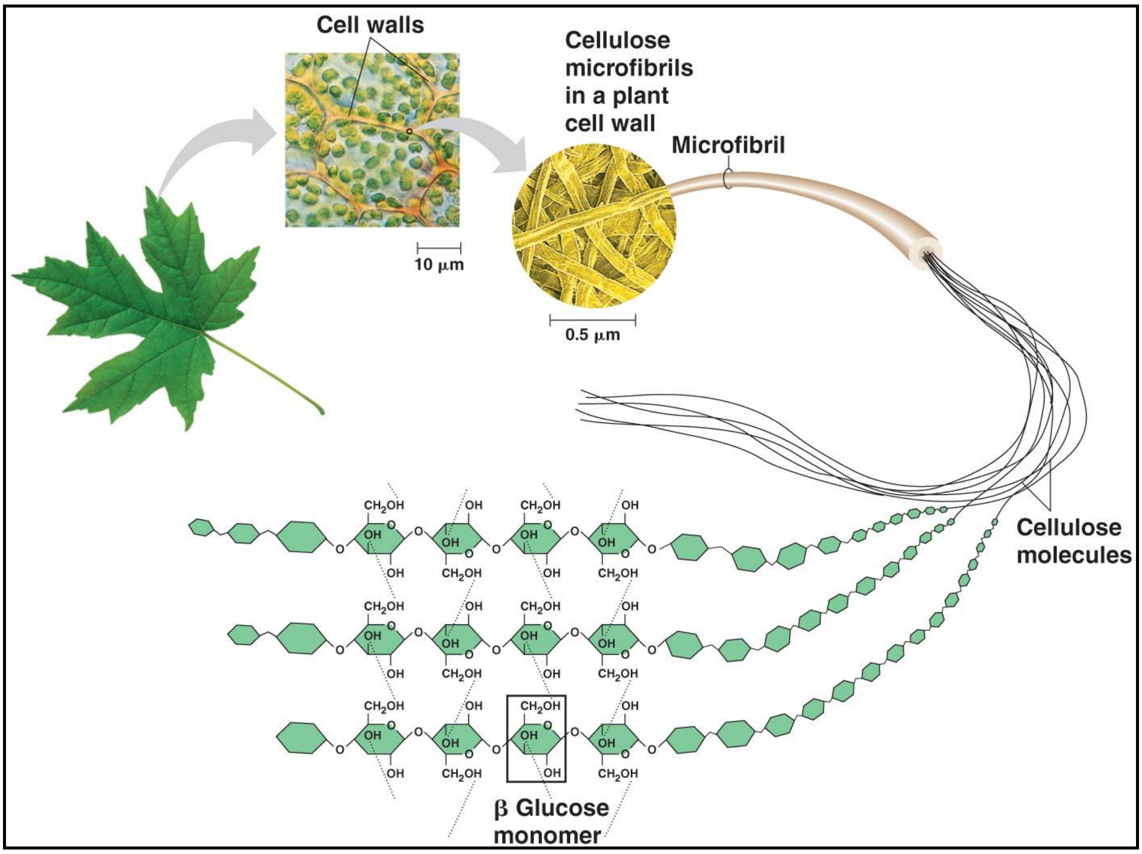


Figure 4.10. Arrangement of cellulose in the process of forming plant cell walls (Source: Campbell and Reece, 2008)

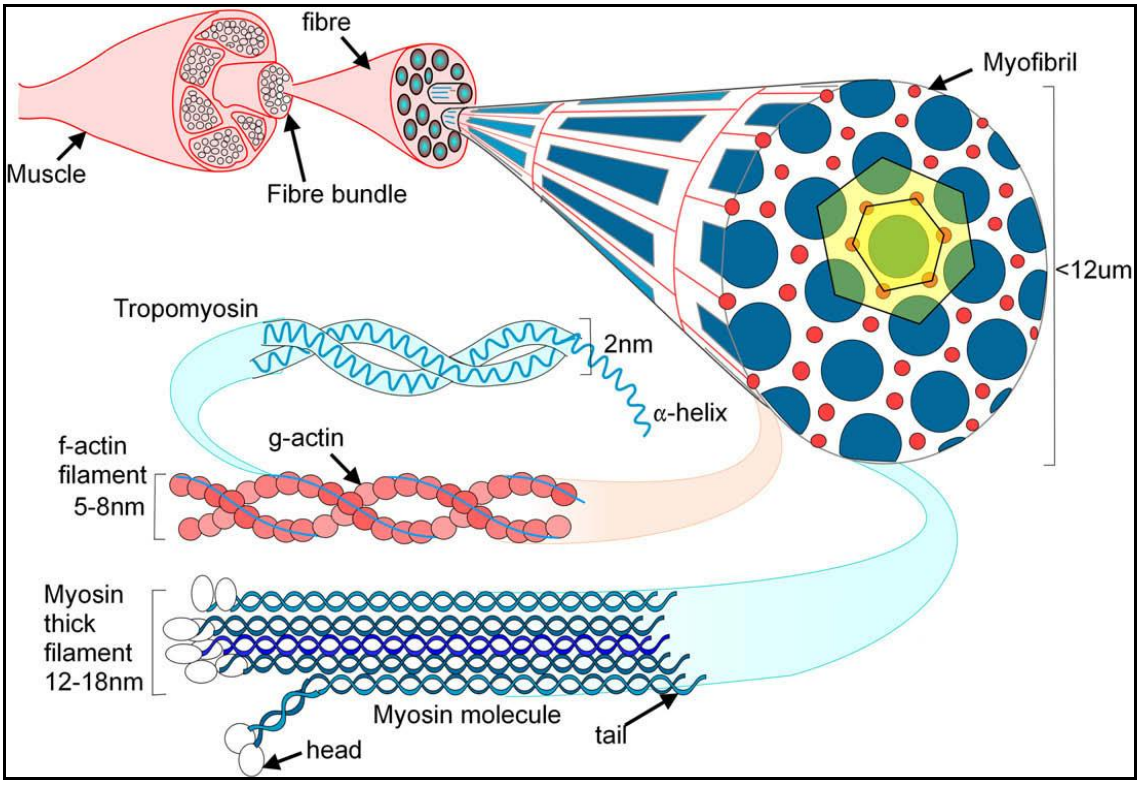


Figure 4.11. Arrangement of myofibrils in the process of forming muscles.
(Source: Scarr, 2009)

Structural system exists for all the living creatures in the same manner (Sheldrake, 1991; Otto, 1995). That's the main reason studying the living creatures not only in terms of species; animals, plants and so on but also in terms of biological structures are significant for understanding deeper. Even we can think that organisms have wide diversity of molecules. There are only four classes of main important biological molecules; carbohydrates, lipids, proteins, and nucleic acids, which all together compose for diversity.

The cell membrane without which life cannot be existed is composed of the carbohydrates, lipids, proteins and the information from the nucleic acids as illustrated in Figure 4.12. The structure and function of the cell depends on the cell membranes. The cell membrane maintains equilibrium and adapt to the external and internal pressures by changing its form and structure.

For deeper analysis, as the architecture of a large molecule helps us to understand how the molecule functions, the order of biologic molecules can provide a new perspective for new innovations. The large biological molecules, polymers are composed of monomers. In Greek, 'poly' means 'many' and 'meris' means 'part', emphasizing that they are composed of many parts. There are only 40-50 common monomers for constructing the wide diversity of polymers. Mainly, the key is the arrangement that the monomers follow a particular linear sequence. The order of the atoms and molecules give new emergent properties to the appeared structures. In that case, analyzing the structural properties of large biological molecules; carbohydrates, lipids, proteins, and nucleic acids are significant.

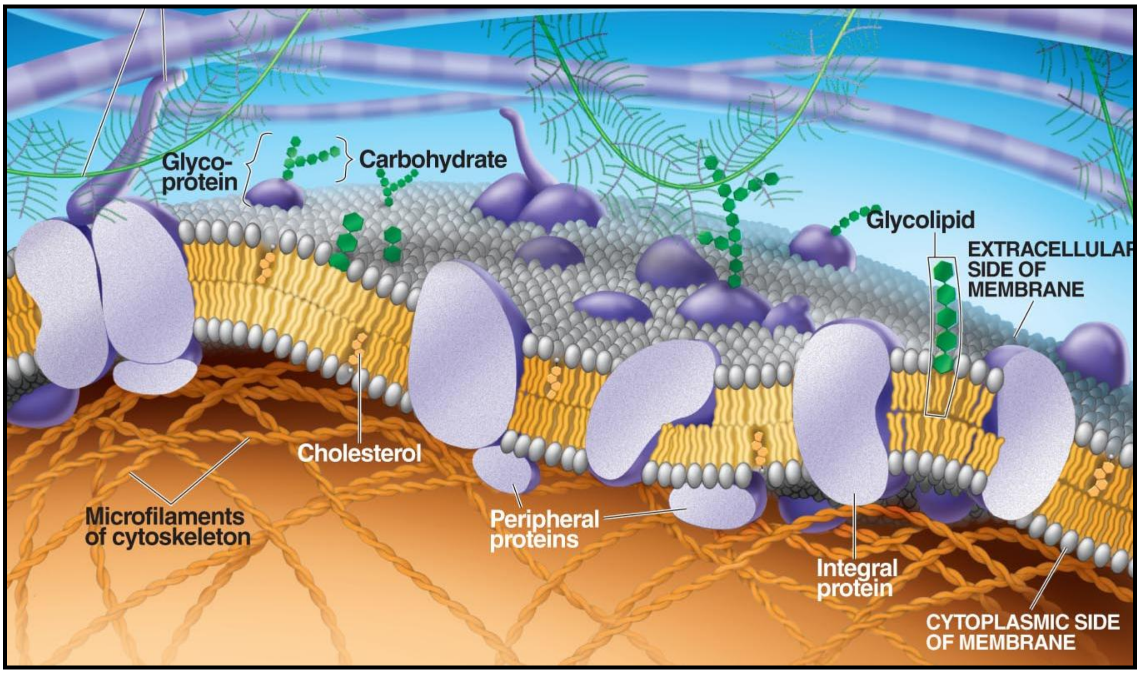


Figure 4.12. Cell membrane model
(Source: Campbell and Reece, 2008)

The following sections 4.3.2.1, 4.3.2.2, 4.3.2.3 and 4.3.2.4 information is summarized from Campbell and Reece, 2008, unless indicated.

4.3.2.1. Carbohydrates

Carbohydrates serve as fuel and building materials for all living structures. Monosaccharides are the basic form and verifies by the carbon molecules arrangement. They are not just the fuel for the cellular work, the parts can also change into other types such as aminoacids and fatty acids. The main monosaccharide is the glucose molecule which is also named as the source of life. There are two types of glucose molecules, α and β ring formed glucose as shown in Figure 4.13. Polysaccharides are composed of the arrangement of the monosaccharides and maintain storage or structural properties.

The structure and function of the polysaccharides are determined by its monomers and the linkage between the monomers. The storage polysaccharides are starch and glycogen and the building polysaccharides is the cellulose. Parallel cellulose molecules held together to form microfibrils which form the cell wall in plants such as shown in Figure 4.10 and Figure 4.13.

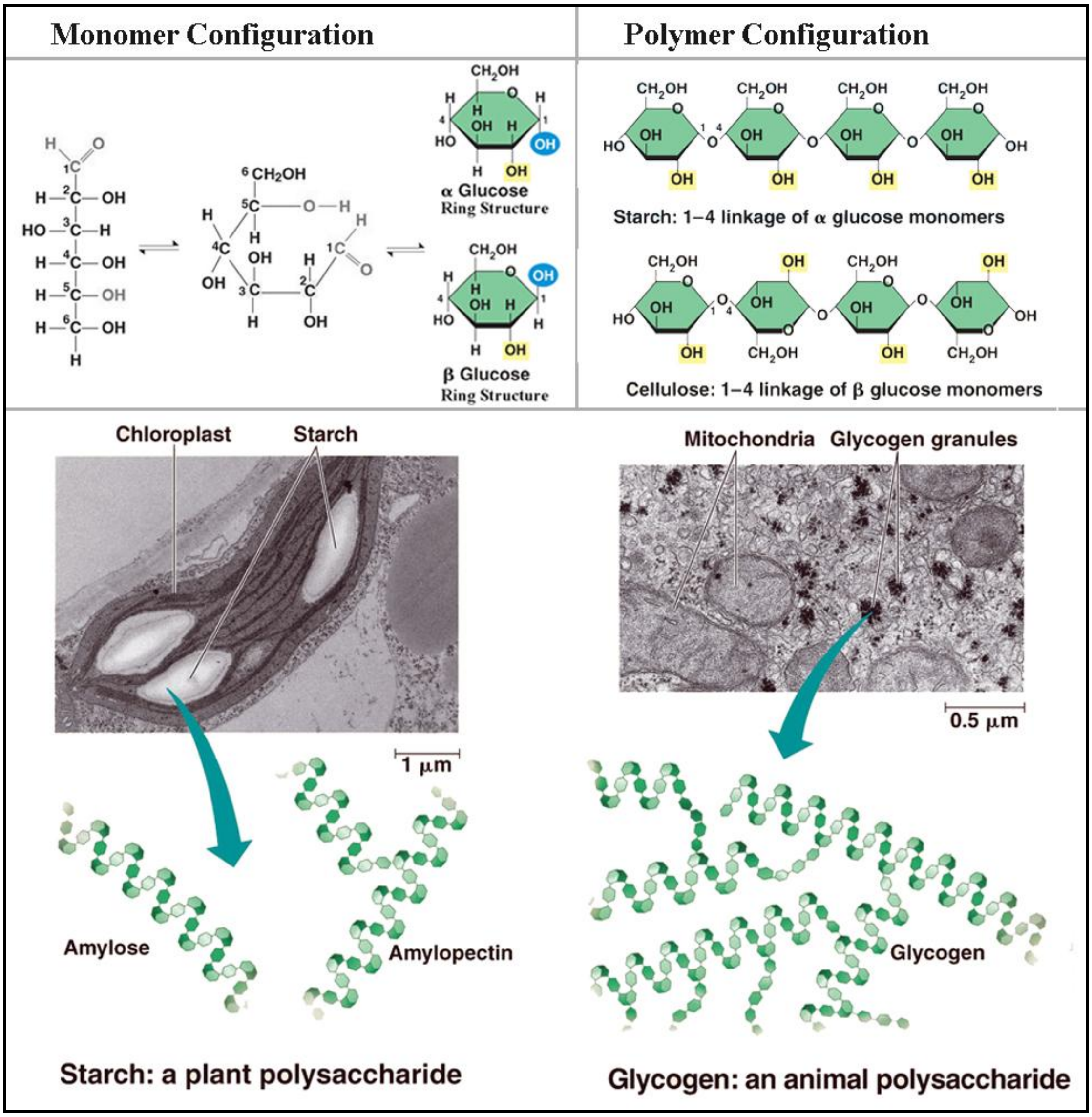


Figure 4.13. α and β ring structure of glucose composing starch or glycogen

4.3.2.2. Lipids

Lipids do not form in polymers as they are not large enough to be considered as macromolecules. Lipids vary in form and function. The most important lipids are fats, phospholipids and steroids.

Fats major function is energy storage and is constructed from three fatty acids differing in length joined to glycerol. When the structure has its maximum bonding, they are solid, and when they are unsaturated- having bonds to be reacted- they are fluid at room temperature (Figure 4.15).

Phospholipids are the major components of all cell membranes and are composed of two fatty acids and phosphate group attaching to glycerol. Phospholipids self-assembly into a bi-layer structure when they are put into water. An important property of the phospholipid bi-layer is its fluid organization that gives capability of the lipids and proteins to turn around or develop (Demirsoy, 1970). This property is highly significant for the cell to balance its inside pressure according to outside. The bi- layer phospholipid membrane the phospholipids have lateral movement or flip-flop movement and they change their forms according the saturation of inside and outside as shown in Figure 4.14. The cell membrane’s fluidity depends on the changing conditions.

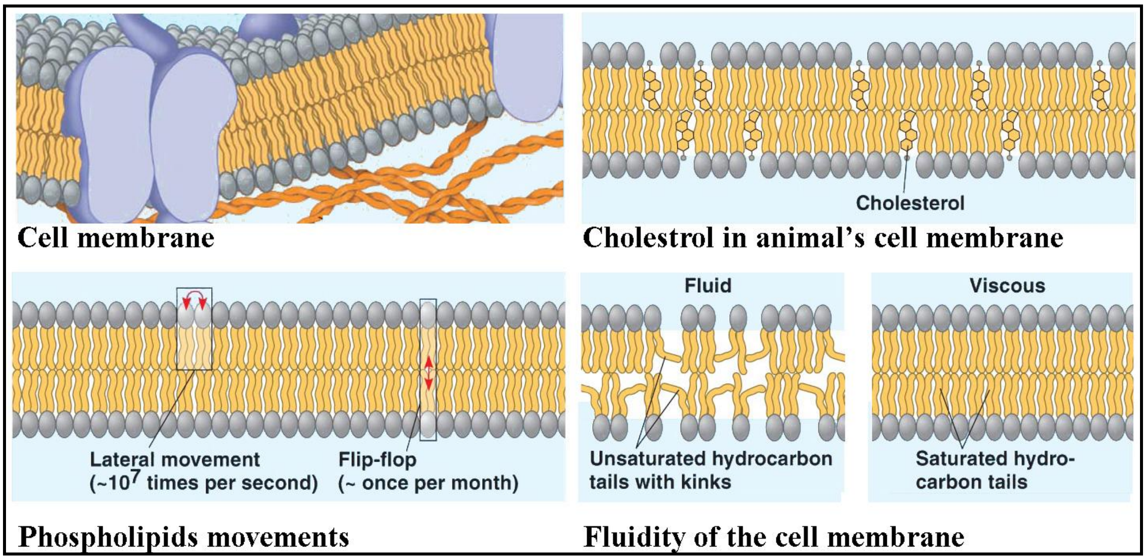


Figure 4.14. Phospholipid bi-layer

Steroids are composed of four associated rings. Cholesterol and hormones can be given as an example to steroids. Cholesterols are structurally important in the animal’s cell membranes as shown in Figure 4.14 and Figure 4.14.

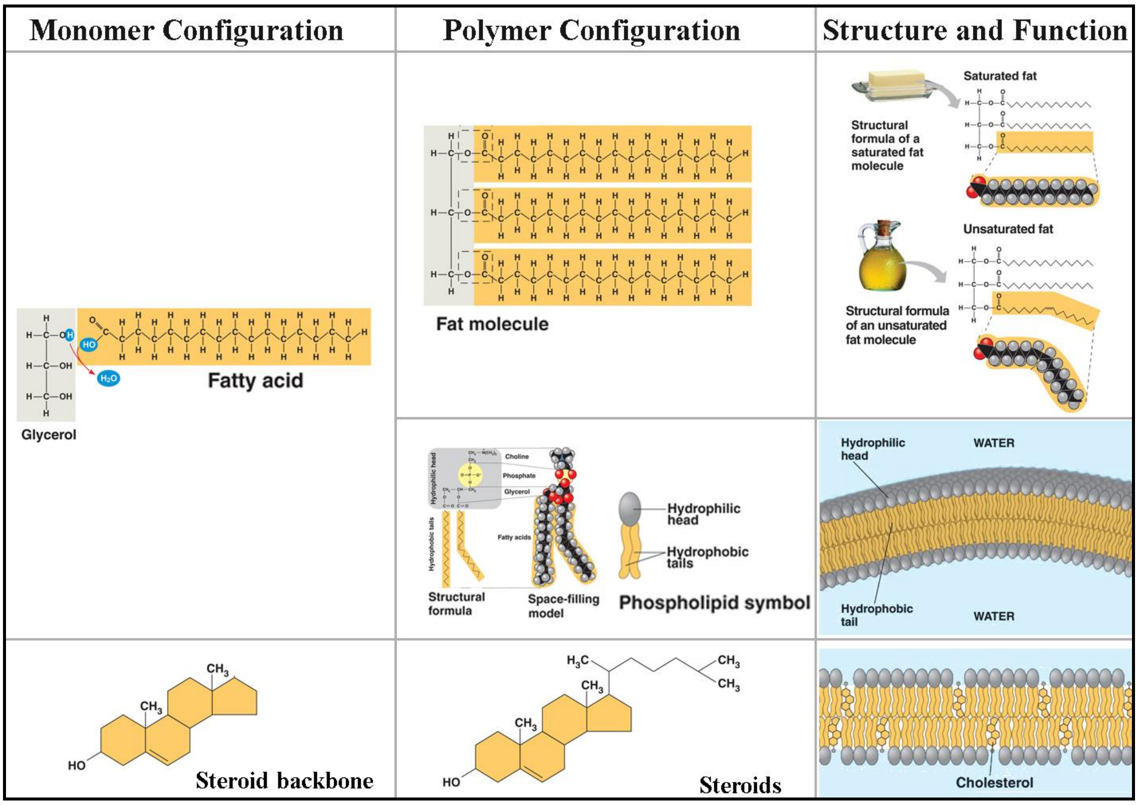


Figure 4.15. Fatty Acids and Steroids make up the fluid bi-layer.

