A STUDY ON THE USE AND DESIGN OF MECHANISMS IN ART AND ARCHITECTURE

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ABSTRACT

A STUDY ON THE USE AND DESIGN OF MECHANISMS IN ART AND ARCHITECTURE

This study consists of research on developmental processes, fundamentals, kinematic properties, and design methods of art and architectural examples that involve mechanisms and a proposal of a novel method of designing polygonal deployable surfaces.

The effect of motion studies on art and architecture is analyzed from the first technical studies of motion and portable examples of architecture. The pre-industrial automata, acoustic designs, musical instruments, water-lifting devices, and aqueducts were designed by artists and architects as well; windmills that are the first rotating structures, clocks, clock towers, construction machines and early examples of movable bridges are examined.

The kinematic properties and fundamentals of mechanisms are analyzed. The kinematic structural analyses of contemporary art and architectural products are conducted by drawing kinematic diagrams, demonstrating link and joint types and numbers; and mobility calculations. The primary units and assembly methods of them are examined. Strengthening the bond among the fields of kinetic architecture, art and mechanism science is intended. The present study is the first source in which examples from the related fields and corresponding kinematic science are explicitly transmitted for artists and architects.

Finally, a novel design method for polygonal deployable surfaces that is adaptable to climatic, functional, visual and/or social needs is developed. The method starts with the kinematic design of the triangular primary unit, which is topologically Bennett's plano-spherical mechanism. The planar position provides covering surfaces, while the spherical linkage generates a 3D dynamic form during movement. The design is adapted to polygons and multiplied in Archimedean tilings. A single actuator can drive all designs. The modularity provides designs versatility and flexibility.

ÖZET

MİMARLIKTA VE SANATTA MEKANİZMALARIN KULLANIMI VE TASARIMI ÜZERİNE BİR ÇALIŞMA

Bu tezde mimari ve sanat alanlarından mekanizma içeren örneklerin gelişim süreçleri, temel prensipleri, kinematik özellikleri ve tasarım yöntemleri incelenmiş; sonrasında tek serbestlik dereceli, çokgenlerden oluşan hareketli yüzeylerin tasarımları için bir yöntem önerisi geliştirilmiştir.

Hareket çalışmalarının mimariyi ve sanatı şekillendirme biçimi, hareketin teknik olarak ilk incelendiği dönemlerden ve mimarinin ilk portatif örneklerinden başlanarak ele alınmıştır. Endüstri öncesi dönemde sanatçılar ve mimarlar tarafından da tasarlanan otomatlar, akustik tasarımlar ve müzik aletleri, suyu yukarıya taşıyan araçlar ve su kemerleri, dönme kabiliyetine sahip ilk yapılardan rüzgâr çarkları, saatler ve saat kuleleri, inşaat makineleri ve hareketli köprülerin ilk örnekleri araştırılmıştır.

Mekanizmaların kinematik özellikleri, temel kavramlarıyla birlikte incelenmiştir. Sanat ve mimarlık alanlarından güncel örneklerin kinematik yapısal analizleri ise kinematik diyagramları çizilerek, uzuv ve mafsal tipleriyle sayıları gösterilerek, serbestlik dereceleri hesaplanarak ortaya konmuştur. Tasarımların temel birimleri ve birleşme özellikleri incelenmiştir. Kinetik mimari, sanat ve mekanizma bilimleri arasındaki köprüleri güçlendirmesi amaçlanmıştır. Mimarlar ve sanatçılar için oluşturulan, bu alanlardaki örnekler ve özellikler incelenip temel kinematik bilgisinin süzülerek toplandığı ilk kaynaktır.