4.3.2.3. Proteins

Mostly, every dynamic function of an organism depends on the proteins which have many structural arrangements resulting in a wide range of functions. Some proteins have a sequence of polypeptides for speeding up the chemical reactions-enzymes, some in structural support, storage, transport, cellular communication, movement and some for defense. Aminoacids are the building blocks of polypeptides, polymers that form proteins. There are 20 aminoacids changing properties depending on their side chains namely functional groups (R groups). The polypeptides differ from the length of this sequence. The aminoacid sequence determines the 3D structure of a protein. Many proteins are roughly spherical or shaped like long fibers. A protein is consist of many polypeptides twisted, folded and coiled. There are 4 levels for protein structure, primary structure is the sequence of the aminoacids, secondary structure is the coiling, twisting and folding in α helix (helix form) or β-pleated structure (mostly hexagonal) occurred by the chains of polypeptides, tertiary structure is determined by the interaction of the R groups (Figure 4.16), and lastly, quaternary is the final protein consisting of multiple polypeptide chains.

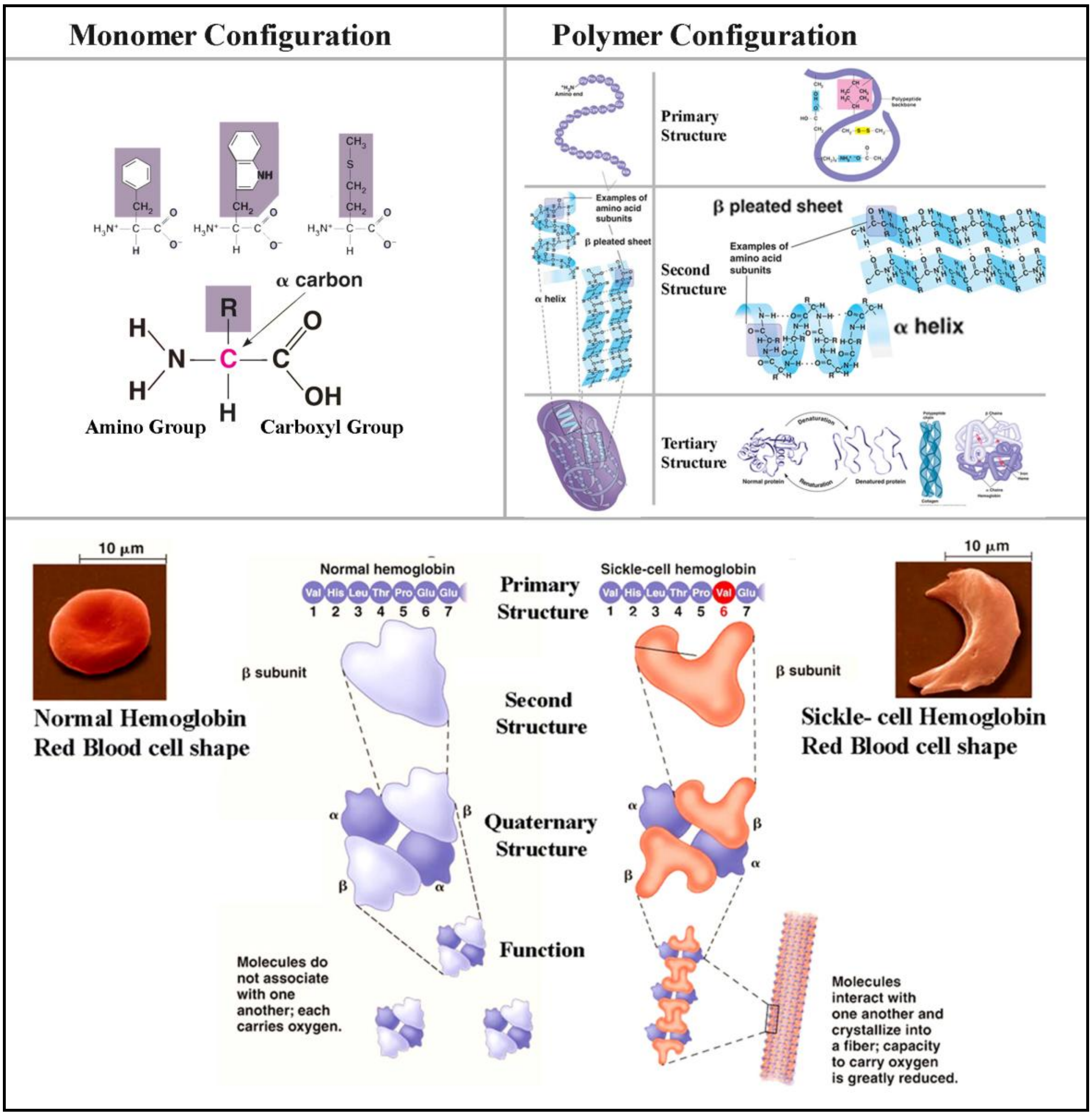


Figure 4.16. Protein Structure depends on the aminoacids sequence

4.3.2.4. Nucleic Acids

Amino acid sequence of a polypeptide is informed by genes. Genes are defined as specific sequence of DNA, a nucleic acid as shown in Figure 4.16. Nucleic acids are the heredity information storage and transmitters. There are two types of nucleic acids, Deoxyribonucleic and Ribonucleic acid. Nucleotides are the monomers of nucleic acids and composed of nucleotides; a nitrogenous base, a pentose sugar and a phosphate group. The nitrogenous bases are six-legged or fused six and five legged members generating the purines and pyrimidines (Figure 4.17). The pentose sugar varies according to its function as DNA or RNA. The sequence of nitrogenous bases along a

DNA or mRNA polymer is unique to every gene. A DNA molecule forms a double helix, composed of two polynucleotides spiraling around a imaginary axis.

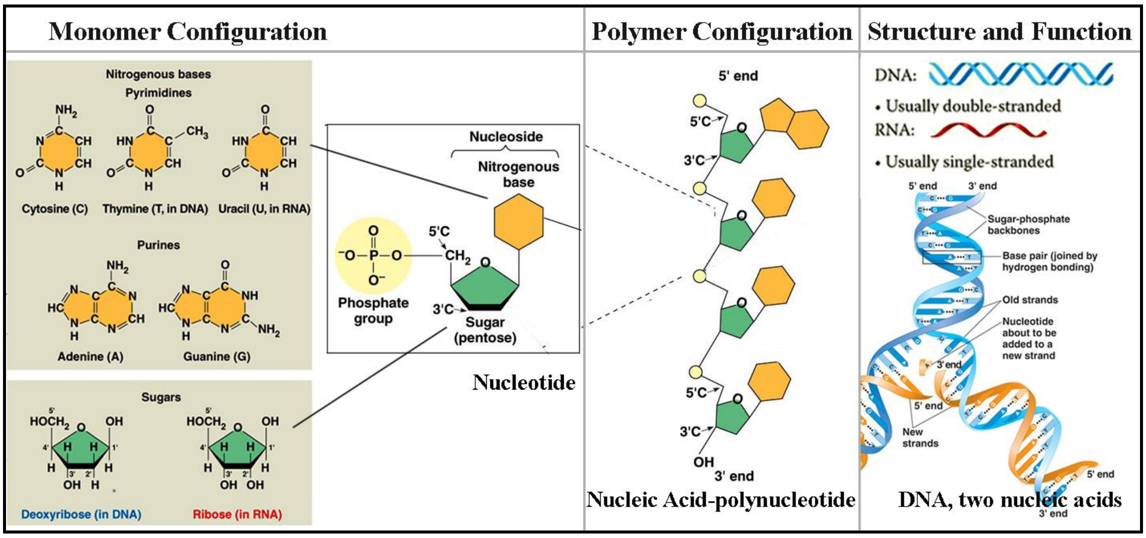


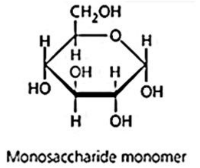
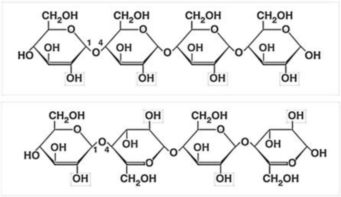
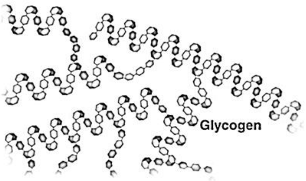
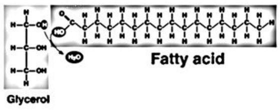
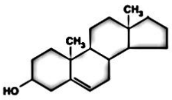
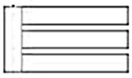
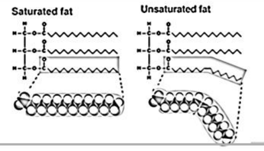
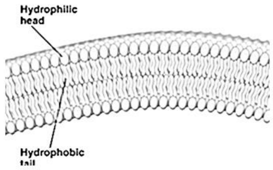
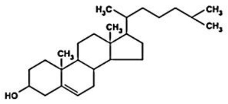
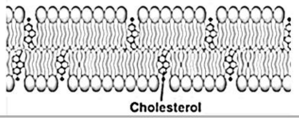
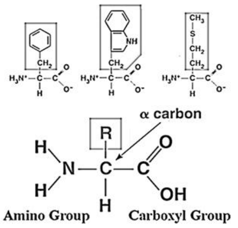
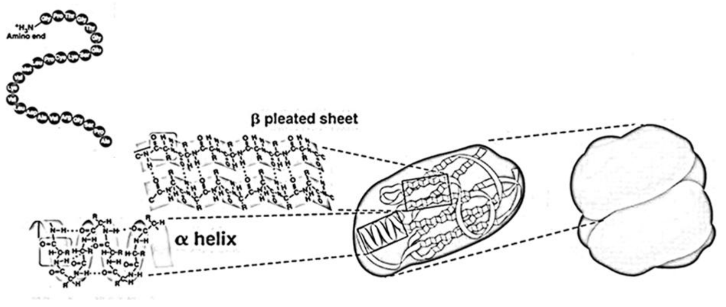
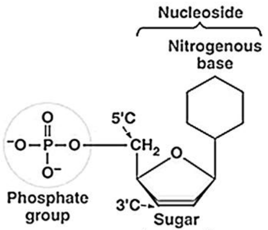
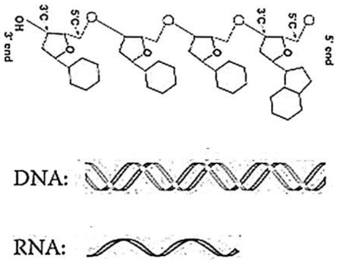
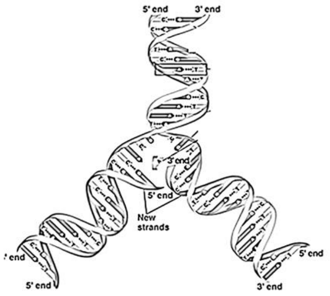
Figure 4.17. DNA and RNA are composed of nucleotides.

4.3.3. Table of the Structural Order in the Components of Cell

Table 4.2. Structural configurations of biological macro molecules

	Monomers	Polymers	Structure and Function Configurations
Carbohydrates	Ring configuration	Linking in parallel configuration	Parallel and ring configuration
Lipids	Ring and linear configuration	Linking in various configuration	Linear and Bi-layer configuration
Proteins	Ring and linear configuration	Linking in various steps, linear, helixal and hexagonal	Spherical configuration
Nucleic Acids	Ring and linear configuration	Linking in parallel and helixal configuration	Double-helix configuration

Table 4.3. Structure of biological macro molecules

	Monomer	**Polymer**	**Structure and Function**
Carbohydrates			
	Ring *configuration*	*Linking in **parallel** configuration*	***Parallel and Ring***
Lipids	 		
			
			
	Ring *and* ***Linear*** *configuration*	*Linking in various configuration*	***Linear and Bi-layer***
Proteins			
	Ring *and* ***Linear*** *configuration*	*Linking in various steps,* ***Linear****,* ***helixal*** *and* ***hexagonal***	***Spherical*** *configuration*
Nucleic Acids			
	Ring *and* ***Linear*** *configuration*	*Linking in **parallel** and **helixal** configuration*	***Double-helix***

4.4. Conclusion

The minimum way of close-packing property in natural structures and the structural order in the building sequence of the natural structures are treasures to focus on. The clues from nature provide richness and efficiency in the design process.

In conclusion, from the analysis of the minimal energy configurations, the hexagonal grid, triangular packing and three-arm node, tetrahedron and Platonic Solids are taking an important role from macro level to micro level. Besides, the non-living structures which are significant of the adaptation of the living units; the cell membrane components, are analyzed. The outcomes from these analyses are mainly the structural order of the monomers and polymers. All the monomers form in linear and ring configurations depending on their structure and function that they build up the polymers. The monomers link in various configurations, parallel, linear, helixal or hexagonal to form the polymers. The structural configurations of the units for structure and function are mainly in parallel, ring, linear, bi-layer, spherical and helixal configurations. They are mostly in dynamic stability or in fluid bi-layer configuration as shown in Table 4.3.

Natural structures are successful not only by their minimal energy configurations but also their minimum effects by their interactions on their environment.

> One could almost redefine biology as the natural history of deployable structures. An organism is successful partly because it uses minimum amount of material to make its structure and partly because it can then optimize its use of that material so that it can influence as much of its local environment as possible (Vincent, 2001).

The molecular configurations have potential for deployable structures. From the geometry of natural structures, the hexagonal grid, triangular packing, three-arm node intersecting at 120^o, tetrahedron are synthesized. From the motion of the structures analyzed by biological macro molecules; the ring configuration and linking principles are emphasized for design process. The outcomes of nature’s building code will be analyzed by mechanical aspects for maintaining a kinetic node.

CHAPTER 5

SPACE LINKAGE MECHANISMS

Architects and engineers search for stability of the structure, but the mechanical engineers usually deals with the mobility of the linkages. In general, a structure or a mechanism is composed in similar ways. Structure is composed of resistant bodies resisting to loads, and in general, structural stability is one of the main requirements. Although, the structures are mostly designed with fixed connections for stability, alternate structures which are capable of geometrical transformation also exist and they are commonly known as deployable structures. In our daily life, we are getting benefits of closed loop linkage mechanisms - deployable structures; such as umbrellas, foldable chairs, and more recently solar panels and deployable roofs. These are achieved because of their capability of geometrical transformation.

5.1. The Design Process of a Mechanism

A mechanism is a mechanical device that has the purpose of transferring motion and force from a source to output. Any machine or device that moves contains one or more kinematic elements such as linkages, cams, gears and belts. In the design process of a mechanism, mainly the generation of a mechanism or selection of a particular mechanism is concerned. Achieving the desired motions for a mechanism, determination of the mechanism type, numbers and types of the joints and links, and also the geometric configurations of the links are significant.

The process of mechanism design is passing through identifying the problem, structural and dimensional synthesis and kinematic analysis as shown in Figure 5.1.

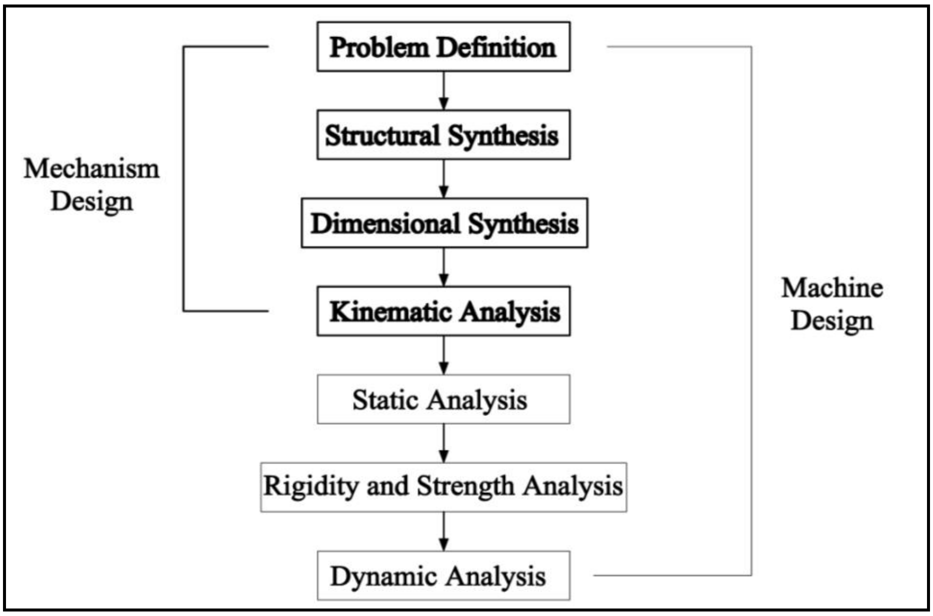


Figure 5.1. The mechanism and machine design process
(Source: Yan, 1998)

Synthesis means to search for a problem which has diversity of solutions that meet the design requirements, besides analysis is the process for verifying a single right answer for the design requirements. Structural synthesis seeks to determine the topology of the linkage type, the jointing type and the number of degrees of the linkage -mobility- for the desired requirements. Dimensional synthesis seeks to determine the exact dimensional proportions; angles, link lengths and pivot distances, and starting position for the determined task and performance. Dimensional synthesis is the process for generating a mechanism. Kinematic analysis deals with the motion characteristics of its components such as velocity, acceleration and position.

This chapter deals with structural synthesis which is the determination of the linkage types, joint types and mobility. These are the fundamental of linkages. Very basic and early decisions in the design process involving kinematic principles can be crucial to the success of any mechanical design.

5.2. Fundamentals of Linkages

A linkage is composed of rigid bodies (links) and connected by kinematic pairs (joints). When it is movable with respect to a reference point or fixed link, it is called a mechanism. Links are connected to form one or multiple open or closed chains. Mechanical linkages are designed for producing an output regarding to an input.

5.2.1. Rigid Body in Space

A rigid body is the solid that does not change its shape or size. For defining a rigid body in space, we need 6 parameters to define it, the coordinates of its center and the rotations of itself; x, y, z, α_x, α_y, α_z as illustrated in Figure 5.2. Hunt (1978) defined, when the number of constraints or unfreedoms is named as *u*, the number of freedoms is named as *f*. In terms of any free rigid body, the total of u and f should be 6 that define the space as in Equation 5.1.

$$u+f = 6 \tag{5.1}$$

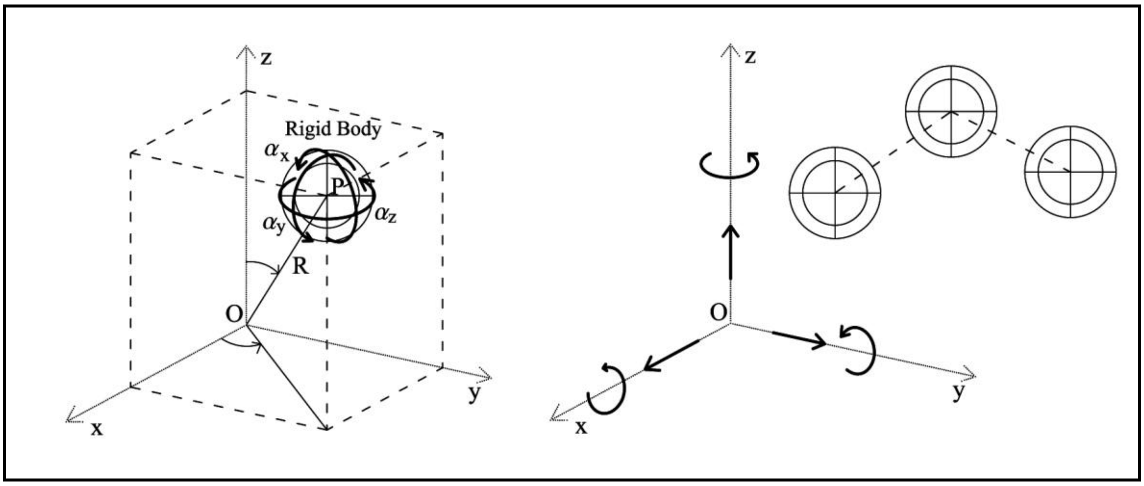


Figure 5.2. Rigid body in space

The degrees of freedom are predicted by the contact relations between the rigid body and referenced coordinate system. Hunt (1978) defined as *n* bodies are all completely unconstrained, one of them can be chosen as the reference body so the total number of relative degrees of freedom is defined in Equation 5.2.

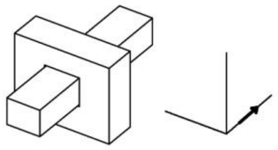
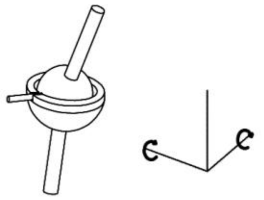
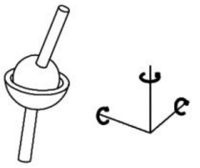
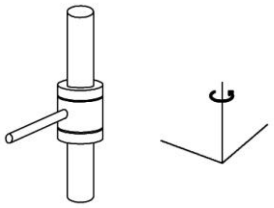
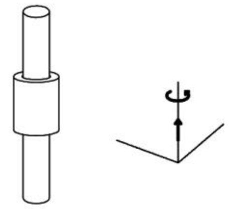
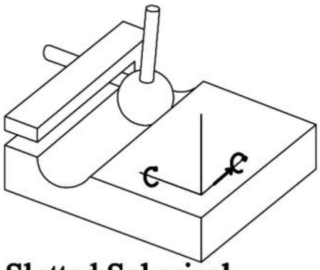
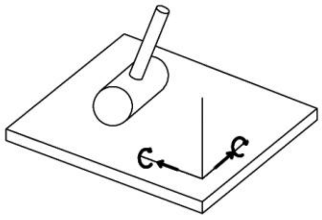
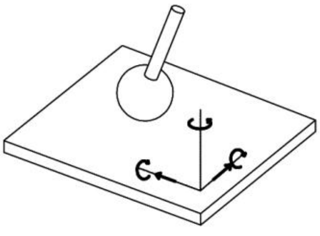
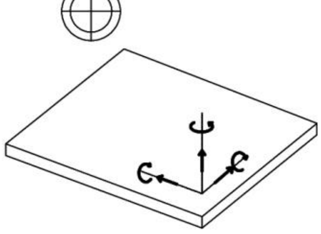
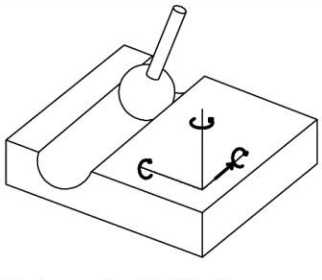
$$\sum motion = 6(n-1) \tag{5.2}$$

The independent constraints between the bodies are called joints, kinematic pairs which are the connectors of *n* number bodies.

5.2.2. Kinematic Pairs, Joints

Joints, also called the kinematic pairs, are the connections between one or more links. The joints have various degrees of freedom that allow the motion between the links.

Table 5.1. The degrees of freedom and joint types

DoF	**1**	**2**	**3**
KINEMATIC PAIRS, Lower Pairs	 **Prismatic, P**	 **Slotted Spherical**	 **Spherical**
	 **Revolute, R**	 **Cylindrical**	 **Slotted Spherical in Cylinder**
DoF	**4**	**5**	**6**
KINEMATIC PAIRS, Higher Pairs	 **Cylinder on Plane**	 **Sphere on Plane**	 **Rigid Body in Space**
	 **Sphere in Cylinder**		

There are mainly two types of kinematic pairs, lower pairs and higher pairs. As ‘pair’ means the relationship between two members, kinematic pair conveys the relationship between the members as jointed. Lower pairs have surface or area contact, while higher pairs have point or line contact. Table 5.1 shows the relation of the kinematic pairs and the degrees of freedom. In the table the rotational motion is shown by circular line along the axis, and translation is shown by a straight line on the axes. Lower pairs, such as prismatic, P for translation, revolute, R for rotation with *dof* equal 1 shown by one circular or straight line. The other *dof* 1 kinematic pair is helical joint, H have screw motion with translation and rotation at the same time.

The number of degrees of freedom of the joints may take any value from 1 to 5 as;

$u = 0$, so that means f = 6 it means there is non-contacting

$u = 6$, so that means f = 0, it means the system is fully rigid (Hunt, 1978).

5.2.3. Kinematic Chains

Mechanisms are obtained by the kinematic chains which are the assemblage of links and joints, connecting in a defined way for providing a controlled output motion in response to the given input.

The kinematic chains are linked to the ground at least with one link or be in reference to a frame as illustrated in Figure 5.3. The kinematic chains can be open - always have more than one degree of freedom - or closed mechanisms which have no open attachment points or nodes and may have one or more *dof* (Norton, 1992).

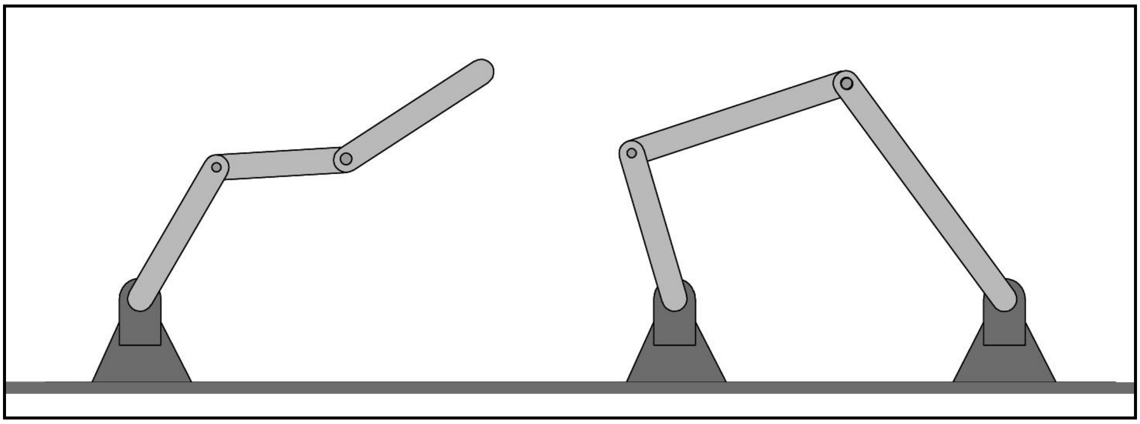


Figure 5.3. Open and closed kinematic chains

Dof of mechanisms shows whether the kinematic chain is a mobile mechanism or a structural group.

dof > 0, when dof is found more than zero, then it is called a mobile mechanism

dof = 0, when dof is found equal to zero, then it is called a structure.

dof < 0, when dof is found less than zero, then it is called a preloaded structure

When the dof of a mechanism is zero, then it is defined as a structural group, which cannot be divided into other groups. The determination of the linkage system whether it is mobile or structural group, is significant for mechanism design. The number of independent input parameters is the mobility of a mechanism. It is possible to predict the mobility directly from the number of the links and the joints in the system.

Calatrava is one of the famous architects that integrate the structural mechanisms into architectural applications in extraordinary way. He used 4 bar linkage mechanisms which provide planar motion in most of his mobile structures. Two of the examples are Ernsting Warehouse and Distribution Centre (Figure 5.4) and Pfalzkeller Emergency Service Center (Figure 5.5).

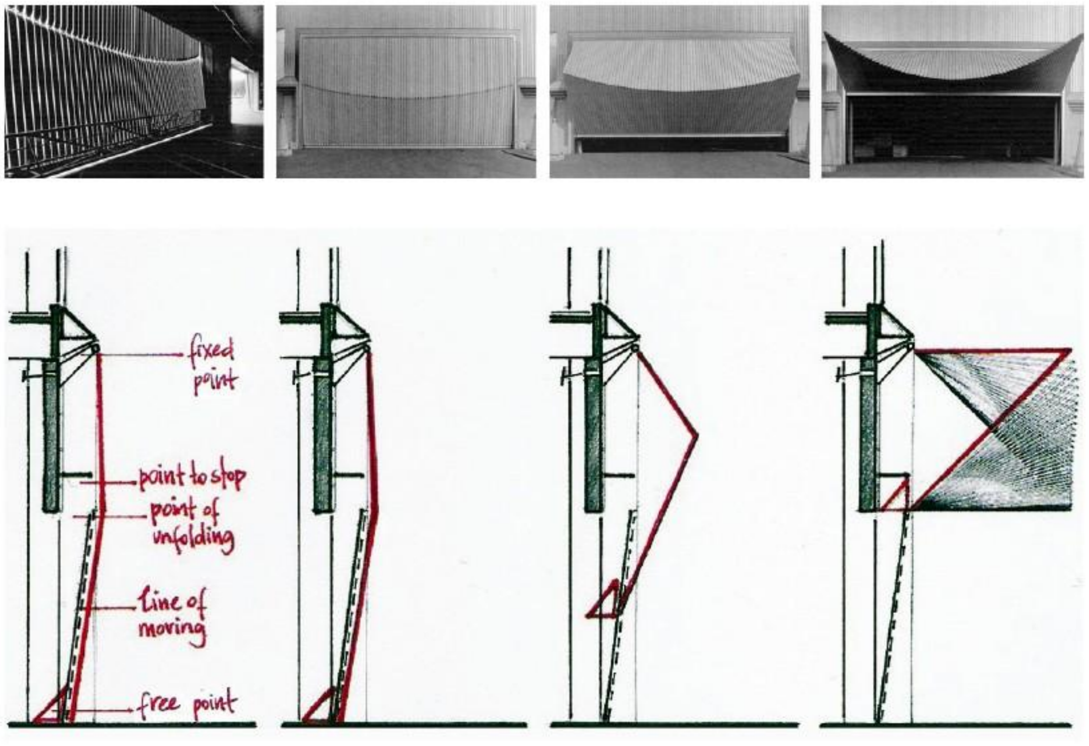


Figure 5.4. Ernsting Warehouse and Distribution Centre
(Source: Yıldız, 2007)

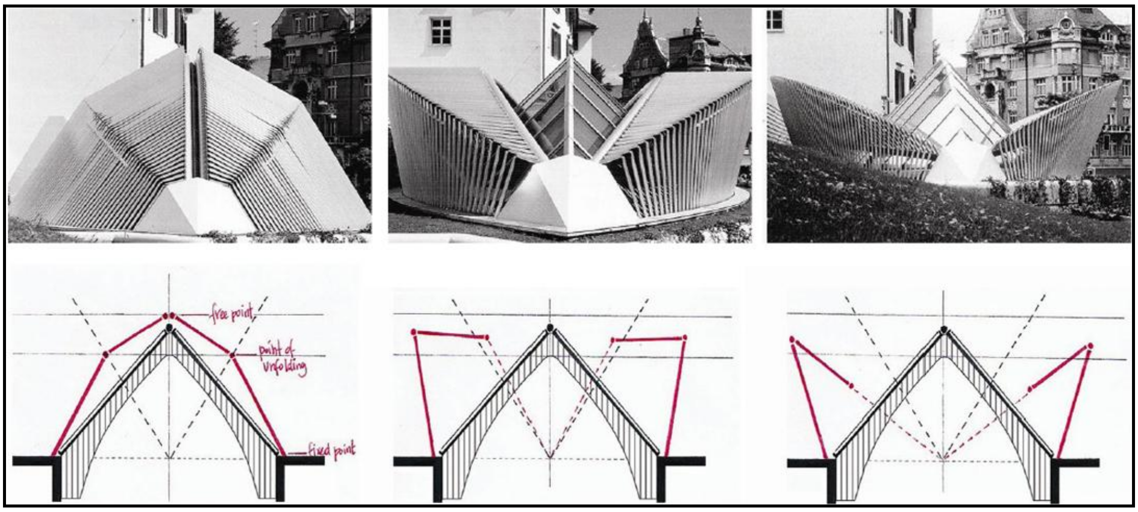


Figure 5.5. Pfalzkeller Emergency Service Center
(Source: Yıldız, 2007)

5.2.4. Mobility Criteria

The mobility of the mechanism is one of the main concerns in the design and analysis of the device. The degrees of freedom are not dependent to the rigid bodies' geometric parameters but dependent to the number of joints and the number of links in the system which are totally called kinematic chains.

Mechanisms as having the purpose of transforming motion, is maintained by the assemblage of resistant bodies connected with joints, to form a closed kinematic chain with one fixed link. It is predicted that the most important qualification of the machines are not the rigid bodies but the joints in the system.

Norton (1992) defines the degree of freedom as "The system's degree of freedom is equal to the independent parameters that are needed to define its position in space at any instant of time.". He defines degrees of freedom briefly, a pencil writing on a sheet of paper has three parameters directly, x,y coordinates and one angular coordinate with respect to the coordinates, θ. The minimum parameters to define the pencil on the sheet is three, x, y and θ. So we can say that the pencil on the sheet has three *dof*. If we hold the pencil above the sheet, then the parameters has three dimensional explanation and has minimum six parameters for defining the pencil according to the plane sheet, x, y, z coordinates and θ, ϕ, Ψ. In this brief explanation, the pencil is the rigid body or link. The rigid body in space has six *dof* as illustrated in Figure 5.1.

Grübler (1917) or Kutzbach (1929) created a mobility formulation; for a mechanism with ‘j’, working joints between ‘n’ bodies. The number of relative *dof* reduced to a number which can be identified with the relative mobility of the system of bodies as shown in Equation 5.3. $\sum_{i=1}^{j} u_i$ represents the constraints for the individual kinematic pairs and ‘*M*’ represents the mobility of the linkage (Hunt, 1978, Chen, 2003).

$$M = 6(n - 1) - \sum_{i=1}^{j} u_i \qquad (5.3)$$

Thus from the Equation 5.1, as it is convenient to define the system in terms of freedoms than degree of constraints, u, we obtain; $u_i = 6 - f_i$ and when we replace the u_i in Equation 5.3, we obtain Equation 5.4 and Equation 5.5.

$$M = 6(n - 1) - \sum_{i=1}^{j} 6 + \sum_{i=1}^{j} f_i \qquad (5.4)$$

or

$$M = 6(n - j - 1) + \sum_{i=1}^{j} f_i \qquad (5.5)$$

For a six linked closed loop mechanism, $\underline{R}RRRR\underline{R}$, with 1dof kinematic pairs, the number of links and the number of joints are equal, n = j. If we put these in the formula Equation 5.6., we obtain a structural group, M = 0;

$$M = \sum_{i=1}^{j} f_i - 6 \qquad (5.6)$$

From this equation, the number of kinematic variables, $\sum_{i=1}^{j} f_i$ should be equal to seven to obtain a kinematic chain with mobility one. However, it is not always the condition as there are some linkages apart from this mobility criterion. Linkages that are not satisfying Kutzbach formula are called over-constrained mechanisms and have mobility. That is the case, when 6R linkage mechanism has motion then it is called over-constrained mechanisms. From Equation 5.5, we obtain Equation 5.7. Euler described the independent loop. The independent loop is the total number of joints minus the number of links plus one as in Equation 5.8.

$$M = \sum_{i=1}^{j} f_i - 6\,(j - n + 1) \tag{5.7}$$

$$L = (j - n + 1) \tag{5.8}$$

As 6 represents the subspace of the linkage; the subspace of the mechanism λ, and the independent loop formula is put to Equation 5.7, we obtain Equation 5.9. The mobility for over-constrained mechanisms can be defined with Equation 5.9 and Equation 5.10, referring to the formula of Freudenstein and Alizade, where λ is the subspace and L is the independent loops in the system of the linkage (Alizade et al., 1985). When the mechanism has more than one independent loop with variable subspaces, the equation can be expressed as Equation 5.10, while *k* represents the subspaces of the loops.

$$M = \sum_{i=1}^{j} f_i - \lambda L \tag{5.9}$$

$$M = \sum_{i=1}^{j} f_i - \sum_{k=1}^{L} \lambda_k \tag{5.10}$$

Equation 5.9 is used for the linkages with constant subspace in constrained and over-constrained mechanisms and Equation 5.10 is for mechanisms with variable subspaces.

5.3. 3D Over-constrained Linkage Mechanisms

The structural synthesis of over-constrained mechanisms is a geometrical methodology for generating the dedicated structural design. Over-constrained geometry is mostly chosen in mechanisms which offer a preference for extra stiffness (Chen, 2003).

A spatial mobile loop can be constructed with minimum four links with revolute joints. Therefore, for constructing 3D over-constrained linkage, 4, 5 or 6 links are used. When they are constructed by revolute joints they are called 4R, 5R, 6R linkages.

Throughout the literature, the first over-constrained mechanism was invented by Sarrus in 1853. Since then, Bricard in 1897, Bennett in 1905, Myard in 1931, Goldberg in 1943, Altmann in 1954, Waldron in 1967, Wohlhart in 1987 and Dietmaier in 1995 invented new over-constrained mechanisms. Basically Bennett , 4R and Bricard 6R linkages are the domain linkages with specific geometric parameters. There are fifteen types in total which are constructed by revolute joints but derived from these 2 main over-constrained mechanisms as shown in Table 5.2.

Table 5.2. Over-constrained Linkage Mechanisms
(Source: Chen, 2003)

Number of Links	Over-constrained Linkage Mechanisms	Dependent Linkages
4	Bennett Linkage	
5	Goldberg Linkage	Bennett Linkage
5	Myard Linkage	Bennett Linkage
6	Altmann Linkage	Bennett Linkage
6	Bennett 6R hybrid Linkage	Bennett Linkage
6	Bennett-joint 6R Linkage	Bennett Linkage
6	Dietmaier 6R Linkage	Bennett Linkage
6	Double Hooke’s joint	Bennett Linkage
6	Goldberg 6R Linkage	Bennett Linkage
6	Sarrus linkage	Bennett Linkage
6	Wohlhart double Goldberg Linkage	Bennett Linkage
6	Waldron hybrid Linkage	Four-bar linkage with lower joints
6	Bricard Linkages	
6	Schatz Linkage	Bricard Linkages
6	Wohlhart 6R Linkage	Bricard Linkages

Revolute joints are widely preferred for motion structures among the other types of joints as they are easy for making and maintaining and have robust performance. A closed loop of six closed links connected by revolute joints generally forms a rigid space structure, however by some geometrical configurations, the structures turned into mobile and classified as 3D over-constrained mechanisms, space mechanisms.

Few over-constrained mechanisms have been invented over the recent half century; however, the most detailed studies of 6R closed loop over-constrained mechanisms are due to Baker (Chen, 2003).

5.4. Bricard Linkages

Bricard linkage is a 3D over-constrained linkage mechanism. Bricard linkages are the only 6R linkages that are not derived from the other 4R, 5R, 6R ones as shown in Table 5.2. Due to this fact, we choose to understand the structural behaviour of Bricard linkage as obtained by 6 legs like hexagons have.

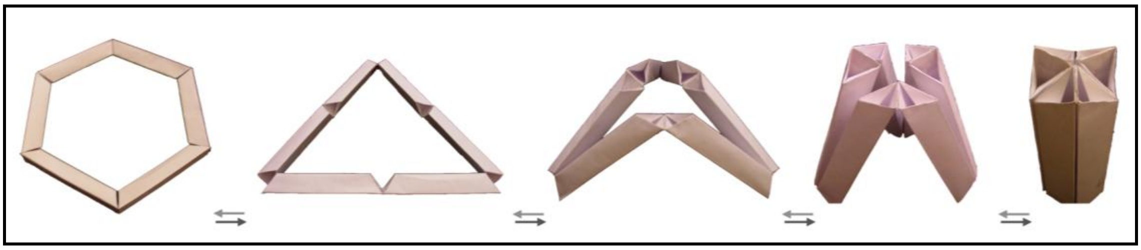


Figure 5.6. 6R loop changing from open to closed state with mobility one

Bricard in 1897 published in ‘Memoire sur la Theorie de l’octaedra Articule’ the existence of mobile octahedral. He defined that there are three types of mobile octahedral loops; line-symmetric octahedral loops, plane-symmetric octahedral loops and doubly- collapsible octahedral loops. He pointed out that all six axes should be in a linear complex which provides mobility as given an example in Figure 5.6. Bricard found 30 years later, other three types; the general line-symmetric case, the general plane-symmetric, and trihedral cases.