Son olarak iklimsel, işlevsel, görsel ve/veya sosyal ihtiyaçlara adapte olabilecek, düzgün çokgenlerden oluşan, açılıp kapanabilen yüzeyler için yeni bir tasarım yöntemi önerilmiştir. Bu yöntem üçgensel temel birimin kinematik tasarımıyla başlar. Bu birim topolojik olarak Bennett'in düzlemsel ve küresel bağlantı biçimini kullanır. Düzlemsel form, düz yüzeyleri kapatmaya uygundur; ayrıca kullanılan küresel bileşen, hareket sırasında 3B dinamik bir form oluşmasını sağlar. Ardından tasarım, çokgenlere adapte edilerek düzenli ve yarı düzenli teselasyonlarda çoğaltılır. Oluşan tasarımların hepsi tek bir motorla kontrol edilebilir. Modüler olması ise tasarımlara çok yönlülük ve esneklik sağlar.

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CHAPTER 1

INTRODUCTION

Movement is fundamentally any kind of change an object experiences with relation to time and space. No object in space can be called motionless. The motion has always been the subject of curiosity, research and design. The dynamic perception of life is projected by designers with respect to the observation and study of movement. The concept of movement, which is the principle concept that equips designers' unique work, gives art and architecture a great opportunity to create unique dynamic designs. The mechanisms in which movement is enabled are subject matters to be investigated. Movable designs and constructions involve the systems that are called mechanisms. Development of technology and *mechanism science,* in both theoretical and applicational terms, allows art and architecture to have movable, flexible characters, thus provides them the adaptability to change.

Strategies and methods of *mechanism design* are similar to those of *kinetic art* and *architecture*. Movable structures in architecture are mostly covered under the fields of *kinetic architecture* and *deployable structures*. The term *kinetic art* also refers to objects with a movable design. Kinetic art and architecture are multidisciplinary fields. The movement is examined in various techniques by those who work in the fields of mathematics, geometry, physics, biology, astronomy, mechanical engineering, structural engineering, mechatronics, industrial design engineering, architecture, art, etc.

Undoubtedly, machines have an extraordinary and significant place in human life. The study of the nature of motion goes back even to antiquity. Motion studies are based on the observation of terrestrial and celestial body movements. In times when almost no laws of physics, such as the law of gravity, planetary motion or magnetism are developed, the aims of achieving ease and order in daily life dynamics, construction building, understanding the world and its operational characteristics or simple recreational motives reveals mechanical system designs. Mechanism design and machine production provided a great amount of progress in human history. In his book, *Ingenium: Five Machines That Changed the World* (2007), Mark Deny covers the historical significance of five types of machinery that have a great impact on human life: 1. Bow and Arrow, 2. Waterwheels and Windmills, 3. Counterpoise Siege Engines, 4. Pendulum Clock Anchor Escapement, 5. Centrifugal Governor. The current study examines some of these inventions that are designed and developed by artists or architects (see Chapter 2.2).

Imitation of life in mechanical areas dramatically accelerates with post-industrial mechanism studies. The Industrial Revolution, which begins with James Watt's steam engine, is a milestone for mechanism and machinery (Rao & Dukkipati, 2006). Mechanism and machine theory is subsequently developed by the application of physics, kinematics and kinetics principles to machinery analysis and synthesis. The great progress of mechanism science obtained by post-industrial scientific research generates motion studies firstly in machinery; with the transfer of this accumulated knowledge, thereafter, in art and architecture.

Machinery is used in art and architecture since ancient times. First examples of kinetic systems that attract the interest of users, artists and architects are mostly recreational automata, water wheels, wind wheels, clocks, movable bridges, construction machines, or portable dwellings and caravans that are compatible with the nomadic lifestyle. The first systems are operated by muscle or natural forces depending on the level of scientific development in the related period. The early machines used for simple purposes such as water wheels are capable of performing a single operation, sometimes at a different speed. They have the advantage of being faster in production and enduring for a longer time. However, these machines are disadvantageous in the sense of adaptability. Today's machinery is different from early machines not only in terms of complexity but also in terms of multi-functionality (Zuk & Clark, 1970). Various sources such as motors driven by electricity or gasoline can operate current machinery. The great progress in computer technology and applicational capabilities result in the wider use of computer systems and sensors that are responsive to light, heat, sound or motion.