Interestingly, Baker (1986) emphasized that the line-symmetric octahedral case of Bricard linkage has the same angular parameters with cyclohexane molecule. Cyclohexane molecule passes from one rigid phase to another by the minimum energy configurations. The chair form-rigid phase- of flexible cyclohexane molecule’s potential energy is highly less than the boat form and others as shown in Figure 5.7 with the corresponding Bricard Linkages.

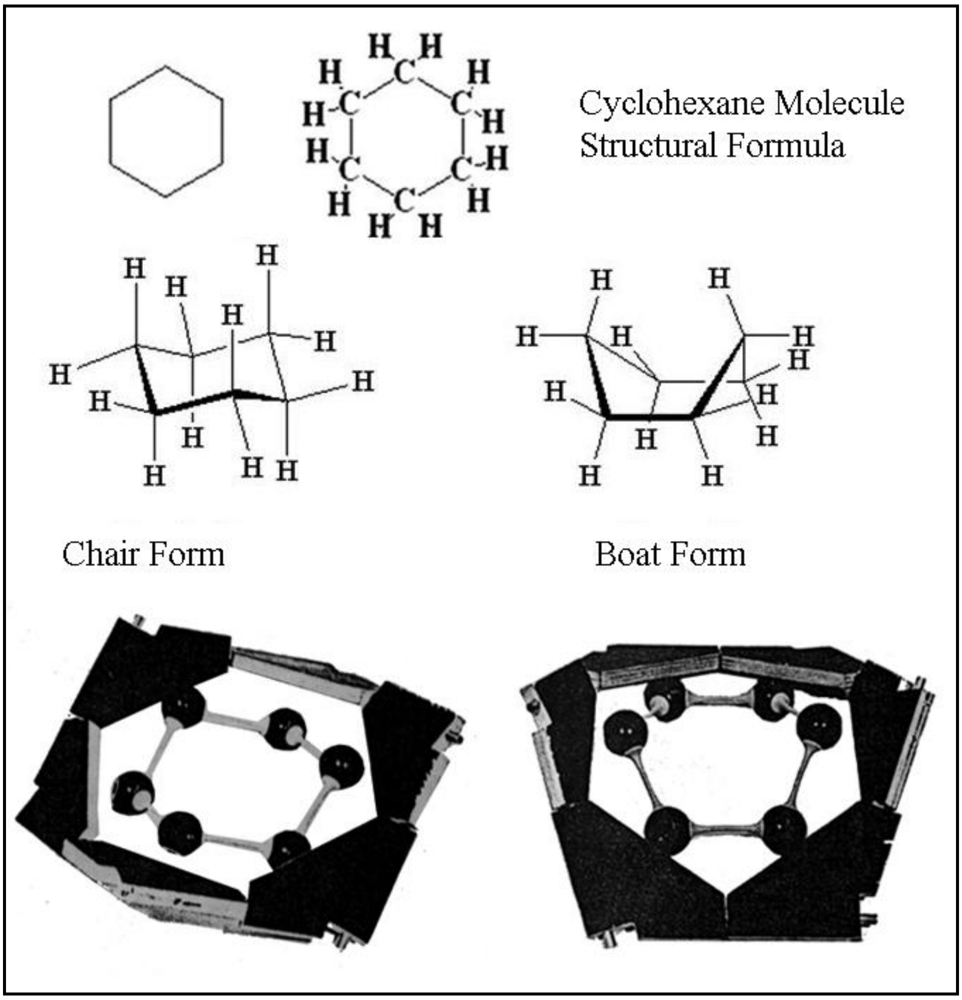


Figure 5.7. The formation of cyclohexane molecule and Bricard linkage
(Source: Baker, 1986)

This case shows the significance of analyzing over-constrained-mechanisms. As defined in chapter 4, the molecules are in linear or ring configurations. As described in chapter 4, for the aim of obtaining a mobile hexagon with the revolute angles intersecting in 120^o in three links, the properties of Bricard linkages should be investigated.

5.4.1. Loop Closure Equation

For measuring the important geometric characteristics of a linkage, Denavit and Hartenberg set forth a standard approach for the analysis of linkages, in which the geometric conditions are the primary for the parameters. These parameters provide a method for open and closed loop systems by the product of the transform matrices.

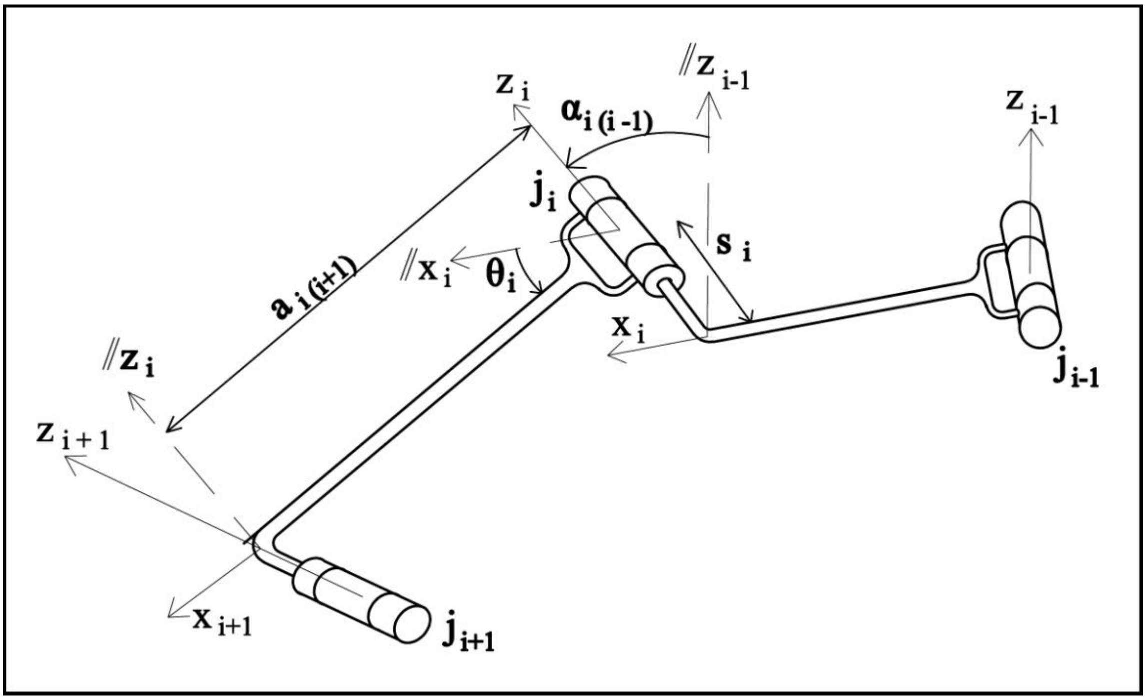


Figure 5.8. Links with revolute joints and Denavit and Hartenberg parameters

As shown in Figure 5.8, ‘a’ represents the shortest distance between two joints, ‘α’, is the angle of skew between the directions of joint axes. ‘S’ is the constant between joints and ‘θ’ is the joint angle between two common normals relating to a joint i. ‘a’ and ‘α’ are the link parameters, while ‘S’ and ‘θ’ are the joint parameters. In general, it can be also defined as, ‘a’, ‘α’ and ‘S’ are the geometrical parameters, while ‘θ’ is the kinematic variable. The x axis is perpendicular to the joint axes and z axis is coincident with joint axis, and the directions of angles are obtained by right-hand rule according to the axes. For defining the position of specified link, we calculate the matrice, where $D_x a_{i,i+1}$ represents the transformation on the x axis about ‘a’, $R_x \alpha_{i,i+1}$ represents the rotation in the x axis at the angle $\alpha_{i,i+1}$, $D_z S_i$ represents the transformation on the z axis about ‘S’ and $R_z \theta_i$ represents the rotation in the z axis at the angle θ_i. This gives ${}^{i-1}T_i$ the transformation matrice as in Equation 5.11. and Equation 5.12.

$$ {}^{i-1}R_{i,}\begin{bmatrix} a_{i,i+1} \\ \alpha_{i,i+1} \\ S_i \\ \theta_i \end{bmatrix} = D_x\, a_{i,i+1}\ , R_x\ \alpha_{i,i+1}\ , D_z S_i\ , R_z\ \theta_i\ = {}^{i-1}T_i \qquad (5.11) $$

$$ {}^{i-1}T_i = \begin{bmatrix} 1 & 0 & 0 & a_{i,i+1} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & \cos a_{i,i+1} & -\sin a_{i,i+1} & 0 \\ 0 & \sin a_{i,i+1} & \cos a_{i,i+1} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & S_i \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{i-1}T_i = \begin{bmatrix} \cos\theta_i & \cos\alpha_i.\sin\theta_i & \sin\alpha_i.\cos\theta_i & a_i.\cos\theta_i \\ \sin\theta_i & \cos\alpha_i.\cos\theta_i & -\sin\alpha_i.\cos\theta_i & a_i.\sin\theta_i \\ 0 & \sin\alpha_i. & \cos\alpha_i. & S_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5.12) $$

In closed loop mechanisms, the product of transformation matrices around a kinematic loop must be equal to the unit matrix, identity transformation as in Equation 5.13, Equation 5.14.

$$ {}^1T_2\ \cdot\ {}^2T_3\ \cdot\ {}^3T_4\ \cdot\ {}^4T_5\ \cdot\ {}^5T_6\ \cdot = {}^1T_6 \qquad (5.13) $$

$$ or \qquad {}^iT_1\ \cdot\ {}^1T_2\ \cdot\ {}^2T_3\ \cdot\ {}^3T_{i-1}\ \cdot\ {}^{i-1}T_i\ \cdot = I = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5.14) $$

For a 6R closed loop such as in illustrated in Figure 5.9 the transformation matrices are given in Equation 5.15,

$$ {}^6T_1\ \cdot\ {}^1T_2\ \cdot\ {}^2T_3\ \cdot\ {}^3T_4\ \cdot\ {}^4T_5\ \cdot\ {}^5T_6\ \cdot = I = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5.15) $$

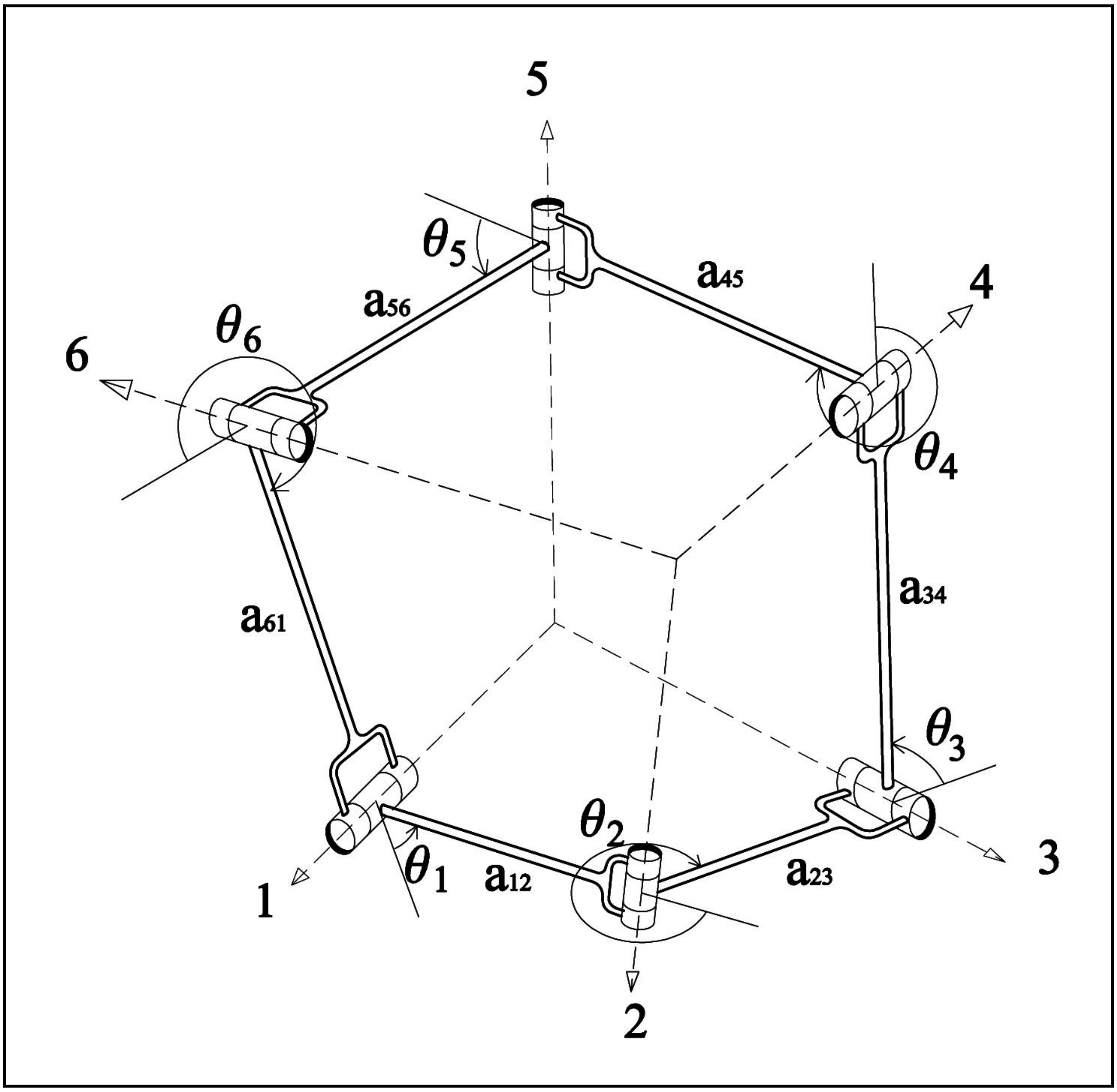


Figure 5.9. Denavit and Hartenberg parameters for 6R loop

5.4.2. Types of Bricard Linkages

Bricard defined the octahedral loops firstly and 30 years later the other three mechanisms. Totally, there are 6 types of Bricard linkages and illustrated with the equations in Table 5.3.

- The line-symmetric octahedral loops;

$$a_{12} = a_{23} = a_{45} = a_{56} = a_{61} = 0$$
$$S_1 + S_4 = S_2 + S_5 = S_3 + S_6 = 0 \tag{5.16}$$

- The plane-symmetric octahedral loops;

$$a_{12} = a_{23} = a_{45} = a_{56} = a_{61} = 0$$

$$S_4 = -S_1, \quad S_2 = -S_1 \frac{\sin\alpha_{34}}{\sin(\alpha_{12}+\alpha_{34})}, \quad S_3 = S_1 \frac{\sin\alpha_{12}}{\sin(\alpha_{12}+\alpha_{34})},$$

$$S_5 = S_1 \frac{\sin\alpha_{61}}{\sin(\alpha_{45}+\alpha_{61})}, \quad S_6 = -S_1 \frac{\sin\alpha_{45}}{\sin(\alpha_{45}+\alpha_{61})} \tag{5.17}$$

- The doubly- collapsible octahedral loops;

$$a_{12} = a_{23} = a_{45} = a_{56} = a_{61} = 0$$

$$S_1 S_3 S_5 + S_2 S_4 S_6 = 0 \tag{5.18}$$

- The general-line symmetric case;

$$a_{12} = a_{45} \quad a_{23} = a_{56} \quad a_{34} = a_{61}$$

$$\alpha_{12} = \alpha_{45} \quad \alpha_{23} = \alpha_{56} \quad \alpha_{34} = \alpha_{61}$$

$$S_1 = S_4 \quad S_2 = S_5 \quad S_3 = S_6 \tag{5.19}$$

- The general plane-symmetric case;

$$a_{12} = a_{61} \quad a_{23} = a_{56} \quad a_{34} = a_{45}$$

$$\alpha_{12} = \alpha_{45} = \pi \quad \alpha_{23} + \alpha_{56} = \pi \quad \alpha_{34} + \alpha_{45} = \pi$$

$$S_1 = S_4 = 0 \quad S_2 = S_6 \quad S_3 = S_5 \tag{5.20}$$

- The trihedral case;

$$a^2_{12} + a^2_{34} + a^2_{56} = a^2_{23} + a^2_{45} + a^2_{61}$$

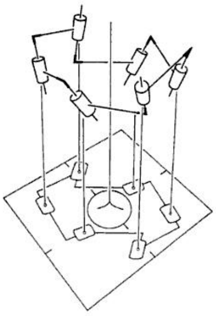
$$\alpha_{12} = \alpha_{34} = \alpha_{56} = \frac{\pi}{2} \quad \alpha_{23} = \alpha_{12} = \alpha_{12} = \frac{3\pi}{2}$$

$$S_i = 0 \text{ for all } i \tag{5.21}$$

Table 5.3. Types of Bricard Linkages
(Figure source: Philips, 1990)

Bricard Linkages

The general line- symmetric case



Equations:

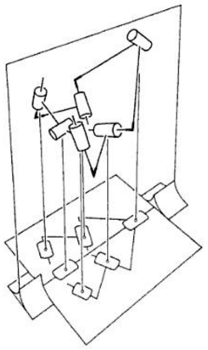
$$a_{12} = a_{45} \quad a_{23} = a_{56} \quad a_{34} = a_{61}$$

$$\alpha_{12} = \alpha_{45} \quad \alpha_{23} = \alpha_{56} \quad \alpha_{34} = \alpha_{61}$$

$$S_1 = S_4 \quad S_2 = S_5 \quad S_3 = S_6$$

Variable parameters: $\theta_1 = \theta_4 \quad \theta_2 = \theta_5 \quad \theta_3 = \theta_6$

The general plane - symmetric case



Equations:

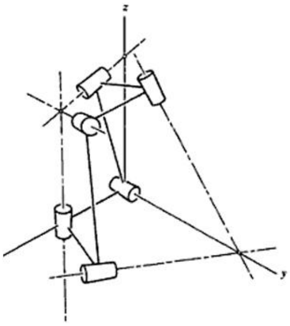
$$a_{12} = a_{61} \quad a_{23} = a_{56} \quad a_{34} = a_{45}$$

$$\alpha_{12} = \alpha_{45} = \pi \quad \alpha_{23} + \alpha_{56} = \pi \quad \alpha_{34} + \alpha_{45} = \pi$$

$$S_1 = S_4 = 0 \quad S_2 = S_6 \quad S_3 = S_5$$

Variable parameters: $\theta_2 + \theta_6 = 2\pi \quad \theta_3 + \theta_5 = 2\pi$

The general trihedral case



Equations:

$$a^2_{12} + a^2_{34} + a^2_{56} = a^2_{23} + a^2_{45} + a^2_{61}$$

$$\alpha_{12} = \alpha_{34} = \alpha_{56} = \frac{\pi}{2} \quad \alpha_{23} = \alpha_{12} = \alpha_{12} = \frac{3\pi}{2}$$

$$S_i = 0 \text{ for all } i$$

Variable parameters:

$$\sin\theta_3 (a_{61} + a_{12}\cos\theta_1) = \sin\theta_1 (a_{34} + a_{23}\cos\theta_3)$$

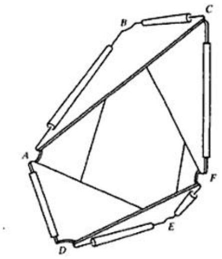
$$\sin\theta_4 (a_{12} + a_{23}\cos\theta_2) = \sin\theta_2 (a_{45} + a_{34}\cos\theta_4)$$

$$\sin\theta_5 (a_{23} + a_{34}\cos\theta_3) = \sin\theta_3 (a_{56} + a_{45}\cos\theta_5)$$

$$\sin\theta_6 (a_{34} + a_{45}\cos\theta_4) = \sin\theta_4 (a_{61} + a_{56}\cos\theta_6)$$

$$\sin\theta_5 . \sin\theta_6 = \sin\theta_2 . \sin\theta_3$$

The octahedral case



General Equation: $a_{12} = a_{23} = a_{45} = a_{56} = a_{61} = 0$

5.5. Conclusion

The closed loop mechanisms have already gained its significance on applications with their ultra lightweight properties. If one's aim is to provide light-weight and deployable structures, mechanism design process is really crucial. The structural synthesis; determination of joint types, linkage types and the mobility of the system is done. For determining the joint type, revolute joints with 1 dof are preferred for mechanism design because of their performance and easy for making. Determination of the linkage type, the over-constrained mechanisms are analyzed as they offer extra stiffness and obtain mobility with fewer materials because of their geometric properties.

The problem definition for a kinetic node design is to maintain a triangle or hexagonal ring structure whose joint axes are intersecting at 120^{o}, and give possibility to integrate in a sequence for stable and dynamic structural systems. For supplying this three-armed node with these qualifications, the Bricard Linkage from 3D over-constrained linkage mechanisms, which is obtained by 6R closed loop forming hexagonal ring, is a way for obtaining the desired geometry.

CHAPTER 6

DESIGN OF A KINETIC NODE

6.1. The Bio-Inspired Design Process for a Kinetic Node

Respecting the environment in architectural design process is passing through a design concept which takes consideration of renewing the energy, the opportunity to reuse the land, the flexibility of recycling the building parts and adaptation of space. Adaptation of space is maintained by adaptable structures. The concept of adaptable structures is inspired by William Zuk and Roger Clark as; reversible, incremental, deformable, mobile structures and disposable architecture. Adaptable structures need a structural order. For achieving all concepts together for adaptable structural system, the structural order is significant in the design process.

Structure is the way of arranging the parts or forming a whole in a particular way by putting the parts together by a specific order. Therefore, structural system is significant as without which nothing can exist. The design process of the structural components and the connectors need appropriate considerations for gaining performance of the structure in order to provide flexibility and interchangeability of spaces that extends the lifecycle of the built structure. Therefore, a technological outcome which has capabilities of portability, reusability, easy to construct, minimizing the cost and material usage and reducing application time is passing through designing an adaptable structure or its components.

The technological outcomes that are inspired from nature provide more efficient solutions to engineering questions. These solutions depend on the levels of analyzing the biological models. The more the analysis highlights the path, the new emergent properties occur. That is the main reason, before coming to point out the desired technological outcome, the engineering field and the biological conceptual model should be analyzed deeply.

In the bio-inspired design process, the conceptual biological model is crucial. It should not just accommodate the physical properties but also the idea for the engineering outcome. The need for shelter for human beings is like the need of a cell for a living organism. Cell adapts to the changing conditions and exists since life begins on earth. The cell, without which life cannot exist, can be taken as a biological model for the built environment and for the structural systems for adaptable enclosed spaces. Cell accommodates the main concepts of physical properties and the concept of adaptation.

The bio-inspired design process is graphed by filling the starting points representing by empty boxes in section 2.3.2. The optimization for achieving adaptable structural system is passing through analyzing the architectural applications and the selected biological model for the desired technological outcome. The starting point of engineering outcome is a building or a structural system, and the biological model is the cell as shown in Figure 6.1. By analyzing the biological model deeper, we will reach to a point of inspiration that can be adapted to the technological outcome.

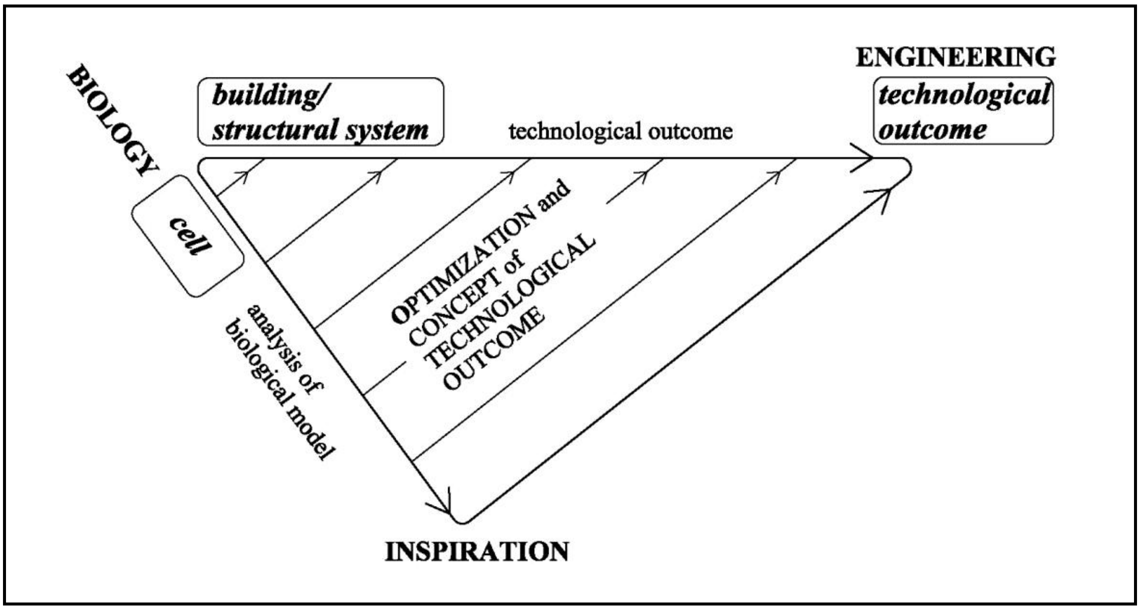


Figure 6.1. The BID Map of conceptual models for technological outcome

Nature’s main principle of minimum energy configurations and form- function correlation is mainly because of using minimum energy to build up its components and for adaptation to the changing conditions. In this design process, we start from the very basic living unit – cell. The geometry and motion of the structure is analyzed by starting from cell. The simple geometry of natural structures is synthesized for reaching to an optimum solution. Also, analyzing the cell’s components that build up the structural system of the cell provide inspiration for motion of the structure. Cell is composed of biological macromolecules, compounds, molecules and atoms. In this process we analyze till molecular level (Figure 6.2).

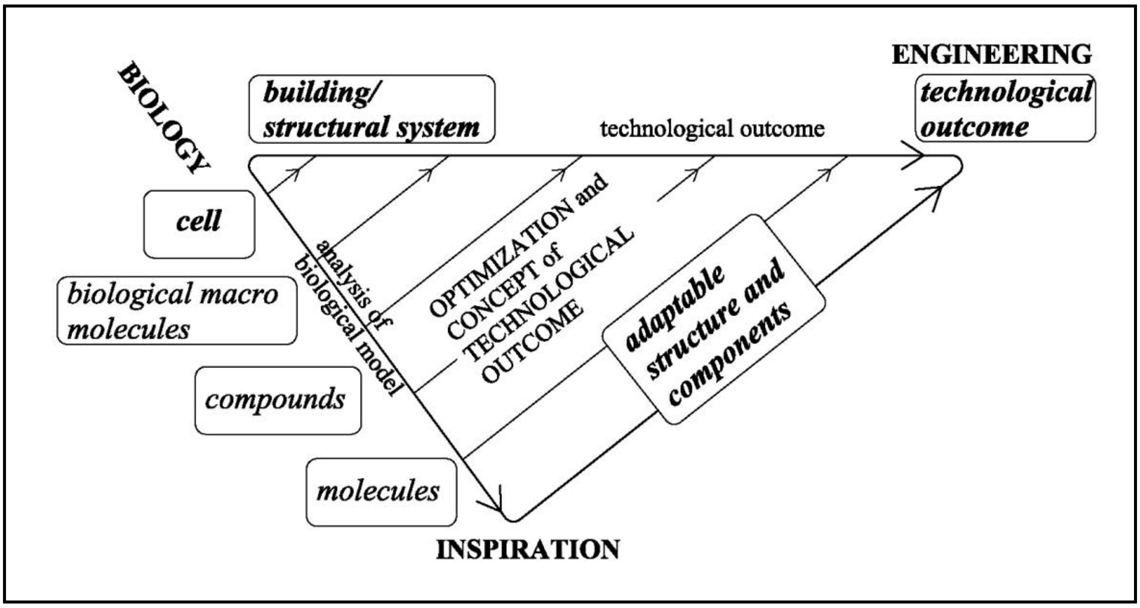


Figure 6.2. The conceptual models and limit is predefined

The minimum energy shapes and the sequence of the parts in making the structure of the biological macromolecules are discussed to understand the logic of the natural structures.

The bio-inspired map is filled up by the analysis from biological aspect and the applied technological outcomes in structural engineering. From the nature’s building code, we analyzed in two separate ways and reached to a combined inspiration point. First way is from the analysis of the simple geometry in organic structures. The efficiency of hexagon, triangular packing, 3 arm node generating 120^o at the junction points and tetrahedron are the outcomes from the first way. The second way is the structural order in the biological macro molecules in the process of forming the cell membrane components. The components are composed in linear, ring, bi-layer, spherical or double-helix configuration which are build up from ring or linear molecules linking in various configurations. These are the outcomes from the second way. For the combined outcome, the inspiration subject is the hexagonal ring. Also, from the analysis of structural systems in architecture, triangle; as resisting the loads and platonic solids; as supplying lightness and high-strength are taken as inputs for the technological outcome. These outcomes become the inputs for design process which is graphed in Figure 6.3.

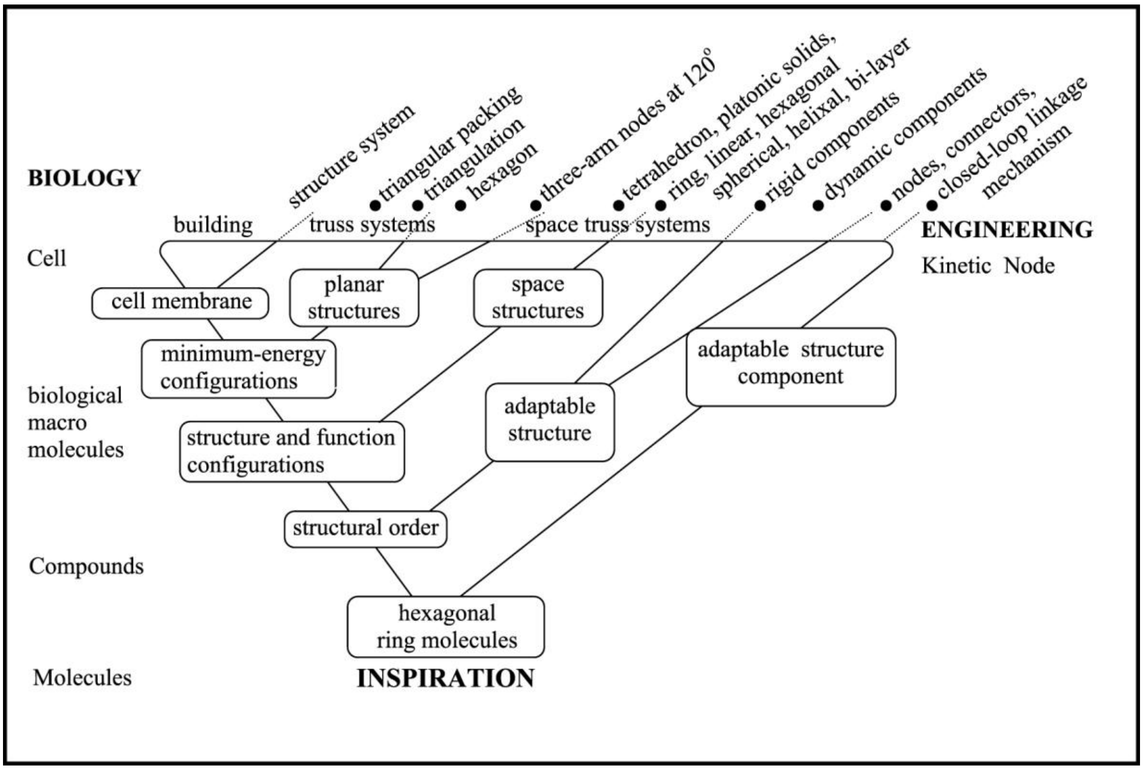
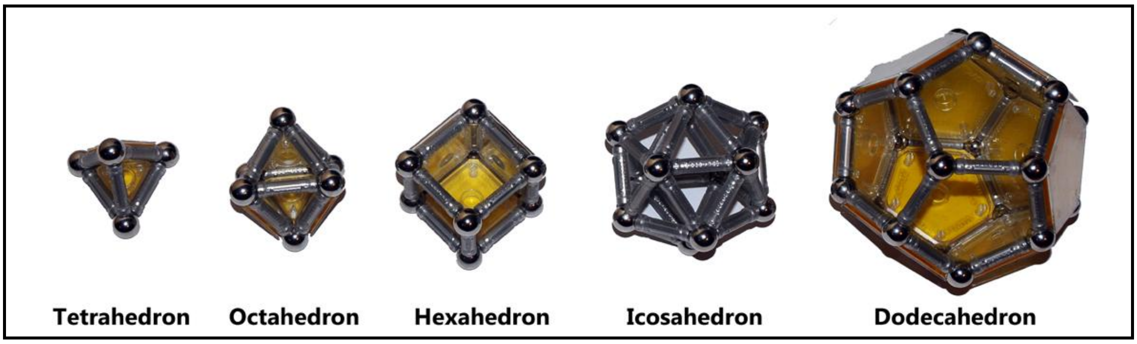


Figure 6.3. The BID map for Adaptable structure component; Kinetic Node

From the analysis of space truss systems, the three-dimensional behaviour of the structure is important and this property is provided by the design of the nodes. The nodes are the most important consideration point for structures, however solute by rigid components and limit the form of the structures. The mobility of linkage mechanisms with three dimensional behaviour gives possibilities to maintain flexibility for stable and dynamic structural systems. Therefore, in this research, a mechanism design is needed with the given inputs from the nature’s building code and the principles of structural systems in the design process for a technological outcome. The technological outcome for adaptable structure component which has mobility for maintaining variable volumes is passing through designing a kinetic node. Therefore, the desired technological outcome is a Kinetic Node for adaptable structures.

The problem definition for the design of a kinetic node should supply a triangle or hexagon ring structure whose joint axes are intersecting at 120^{o}, and give possibility to integrate in a sequence for stable solids, Platonic solids and stable and dynamic structural systems.

6.2. The Geometric Properties of the Desired Kinetic Node



tetrahedron (4 faced), octahedron (8 faced), hexahedron (6 faced), icosahedron(20 faced, dodecahedron (12 faced)

Figure 6.4. The Platonic solids

The geometric properties of Platonic solids will be defined since they gain their importance because of the economic unfolding of space and their properties of high-strength and lightweight in structural systems. They are also taking an important role from macro to micro level in natural structures.

In chapter 3, section 3.4.4, the lattice structure of the platonic solids was defined. It is found that the hexahedron and dodecahedron is movable when constructed by struts. The cube and dodecahedron let more efficient volume to use and provide wider openings despite the triangulated octahedron and icosahedron. When analyzing hexahedron and dodecahedron, they have a common structural system. They are both constructed with a node integrated with three struts and the angles between the struts are the same in every single configuration. These are the reasons the hexahedron and dodecahedron are taken for consideration.

In Figure 6.5, the vertices are the connection points, and the edges can be counted as the number of struts. Faces are the polygonal plates. Dihedral angles are the angles between the faces and the vertex angles are the angles between the edges. Also the volume qualifications can also be seen if these polyhedrons are constructed with same size node and struts.

In platonic solids as all the vertex and dihedral angles are equal for each polyhedron as shown in Figure 6.5. The analysis for 3 polyhedrons, it is found out that when one axis such as x is fixed, y and z axis change respectively to each other and in the planer configuration the x, y, and z axes generate 120^{o} as shown in Figure 6.6.

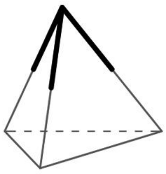
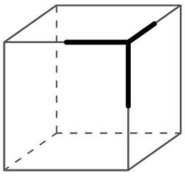
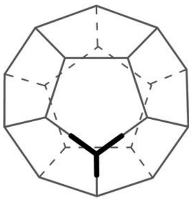
Platonic Solids connecting with three struts at the nodal point			
	 Tetrahedron	 Hexahedron	 Dodecahedron
vertices, nodes	4	8	20
edges	6	12	30
faces	4	6	12
dihedral angles	70.53	90	116.57
vertex angles	60	90	108
volume	0.11285	1	7.66312

Figure 6.5. The Platonic solids geometrical aspects

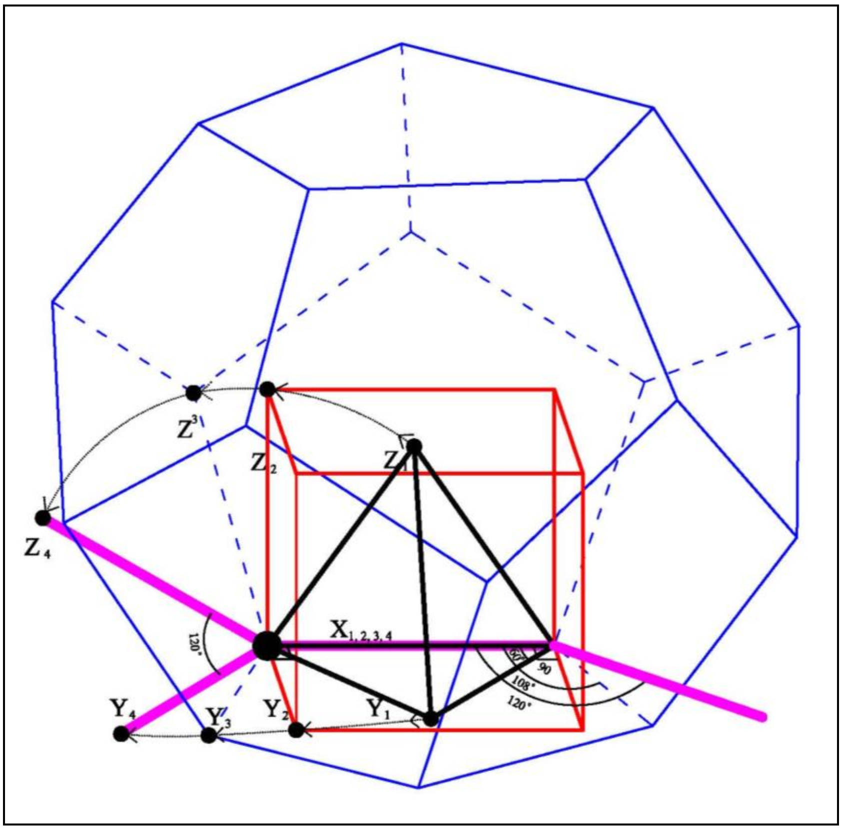


Figure 6.6. The geometrical aspect of the Platonic solids’ nodal point
(Source: Acar and Korkmaz, 2010)

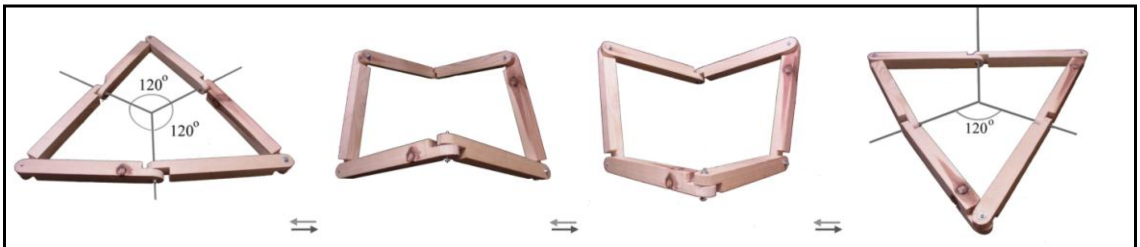
From the analysis by 2 dimensional shapes, hexagonal grids and three armed nodes and triangular packing will be also the inputs for mechanism design process with the geometric properties of Platonic solids.

6.3. The Mechanism Design Process of the Kinetic Node

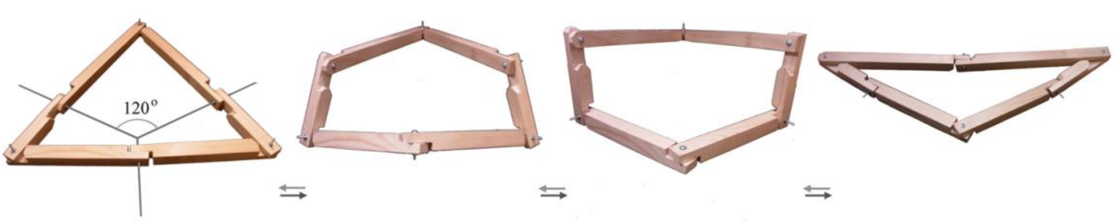
The trihedral case of Bricard linkage in which all three axes meet at a point and generating 120^{o} in its planar form is chosen for generating the right angles.