Numerous movable products are currently developed by designers from various fields. Rapidly changing lifestyles, recently generated materials, technological development and the progress in transportation and production procedures revealed different conception and methods for art and architecture. This process results in the generation of changeable, portable, easily dismountable and thus adaptable designs.

Mechanical expression becomes more common in daily life with the development of disciplines that examine and model motion. A wide range of products from toys, sculptures, industrial products, dance and theater stages, to bridges, buildings, building components and structures represent the new aesthetic perception very well. Motion attracts the interest of several painters as well. Therefore, the production of visual illusions and designs varying with respect to dimension occurs. While the idea of kinetic design goes a long way back in time, it is the development of *mechanism science* that makes its application to industrial production possible and reveals significant progress in the areas of architectural design.

The transmission of movement from one point to another is as useful as the ability to stand in balance under the presence of multiple forces for human beings. *Kinetics* and k*inematics* are two of the disciplines of *dynamics*. *Kinematics* examines the geometry of motion in members of mechanisms without regard to affecting forces. Force and energy, on the other hand, are also taken into account in *kinetics*. Kinematics consists of two parts: *analysis* and *synthesis.* The *kinematic synthesis* and *analysis* methods applied numerous studies in the fields of art, architecture and engineering.

1.1. Kinetic Art and Architecture

Kinetic art is “a model of dynamic perceivable expression” (Chen, Lin, & Fan, 2015, p.922). The Industrial Revolution and the accelerated use of mechanisms in art reveal great progress in kinetic art. Some avant-garde artists are Marcel Duchamp, Naum Gabo and László Moholy-Nagy (Ventura, 2014). Naum Gabo and Antonie Pevsner, in *The Realistic Manifesto* in 1920, define the formation of time and space perception as their primary purpose. Representing time by kinetic elements, they claim that static rhythms are not the only option for plastic arts (Bann, 1974). The core of kinetic art remains to be artwork with harmonic rhythms of mechanics, aesthetics and psychology in terms of human perception (Popper, 1963). Knowledge of mechanics, magnetics, electrodynamics, aerodynamics, etc. requires an agreeable amount of experience or knowledge of practical engineering in kinetic artwork as well (Rycroft, 2012).

Kinetic art represents motion in two categories. The first one is *mechanic motion* which generates real movement. The second is *optical illusions* which use a stationary piece that is designed to create a sense of motion (Chen et al., 2015). Examples of kinetic art are not only movable pieces that involve mechanisms as in kinetic sculptures, but also optical illusions leading to visual diversities such as in *Dadaism* or *Optical Art*. Kinetic artwork in which illusional, mechanical or combined methods are applied express, theorize and develop movement.

Visual illusions that are generated by the brain through the retina are the essence of Optical Art (Chen et al., 2015). An optical illusion consists of 2D images that are perceived to be in motion by their color and shape. Victor Vasarely, for example, is one leading artist of the aforementioned field. Movement of the eyes from right to left on the plane of the painting in Vasarely's *Supernovae* (1959-61) generates a sense of motion. A painting of him (1969) on the Bonn University Juridicum (faculty of law) wall carries geometrical shapes consisting of light and dark stripes in varying lengths that are positioned in systematic repetition and combination, creates an illusional sense of motion despite the fact of being steady in reality (see Figure 1.1).

The second category in the field of kinetic art is mechanical motion, which presents actual motion in the design. *Movable (action) origami* and *kirigami*, *pop-up* paper engineering, automata and movable sculptures are examples of this category. Both mechanism and mathematical knowledge are essential for such artwork.