6.3.1. Trihedral Case of Bricard Linkage

In trihedral case of Bricard Linkage, if the link lengths are equal or the mechanism is plane symmetric, 120^{o} intersecting rotational axes is achieved in its planar form such as shown in Figure 6.7.



all link lengths are equal and intersecting at 120^{o}



plane symmetric and intersecting at 120^{o}

Figure 6.7. Trihedral Bricard linkages intersecting at 120^{o}

For determination of the lengths of the links and their relations among joint angles, the following equations are applied (Baker, 1980). The variable parameters for trihedral Bricard linkage are given in Equation 6.1.

$$\sin\theta_3\,(a_{61} + a_{12}\cos\theta_1) = \sin\theta_1\,(a_{34} + a_{23}\cos\theta_3)$$
$$\sin\theta_4\,(a_{12} + a_{23}\cos\theta_2) = \sin\theta_2\,(a_{45} + a_{34}\cos\theta_4)$$
$$\sin\theta_5\,(a_{23} + a_{34}\cos\theta_3) = \sin\theta_3\,(a_{56} + a_{45}\cos\theta_5)$$
$$\sin\theta_6\,(a_{34} + a_{45}\cos\theta_4) = \sin\theta_4\,(a_{61} + a_{56}\cos\theta_6)$$
$$\sin\theta_5 \,.\, \sin\theta_6 = \sin\theta_2 \,.\, \sin\theta_3 \qquad (6.1)$$

When calculate this variable parameters for the determined vertex and dihedral angles of Platonic solids; $\theta_1 = \theta_3 = \theta_5 = \theta$, and $\theta_2 = \theta_4 = \theta_6 = \psi$, the link lengths are gained equal which is the special case for trihedral Bricard Linkage.

6.3.2. Kaleidocycle

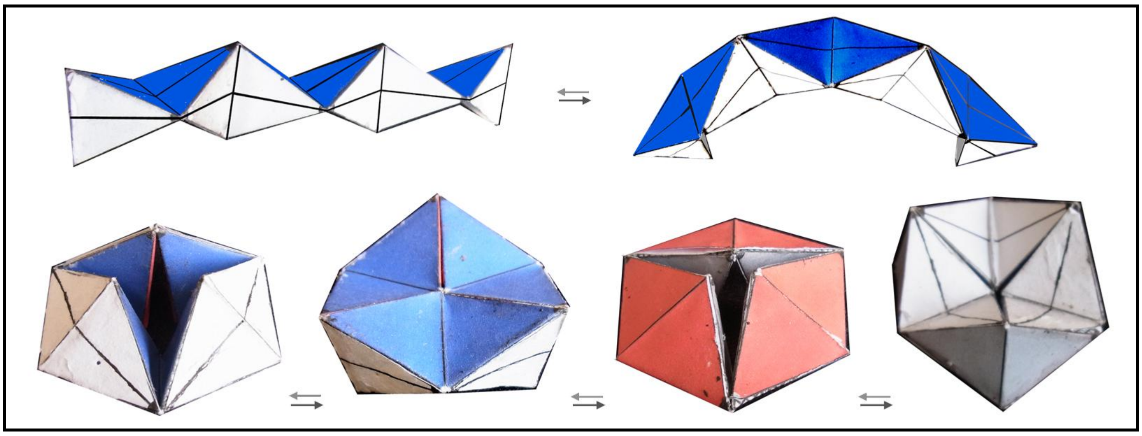


Figure 6.8. Six identical tetrahedrons forming kaleidocycle

Kaleidocycle means ‘beautiful ring’ in Greek language. It is obtained by same six identical tetrahedron shape solids in a kinematic chain and when they form a closed loop, the mechanism turned into a 3D ring with infinite motion (Figure 6.8). Kaleidocycle is composed from a special case of trihedral Bricard linkage as expressed in Figure 6.9. The geometrical properties are given in Equation 6.2; and the variable parameters are given in Equation 6.3.

$$a_{12} = a_{23} = a_{34} = a_{45} = a_{56} = a_{61} = a$$
$$\alpha_{12} = \alpha_{34} = \alpha_{56} = \frac{\pi}{2} \qquad \alpha_{23} = \alpha_{12} = \alpha_{12} = \frac{3\pi}{2}$$
$$R_i = 0 \text{ for all } i \qquad \text{(Eq 6.2)}$$

$$\theta_1 = \theta_3 = \theta_5 = \theta$$
$$\theta_2 = \theta_4 = \theta_6 = \psi \qquad \text{(Eq 6.3)}$$

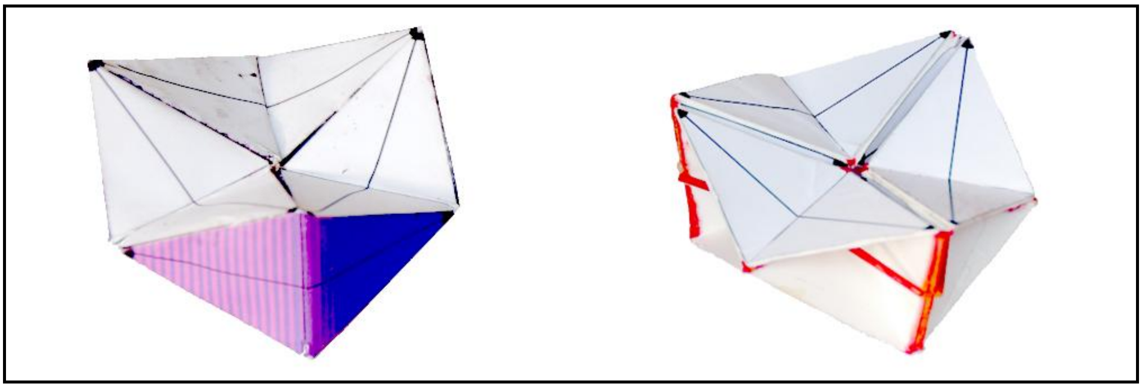


Figure 6.9. The trihedral orthogonal Bricard Linkage, kaleidocycle

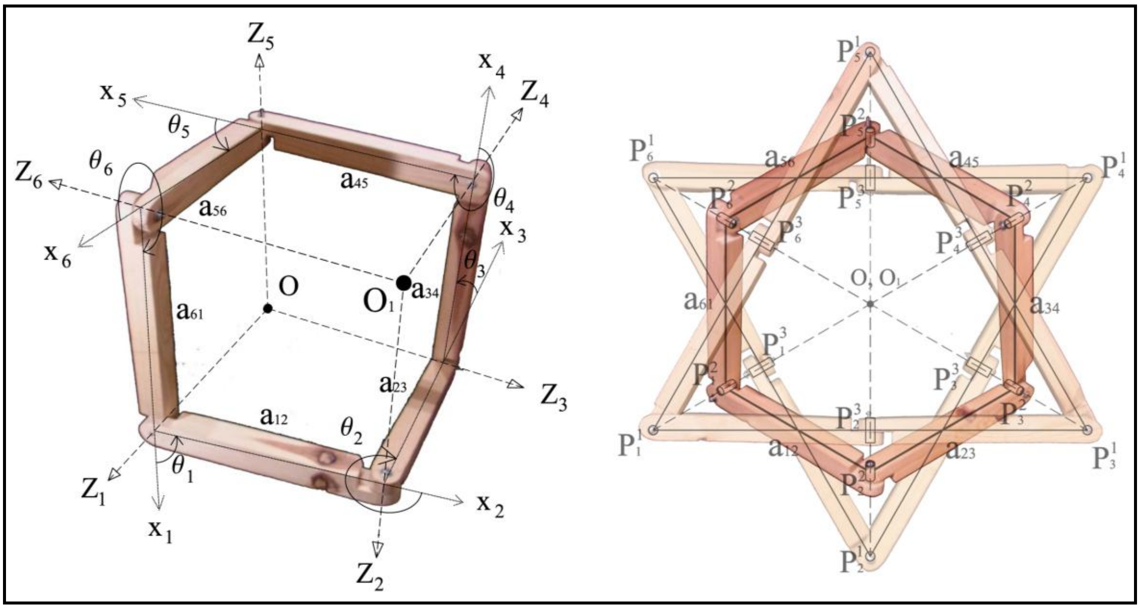


Figure 6.10. The structure of kaleidocycle

In the planar case, this structural mechanism form in triangle, and the three rotation axes intersect at 120^{o} as shown in Figure 6.10. That means the desired three dimensional behaviour of the three arm node can be achieved with mobility one as all the angles change dependently to each other. For the desired geometric design requirements, Trihedral Bricard linkage mechanism is the right answer for the design of kinetic node. This linkage mechanism is not the only possible solution. But from the analysis of the above chapters trihedral Bricard linkage mechanism is found as the proper mechanism. In Figure 6.11, the relations of the angles are given. The hollow angle lines represent the dihedral angles and the filled angle represents the vertex angles for Platonic solids. However, for obtaining three arm node, the design of the structural mechanism should be modified.

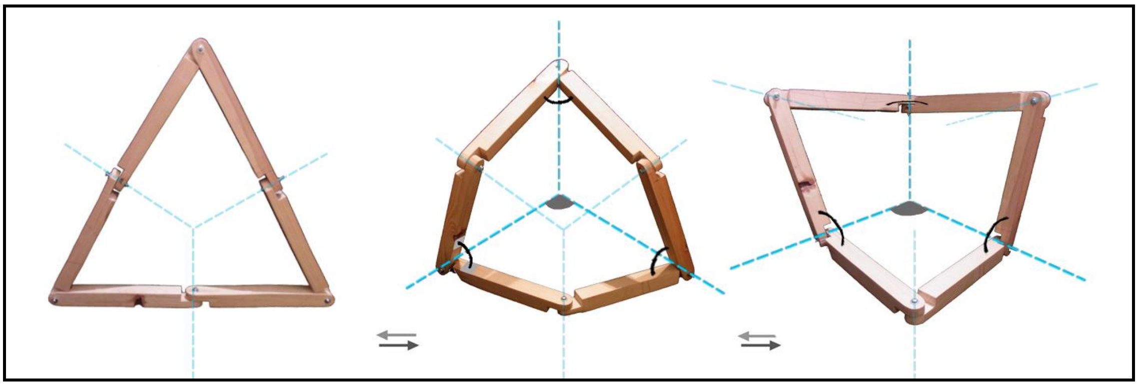


Figure 6.11. The angular relationships and the motion

6.4. Proposed Kinetic Node

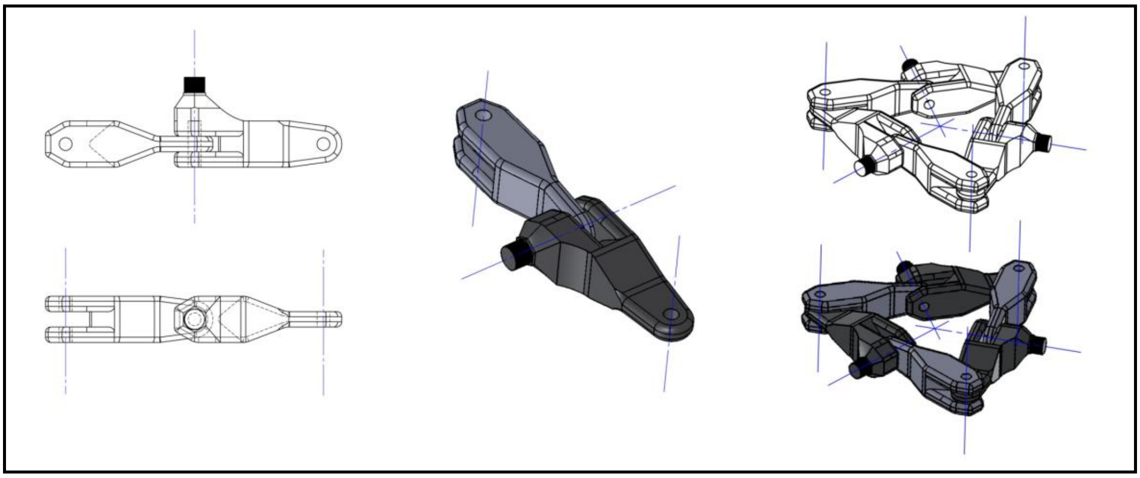


Figure 6.12. The linkage in the process of creating the three arm node.

The design of the linkages can be obtained by taking the axes into consideration. Each rod has two joint axes which are perpendicular to each other. At the axes which intersect at one point, hexagonal sleeve and dowel pin is placed for the bolts of the struts that will attach to the node easily. Three of the kinematic chains are linked together to form a closed-loop, ring mechanism. Eventually, three arm kinetic node is obtained as shown in Figure 6.12. The geometric properties; the dihedral and vertex angles of tetrahedron, hexahedron, dodecahedron and 120^{o} are obtained by the kinetic node as shown in Figure 6.13.

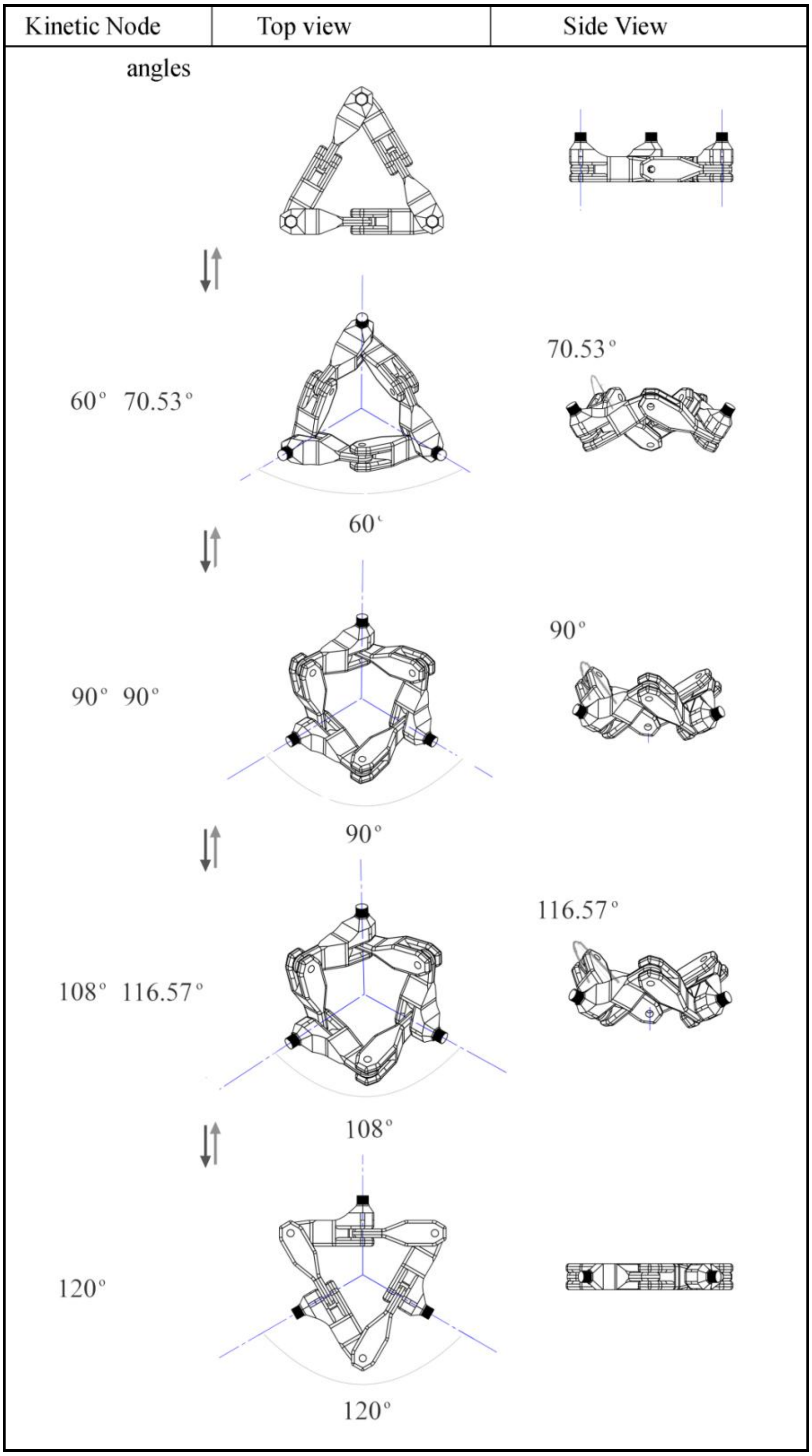


Figure 6.13. The geometric properties are maintained by the kinetic node

The proposed node gives capability to obtain different structural systems;; tetrahedron, hexahedron, and dodecahedron from the Platonic solids, some other stable solids and also stable and dynamic hexagonal grid by just adding the identical nodes to each other in a sequence as shown in Table 6.1 and 6.2 from the reference of Table 4.2.

6.5. Kinetic Node Applications for Variable Forms

In the design process of the node, over-constrained mechanisms are analyzed because of their three-dimensional behaviour. Since, the node is designed by over-constrained mechanism, the three dimensional behaviour sustain stability to the unstable platonic solids without triangulation on the face of the polyhedrons. The node provides wide diversity in volumes and grid systems by not only stable structures but also dynamic solutions.

The nodes assembly to the other nodes by rigid connections. The analysis of the structural systems is made from the mobility formula of Freudenstein and Alizade , where $\sum_{i=1}^{j} f_i$ is the number of kinematic variables, λ is the subspace and L is the independent loops in the system of the linkage. When the mechanism has more than one independent loop with variable subspaces, the equation can be expressed as Equation 6.4, while *k* represents the subspaces of the loops. If mobility is obtained over zero, it is a mobile structure. When mobility is equal to zero, it is a structure. If it is low than zero, than it is called pre-loaded structure.

$$M = \sum_{i=1}^{j} f_i - \sum_{k=1}^{L} \lambda_k \qquad (6.4)$$

6.5.1. Stable Platonic Solids Obtained by Identical Kinetic Nodes

By analyzing deeply the structural behaviour of the kinetic node gives capability for stabilizing the cube and dodecahedron with high strength (dof of the system is minus). That means, the structural systems can be constructed without need for triangulation and even some struts can be removed if needed. In that case, whole square and pentagon openings can be obtained. The variable structural orders of the bio-inspired kinetic node give more opportunities then it was expected by providing stability to the unstable solids with mobile nodes. By the process of a mechanism design, the initial mobility is changed to a final stability such as in biological macro molecules, compounds and molecules.

6.5.1.1. Tetrahedron

When three of the nodes are added in the form of a triangle, the third dowel pins of the node enables the forth node to construct easily as shown in Figure 6.14. The structural mechanism loses its mobility and gain stability. In this case, as it is dedicated, triangle and tetrahedron are stable structures, however the node let obtaining the tetrahedron structural system.

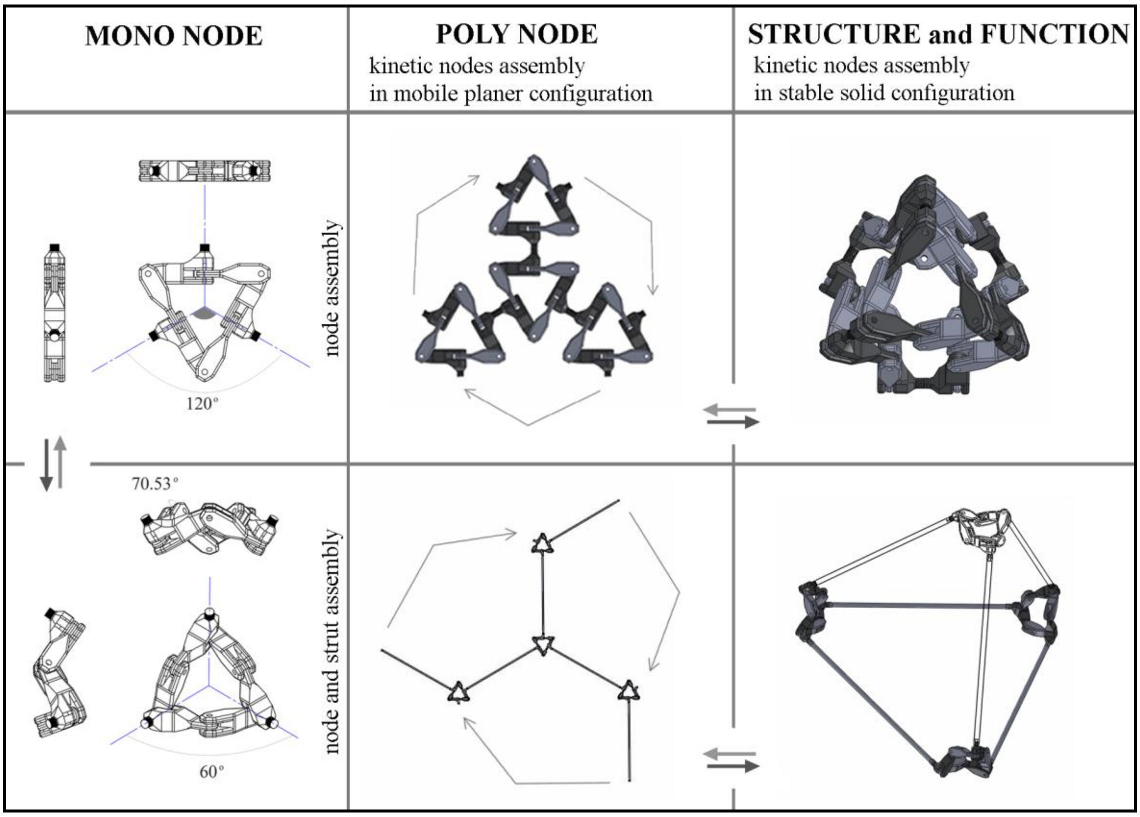


Figure 6.14. Tetrahedron is obtained by using four kinetic nodes

In Equation 6.5, since there are 4 nodes with 6 revolute joints, the number of kinematic variables is obtained by multiplying the joints and the number of the nodes. As the nodes are 3D over-constrained mechanisms with 6R, their subspace, λ is 5. And there are 4 independent loops in subspace 5, and 3 -faces minus one- in subspace 6. The loops and the connecting method of nodes and struts are shown in Figure 6.13.

$$M = \sum_{i=1}^{j} f_i - \sum_{k=1}^{L} \lambda_k \qquad \begin{aligned} M &= 6x4 - 5x4 - 6x3 \\ M &= -14 \end{aligned} \qquad (6.5)$$

6.5.1.2. Hexahedron

When four of the kinetic nodes are added in the form of a square the structure directly gains stability. In this case, it is possible to say that this proposed node discarded the needs for triangulation at nodal points shown in Figure 6.15.