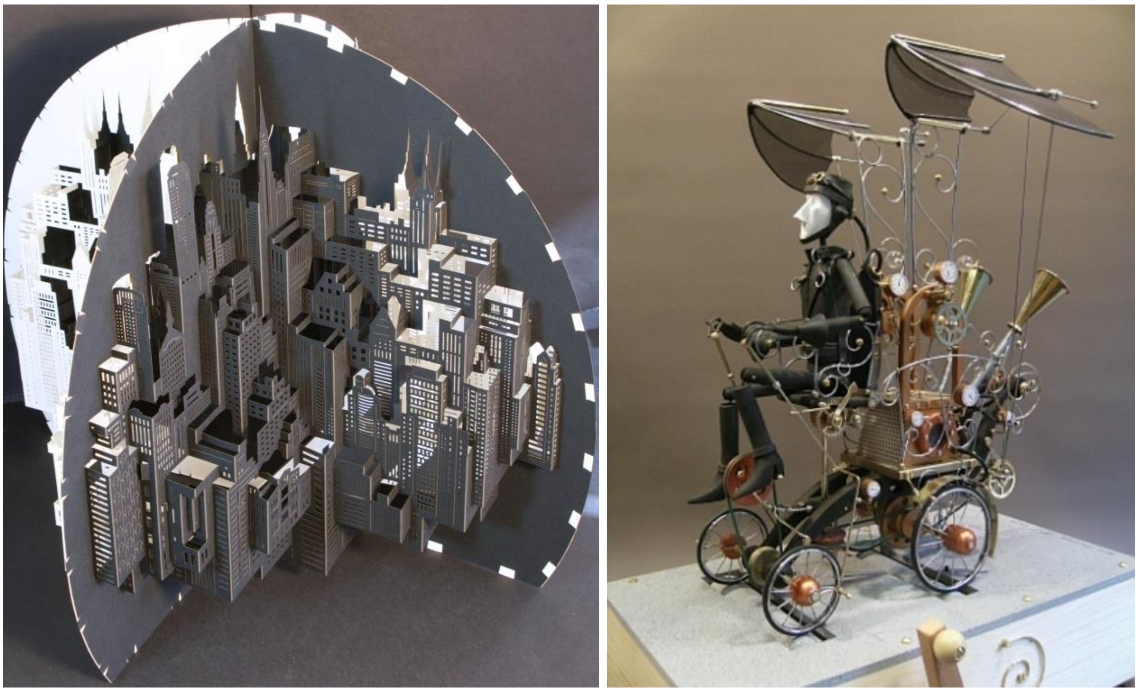
Figure 1.1. Optical illusion generated by a mural in the facade of the Juridicum, University of Bonn, by Victor Vasarely, 1969
(Source: Vielfaeltig2010, 2011)

Origami, the Japanese art of paper folding, is a design method carrying great opportunity for kinetic production. Kirigami is a combination of origami and paper-cutting, generally from a single piece of paper. The folding and cutting processes are followed by openly exposing pieces. Pop-up books differ from Kirigami in terms of being generated by several cohesive pieces of paper; consist of popping images that are triggered by turning of the pages in a book. A great example of the kirigami technique is *Cosmopolitan* by Ingrid Siliakus. Inspired by the buildings of New York City, *Cosmopolitan* is a 2D paper-cutting piece that generates a 3D artwork after opening (see Figure 1.2.(a)). Four sides of the single-piece paper are connected to each other by a complementary design. Siliakus' design can be entirely flattened into a 2D piece. Works of Siliakus, which are mostly based on architectural forms, are known as *paper architecture* (Siliakus & Exto, n.d.).

Various mechanisms integrate the freedom and artistic expression of origami to engineering and architecture. While differing in materials and production processes, origami in paperwork and architecture have quite similar design principles in mathematical terms. Origami frequently inspires compact, deployable designs. A branch of it, *action origami* provides a significant basis for development by generating movable structures (Bowen, Grames, Magleby, Howell, & Lang, 2013). The application of action origami principles to kinetic architecture and deployable structures provides the advantage of obtaining an easily storable and transportable object that can be fully closed and flattened using mostly plates and revolute joints. A significant number of designers and artists today work in this field.

Automata and mechanical toys represent the oldest examples of kinetic art as well as being accepted as the first examples of simple mechanisms that are used in contemporary robot production. Artists and engineers produce automata that are designed with a wide range of systems from the simplest to the most complicated using various mechanism types such as linkage, cam and gear with varying material and shape. Kate Newstead's *Transport of Delight* (2011), for example, a 50 cm tall wood, brass and rubber design is shown in Figure 1.2.(b).

Contemporary products include numerous movable sculpture designs that generate a mechanical representation of motion. Not only imitations of living creatures but also different creations of unique mechanical species are possible. Designers produce motor and electrical systems and even smart (actively controlled) objects controlled by simple human force or by computer added sensors and interactive systems



(a) (b)

Figure 1.2. Examlples of kinetic art with mechanical expression
(a) Kirigami Design of *Cosmopolitan* by Ingrid Siliakus
(Source: Siliakus, 2011)
(b) An Automaton of *Transports of Delight* by Keith Newstead
(Source: Cabaret Mechanical Theatre, 2010)

that are activated by human or natural force. Artists like Marcel Duchamp, Jean Tinguely, Reuben Margolin, Anthony Howe, Alexander Calder and Theo Jansen produce numerous pieces in the aforementioned field. The stainless steel sculpture, *Shidahiku* by Anthony Howe (2017), in which 18 simultaneously rotating bars are triggered by the wind force, is shown as an example in Figure 1.3.

Motion is a major component of dance choreography, stage and theater design. Reuben Margolin's kinetic sculpture, *Connected* (2011), in which change is generated by cables attached to a human body, is shown in Figure 1.4.

The number of flexible, adjustable and configurable design products of interior architecture such as movable separator walls, furnitures, urban objects, fountains and industrial design products of landscape architecture accelerates day by day. Small apartments or small spaces such as boats or temporary facilities often carry portable multi-functional furniture that are specifically designed to be both light and transformable. For example, the bench design of the students from Columbia University in New York City is a dynamic representation of daily life as well as a sitting place