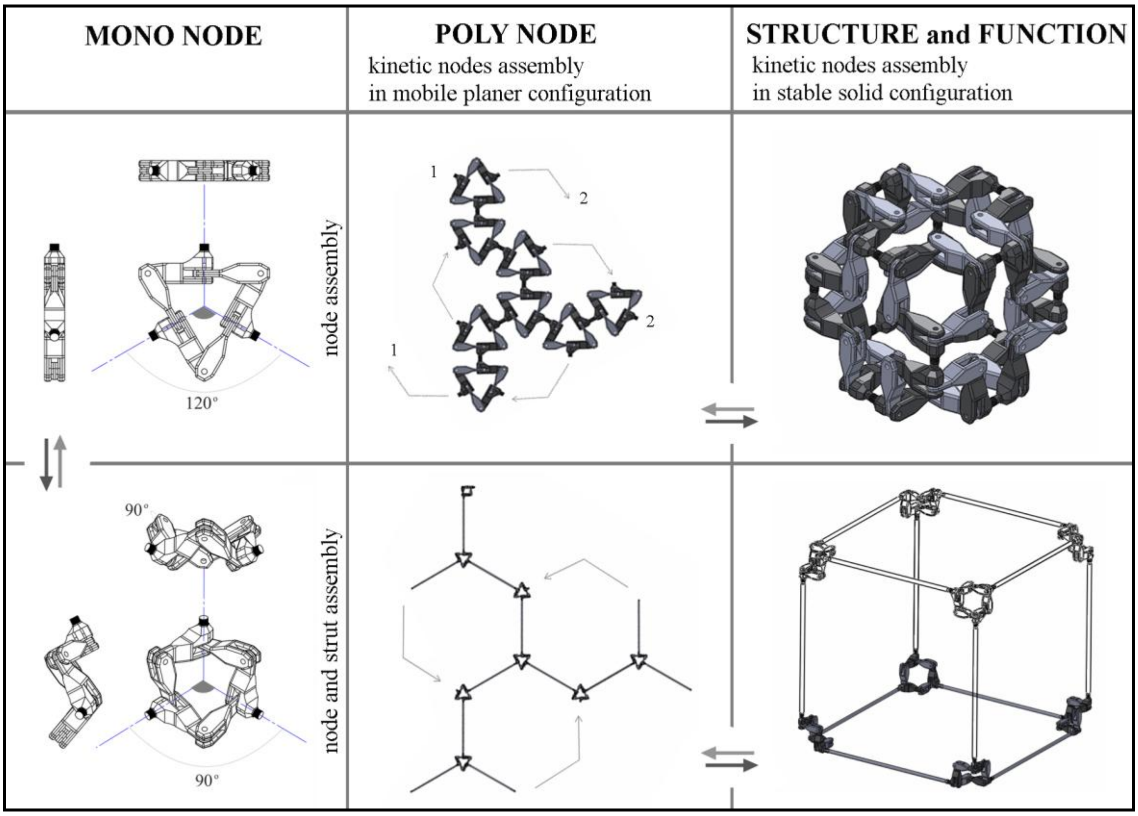


Figure 6.15. The stable hexahedron is obtained by using eight kinetic nodes.

In Equation 6.6, since there are 8 nodes with 6 revolute joints, the number of kinematic variables are obtained by multiplying the joints and the number of the nodes. As the nodes are 3D over-constrained mechanisms with 6R, their subspace, λ is 5. And there are 8 independent loops in subspace 5, and 5 independent loops in subspace 6. The connecting method of nodes and struts are shown in Figure 6.15.

$$M = \sum_{i=1}^{j} f_i - \sum_{k=1}^{L} \lambda_k \qquad \begin{aligned} M &= 6x8 - 5x8 - 6x5 \\ M &= -22 \end{aligned} \tag{6.6}$$

6.5.1.3. Dodecahedron

When five of the kinetic nodes are added in the form of a pentagon the structure gains stability. By adding the left fifteen nodes, the stable spherical space is obtained with huge openings with no need of triangulation at the nodal points as shown in Figure 6.16.

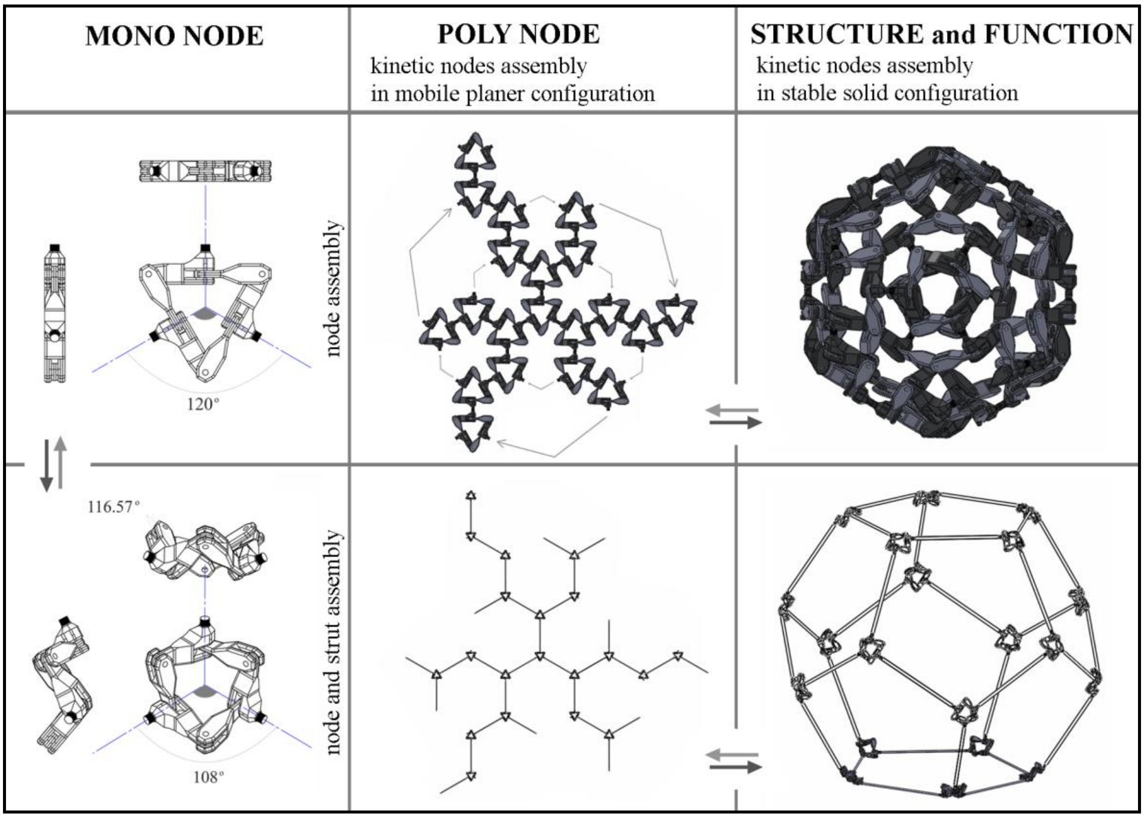


Figure 6.16. The stabile dodecahedron is obtained by using twenty kinetic nodes.

Stable dodecahedron can be obtained by twenty kinetic nodes. This structural system also enables pentagon openings without need for triangulation from the nodes.

$$M = \sum_{i=1}^{j} f_i - \sum_{k=1}^{L} \lambda_k \qquad \begin{aligned} M &= 6x20 - 5x20 - 6x11 \\ M &= -46 \end{aligned} \tag{6.7}$$

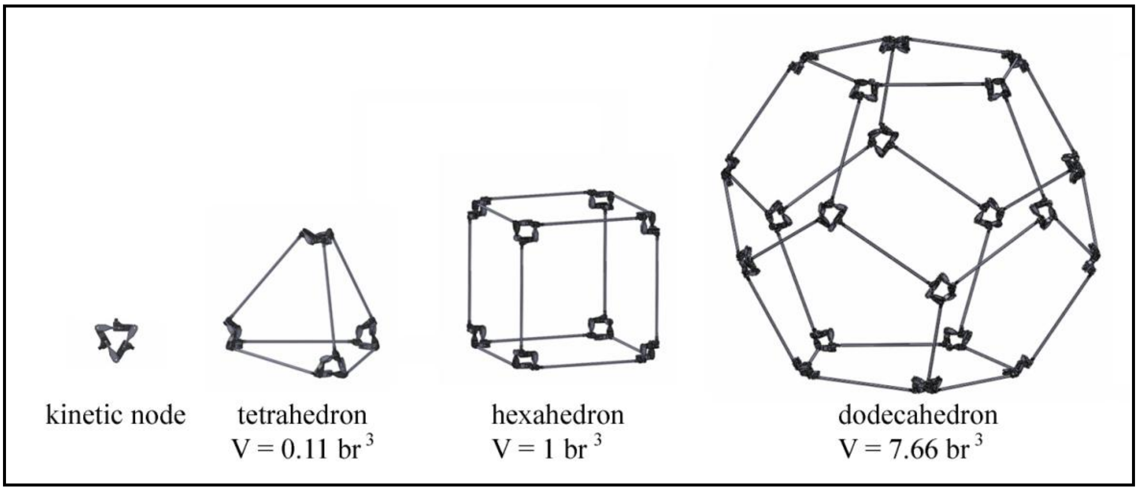


Figure 6.17. The variety of volumes defined by the same kinetic node

This structural difference also provides variety in volumes of the spaces as shown in Figure 6.17.

6.5.2. Other Stable Solids Obtained by Kinetic Node

The kinetic node also enable to obtain other stable solids; triangle prism, triple-helix structure and rectangular box. Triangle prism is obtained by two kinetic nodes at the angle 0^o.the triple helix is obtained by multiple kinetic nodes at the angle 60^o. Also, rectangular box is obtained by 8 kinetic nodes at the angle 60^o as shown in Figure 6.18, Figure 6.19 and Figure 6.20 respectively. They are also proved from the mobility formula that they are pre-stressed structures.

6.5.2.1. Triangle prism

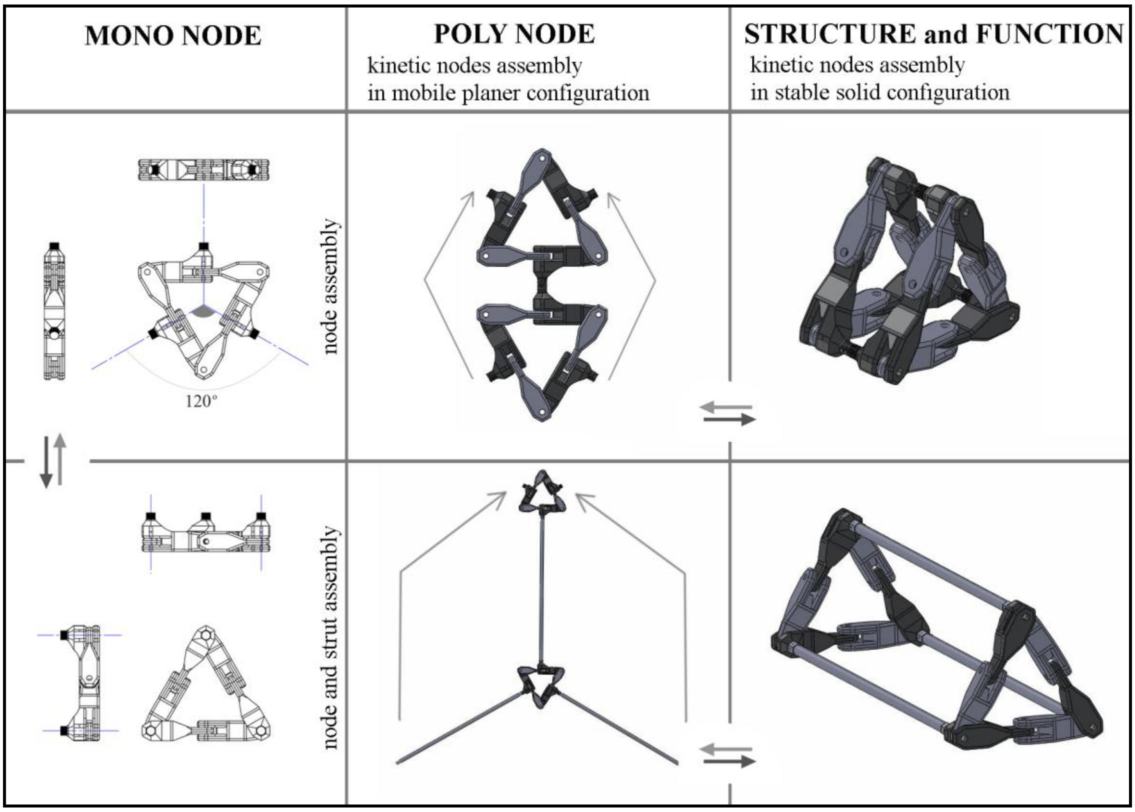


Figure 6.18. Triangle prism is obtained by assembling two kinetic nodes

Triangle prism can be obtained by two kinetic nodes.

$$M = \sum_{i=1}^{j} f_i - \sum_{k=1}^{L} \lambda_k \qquad \begin{aligned} M &= 6x2 - 5x2 - 6.2 \\ M &= -10 \end{aligned} \tag{6.8}$$

6.5.2.2. Triple-Helix Structure

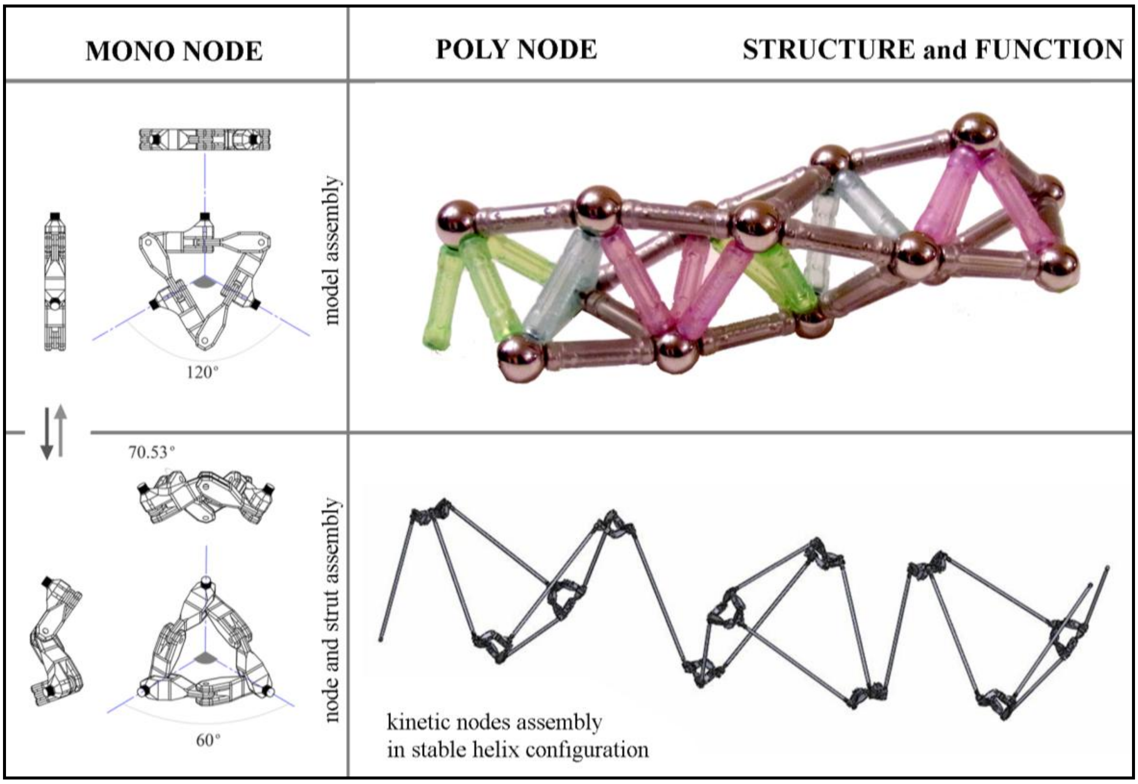


Figure 6.19. Helixal structure is obtained by assembling multiple kinetic nodes

Triple-helix structural system can be obtained by multiple kinetic nodes when the node is at the angle of 60^o, as shown in Figure 6.19.In every node, as triangle is maintained the other added strut is also stable. Analyzing the mobility with four kinetic nodes is given in Equation 6.9.

$$M = \sum_{i=1}^{j} f_i - \sum_{k=1}^{L} \lambda_k \qquad \begin{aligned} M &= 6x4 - 5x4 - 6.2 \\ M &= -8 \end{aligned} \tag{6.9}$$

6.5.2.3. Rectangular box

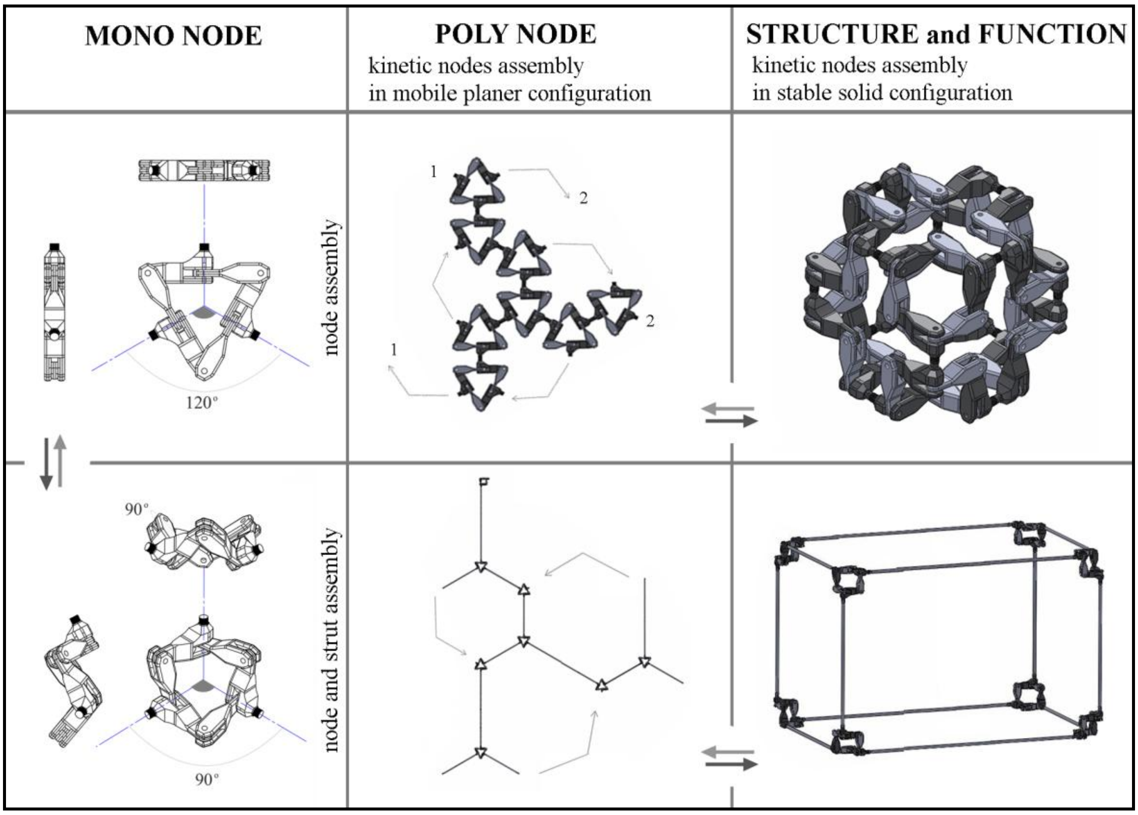


Figure 6.20. Assembling eight kinetic nodes with different sizes of struts

Rectangular box can be obtained with eight kinetic nodes and different strut lengths.