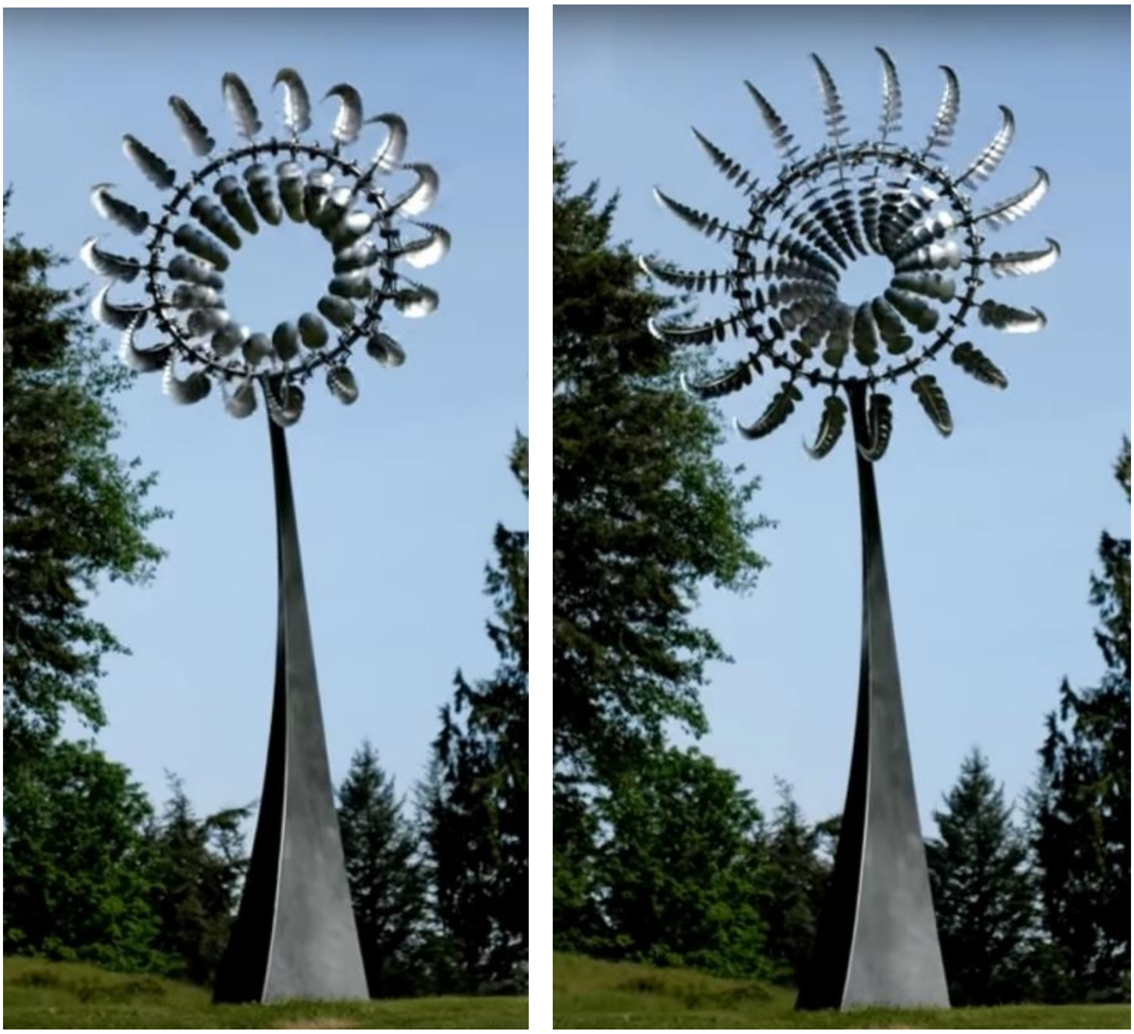


Figure 1.3. Kinetic wind sculpture in motion at two positions
(Source: Howe, 2017)

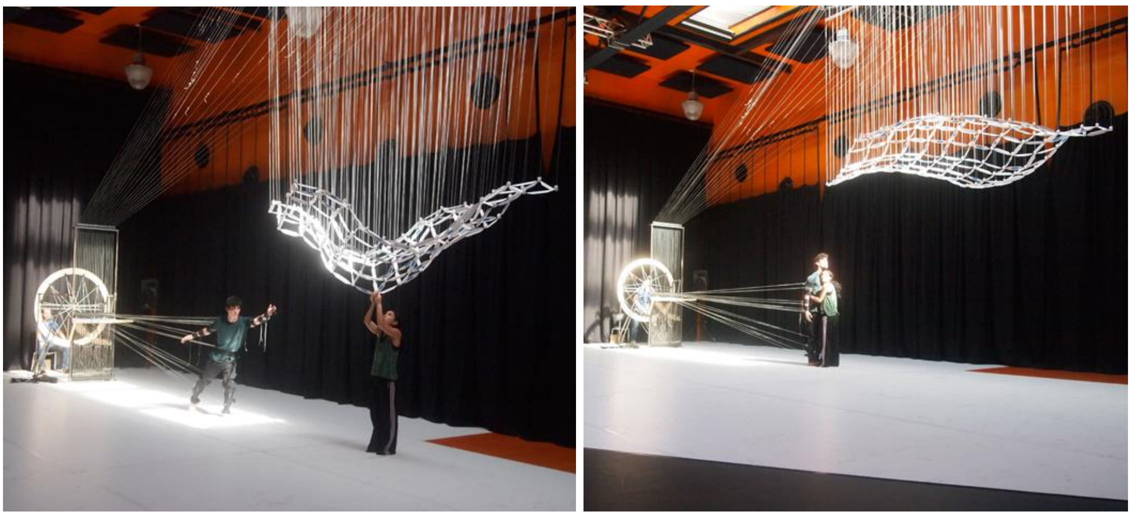


Figure 1.4. Motion activated via cables attached to a human body in kinetic sculpture, *Connected*
(Source: Margolin, 2020)

Figure 1.5. The bench activated by the occupant’s pressure, *Polymorphic*
(Source: Chang & Bustler Editors, 2011)

based on the equilibrium principle. As it is shown in Figure 1.5, the sitting place can be adjusted with respect to the user's body profile.

Kinetic architecture is described by Zuk & Clark (1970) as an adaptable form of architecture that is based on the mechanistic-technological approach. Kinetic architecture is also defined as “buildings, or building components, with variable location or mobility and/or variable geometry or movement” (Fox & Yeh, 2000, p.2). There are various titles that examine movable structures with respect to their characteristics. One of the most widespread subjects studied in such term is deployable structures. A *deployable structure* is “a generic name for a broad category of prefabricated structures that can be transformed from a closed compact configuration to a predetermined, expanded form, in which they are stable and can carry loads” (Gantes, 2001, p.3).

Even though these movable structures are not new in human history, adaptations of development in mechanism science to architecture provide greater movement. The rapid change in technology, materials, lifestyle and culture, are some of the reasons for the accelerating use of kinetic architecture in daily life. Besides the great development of information technology, increasing demand for a cleaner world also plays a major role in the construction of these highly functional, creative structures (Kronenburg, 2003). The pressure caused by physical, environmental, social and cultural needs results in consideration of the fourth dimension in architecture (Zuk & Clark, 1970). The most common drive for the construction of movable buildings is the need for a practical solution to a certain problem where standard architectural principles do not suffice.

The use of retractable, transformable, demountable, transportable, foldable and configurable system designs reveal lightweight, responsive and adaptable structures. Long-lasting, applicable, environment-friendly systems with the potential of transformation and change develop in line with the systems that are adaptable to daily life conditions. Designers generate deployable structures in any form generally with characteristics of being compact, lightweight and user-friendly. These provide the advantages of being easy to store, transport and construct.

The design of deployable structures on an architectural scale provides protection and control in temporary facilities such as in exhibition structures, shelters like those in traveling theaters and circuses, greenhouses, aerospace structures, military systems or emergency shelters. They can carry adaptable protection purposes as in sports facilities covering swimming pools, tennis courts, large stadiums or temporary covers for outdoor activities. Multifunctionality by changing the shape is another potential advantage of kinetic design as in movable bridges. Movable building components take an effective role in environmental control such as the sun in shading panels, on sound in acoustic designs, on the wind, rain, etc.

Emilio Pérez Piñero is the first structural designer in the field of modular and deployable architecture (Escrig, 1996). The traveling theater design of Piñero in 1960s (Figure 1.6) is as much as a key structure for the current field as the steam machine that is produced in 1763 is for the Industrial Revolution. Theodore Zeigler, Felix Escring, Frei Otto, Santiago Calatrava, Buckminster Fuller, Chuck Hoberman, Charis Gantes, Sergio Pellegrino, Zhong You, Yan Chen, Robert Kronenburg and Koray Korkmaz are some of the outstanding names working in the fields of kinetic architecture and deployable structures.

Hanaor and Levy classify deployable structures with respect to two main characteristics: kinematics and morphology (see Figure 1.7). *Rigid links* and *deformable bodies* are two main categories in which kinematics of deployable structures are examined (Hanaor & Levy, 2001). Bars or plates are examples of rigid bodies while cables and membranes are of deformable bodies.