$$M = \sum_{i=1}^{j} f_i - \sum_{k=1}^{L} \lambda_k \qquad \begin{aligned} M &= 6x8 - 5x8 - 6x5 \\ M &= -22 \end{aligned} \tag{6.10}$$

6.5.3. Stable Hexagonal Grid

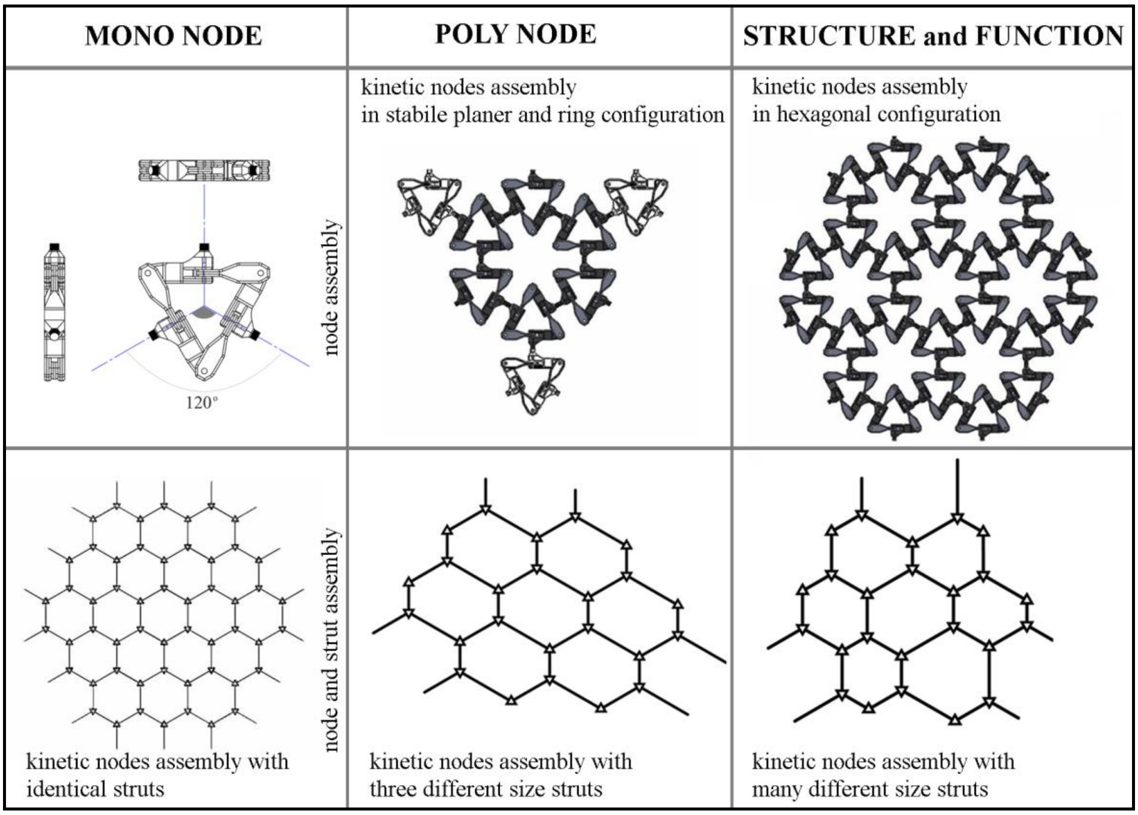


Figure 6.21. Stable hexagonal grid is obtained by six and multiple kinetic nodes

The hexagonal grid maintains stability when connected at least six nodes. The hexagonal opening is also obtained without need for triangulation. The mobility of the six nodes calculation is below. As defined before, the λ of the node is 5, however when composed by six nodes, λ is 6 since it is like a rigid body in the space.

$$M = \sum_{i=1}^{j} f_i - \sum_{k=1}^{L} \lambda_k \qquad \begin{aligned} M &= 6x6 - 5x6 - 6.1 \\ M &= 0 \end{aligned} \tag{6.11}$$

6.5.4. Dynamic Bi-layer Obtained by Proposed Kinetic Node

The 6 identical nodes are added to each other in different sequence, by changing the directions of 3 nodes, the kinematic chain provide motion in λ=5. The hexagonal grid and extendable configurations have potential to turn into bi-layer form.

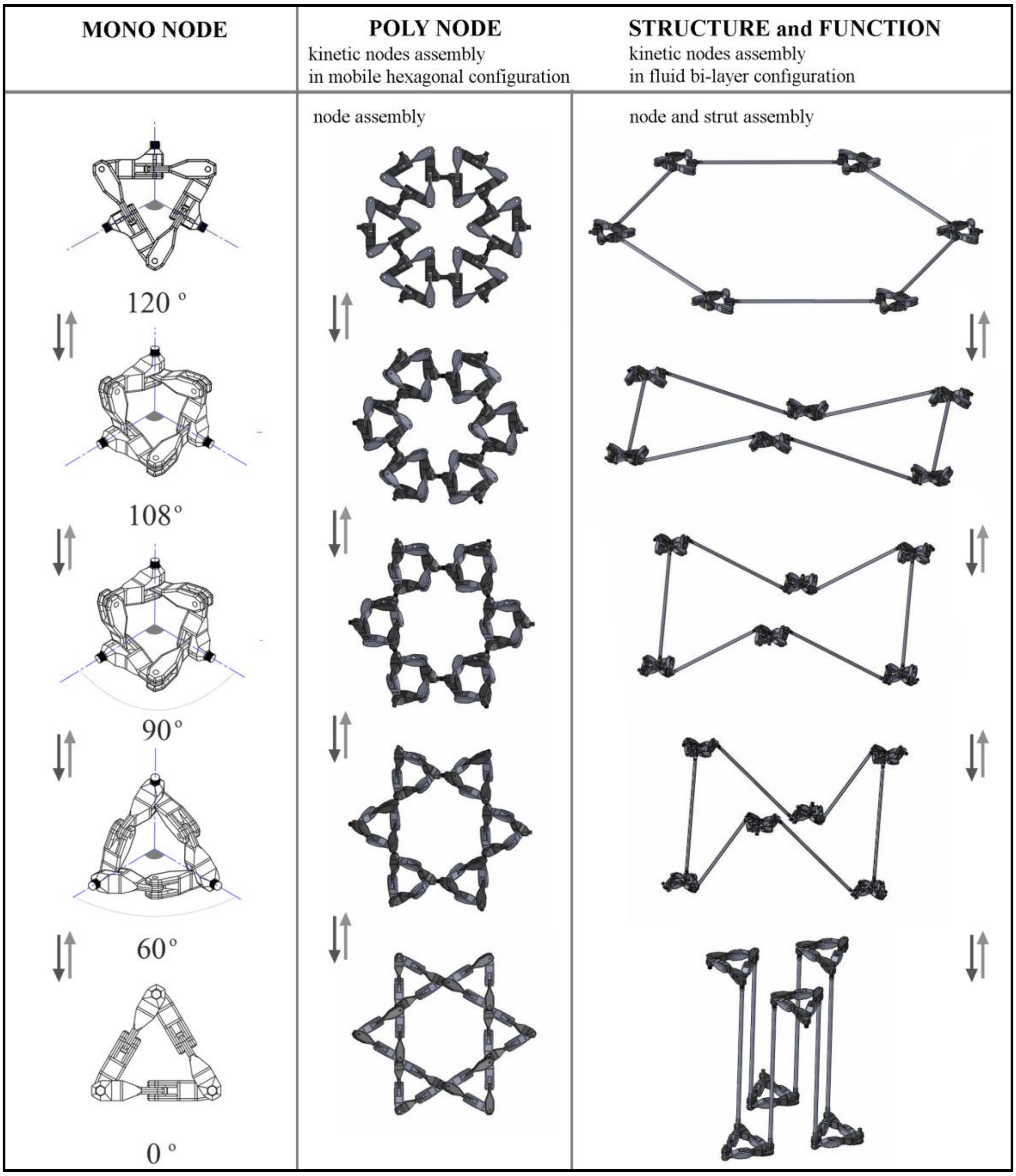


Figure 6.22. Bi-layer structure can be obtained by six and multiple kinetic nodes

$$M = \sum_{i=1}^{j} f_i - \sum_{k=1}^{L} \lambda_k \qquad \begin{aligned} M &= 6x6 - 5x6 - 5.1 \\ M &= 1 \end{aligned} \tag{6.12}$$

6.6. Table of the Structural Systems in Respect of Table 4.3

Table 6.1. Platonic Solids and other stable solids obtained by kinetic node

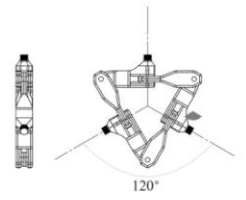
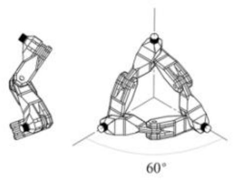
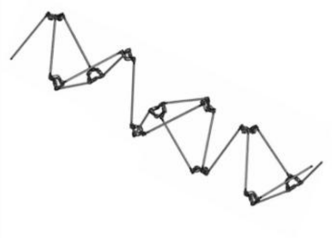
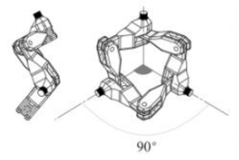
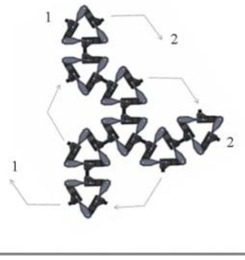
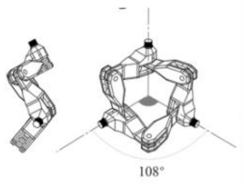
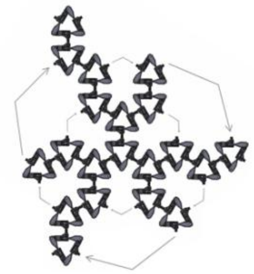
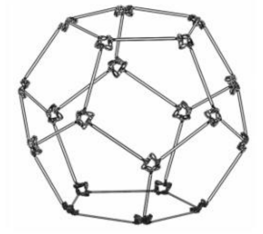
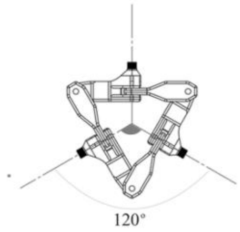
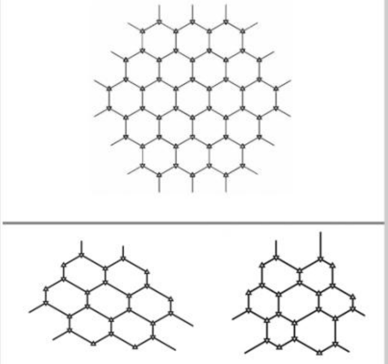
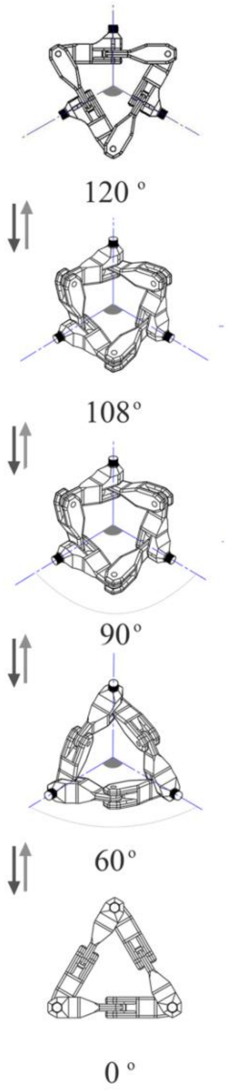
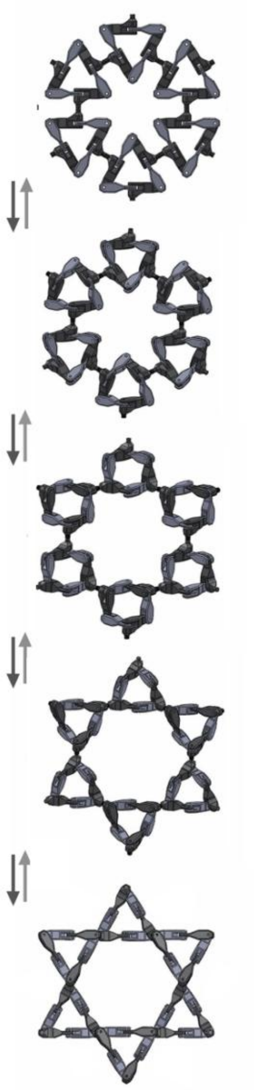
MONO NODE		**POLY NODE** kinetic nodes assembly in mobile planer configuration	**STRUCTURE and FUNCTION** kinetic nodes assembly in stable solid configuration	
	**PARALLEL LINKING and FORMING LINEAR and RING CONFIGURATIONS**			
				**HELIXAL**
				**PLATONIC SOLIDS / SPHERICAL CONFIGURATIONS**
				
				

Table 6.2. Stable Hexagonal Grid and Dynamic Bi-layer

MONO NODE	**POLY NODE** kinetic nodes assembly in mobile planer configuration	**STRUCTURE and FUNCTION** kinetic nodes assembly in stable solid configuration
	**PARALLEL LINKING and FORMING HEXAGONAL CONFIGURATIONS** 	 **STABLE HEXAGONAL GRID**
		 **DYNAMIC HEXAGONAL GRID and BI-LAYER CONFIGURATION**

CHAPTER 7

CONCLUSION

The main aim of this thesis is to propose a kinetic node for adaptable structures by bio-inspiration design process. In this chapter, the main achievements will be summarized in the design process of a kinetic node.

7.1. Main Achievements

- Bio-inspired Design Process

The first effort of this thesis was to analyze the bio-inspiration examples applied for technological outcomes. The bio-inspired design processes were synthesized because of the potential for practical engineering solutions. However, there is no proper approach for technological outcome, especially for architectural field. Biomimetic map defined by Julian F. V. Vincent was choosen and applied for the design process.

In the design process of a kinetic node, it was important to synthesis the biological model till the adaptable structure concept was achieved. The cell and the cell membrane components are selected as the biological model. The biological models are analyzed by structural aspects and supplied efficient solutions to apply into structural engineering field, which has not proposed in architectural field before.

The minimum way of close-packing property in natural structures and the structural order in the building sequence of the natural structures inspired structural orders for adaptable structures and their components. The clues from nature provided richness and efficiency in the design process.

In nature, adaptation depends on the capability of change and motion. The outcome of nature’s building code; hexagonal grid, triangular packing, three-arm node intersecting at 120^o in planar configuration, tetrahedron, the ring configuration and linking principles were maintained. From the light of the outcomes from the biological model analysis, a connection- kinetic node was needed for adaptable structural system that can be applied to variable structural orders from the mechanical aspects.

- Mechanism Design for Kinetic Node

The outcomes of biological model analysis supplied the problem definition for a kinetic node. The kinetic node should be in the form of a triangle or hexagonal ring (closed-loop) structure whose joint axes intersect at 120^o, and give possibility to integrate in a sequence for stable and dynamic structural systems.

If one's aim is to provide light-weight and deployable structures, mechanism design process is really crucial. The structural synthesis; determination of joint types, linkage types and the mobility of the system was done. For determining the joint type, revolute joints with 1 dof were preferred for mechanism design because of their performance and easy for making. Determination of the linkage type, the over-constrained mechanisms were analyzed as they offer extra stiffness and obtain mobility with fewer materials because of their geometric properties. The closed loop mechanisms have already gained its significance on applications with their ultra lightweight properties. For supplying this three-armed node and ring- closed loop mechanism-configuration, the Bricard Linkage from 3D over-constrained linkage mechanisms, which is obtained by 6R closed loop forming hexagonal ring, provided a way for obtaining the desired geometry with three dimensional behaviour.

- Adaptable Structural Systems obtained by proposed kinetic node

William Zuk and Roger Clark named adaptable structures in five classification; incremental, reversible, deformable, mobile and disposable. All five classifications of the adaptable structures are considered for the design of the kinetic node.

The space truss structures are analyzed because of their three dimensional behaviour, high strength and lightweight properties. Space truss structural systems have also inner potential for adaptable structures; however, after building the construction, the system lost its potential. The nodes are the main consideration parts of the structural system and determine the area of the plane and further the volume of the space. The nodes are mainly solute by rigid components which limit the application diversity or the nodes become complex because of triangulation at the nodal points for gaining stability. Although, the structures are mostly designed by rigid connections, alternate structures which are capable of geometrical transformation also exist. This geometrical transformation can provide new structural systems for adaptable structures.

In natural structures from molecules to high levels of order have a capability of changing their forms from one rigid phase to another in minimum energy configurations. In that case, the analysis from the building sequence of biological macro molecules inspired the structural orders for adaptable structures.

The innovative design of the kinetic node provided variable stable and dynamic structural orders inspired by the analysis of biological model. The variable forms are in hexagonal, spherical, helix and bi- layer configurations. Stable tetrahedron, hexahedron, dodecahedron, triangle prism, rectangular box, triple helix and hexagonal grid are obtained. Also, deployable hexagonal grid and bi-layer structural system is maintained by just adding the identical kinetic node to each other.

Briefly, the bio-inspiration design process supply many innovative solutions for many disciplines from social sciences to applied sciences. The main issue is to ask nature how to solve the problems for human-based questions by learning deeply from its infinite knowledge.

7.2. Final Remarks and Future Works

The research reported in this thesis opens up many opportunities for future works in architecture. The multidisciplinary approach of biology, mechanism, and geometry provided a new structural system for architectural applications. Bio-inspiration is a way for finding practical solutions to engineering questions in respect of sustainability. The demand for sustainability is inevitable for this century. Bio-inspiration supply solutions for using the resources and energy efficiently, controlling the hazardous substances, supplying functionality to the materials and structures and providing profits for our environment.

There is an increasing recognition that buildings play a vital role on the environment and society. These impacts force the designers to question *structure, space and time* correlation. Structure which affects the form should response to the pressures acting on it with the demands of time, even environmental or sociological. Mainly for that reason, responsive systems became an increasing topic in architecture in 1960’s. However, because of the lack of computer-based systems, this approach is short-lived in architecture but begin to be a research field in engineering.

The buildings are always facing changing conditions from the very beginning step of design to the 10 or 20 years after built. It cannot be wrong to say that the most important component within architecture is the design of the structure. The structural systems in responsive aspects should consider the lightness, the controllable rigidity and capable of deformation. These properties are important for the responsive structures to work in utility. Natural structures provide unlimited versions for lightweight structures. The goal should be reaching to an optimum solution for the structural system by inspiring from nature. In nature as they response to the environment, the structural order is always in dynamic equilibrium. However, this property is regarded in man-made structures. Kinetic architecture is one of the architectural field which deals with motion in structural systems.

In this thesis, the structural order and the connection types are discussed in kinetic aspects. Since the structure is the main component, this bio-inspired design of the kinetic node provides challenges for variable stable and dynamic structures. In conclusion, the structure for the responsive architecture can be obtained by kinetic aspects, however needs more verifications to be really sustainable.

Natural structures are a treasure to focus on designing new structural systems. The clues from nature provide richness and efficiency in the design process. Feedback mechanism is paramount in natural structures and should be considered as the design parameter for sustainable built environment.

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