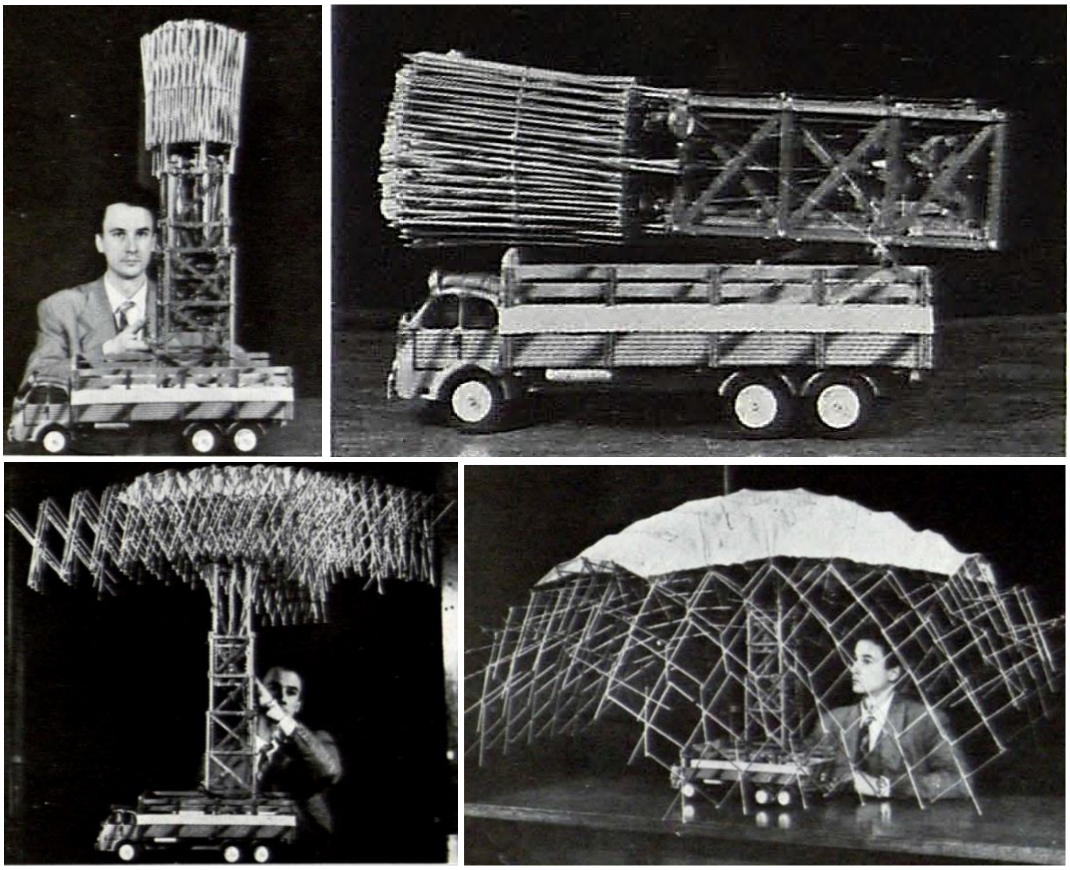


Figure 1.6. Emilio Pérez Piñero's Deployable Theatre
(Source: Piñero & Urgoiti, 1961)

Engineers, architects and designers who have been investigating motion for ages reveal movable designs that are adaptable, sustainable, flexible, dynamic, and changeable in terms of time and space. Kinetic art and architecture are based on mechanism design strategies, methods and principles. Mechanisms of art and architecture use similar kinematic design and analysis processes of mechanism science. Various mechanisms are revealed depending on utilization and purpose. The forefront position of load-bearing capacity in structure design, for example, has a direct effect on number and type selection of links and joints. Links such as bars and plates are used not only for motion transmission but also for covering purposes as in buildings. Transmission of motion from a point to another may be the essence in mechanical engineering while the first and final positions can be in architecture and each moving piece or even the motion itself may be in art. Velocity and acceleration have minor importance in kinetic architecture.

The present thesis is thus restricted with structural analyses and designs that are conducted to detect and design the characteristics of motion in art and architecture.

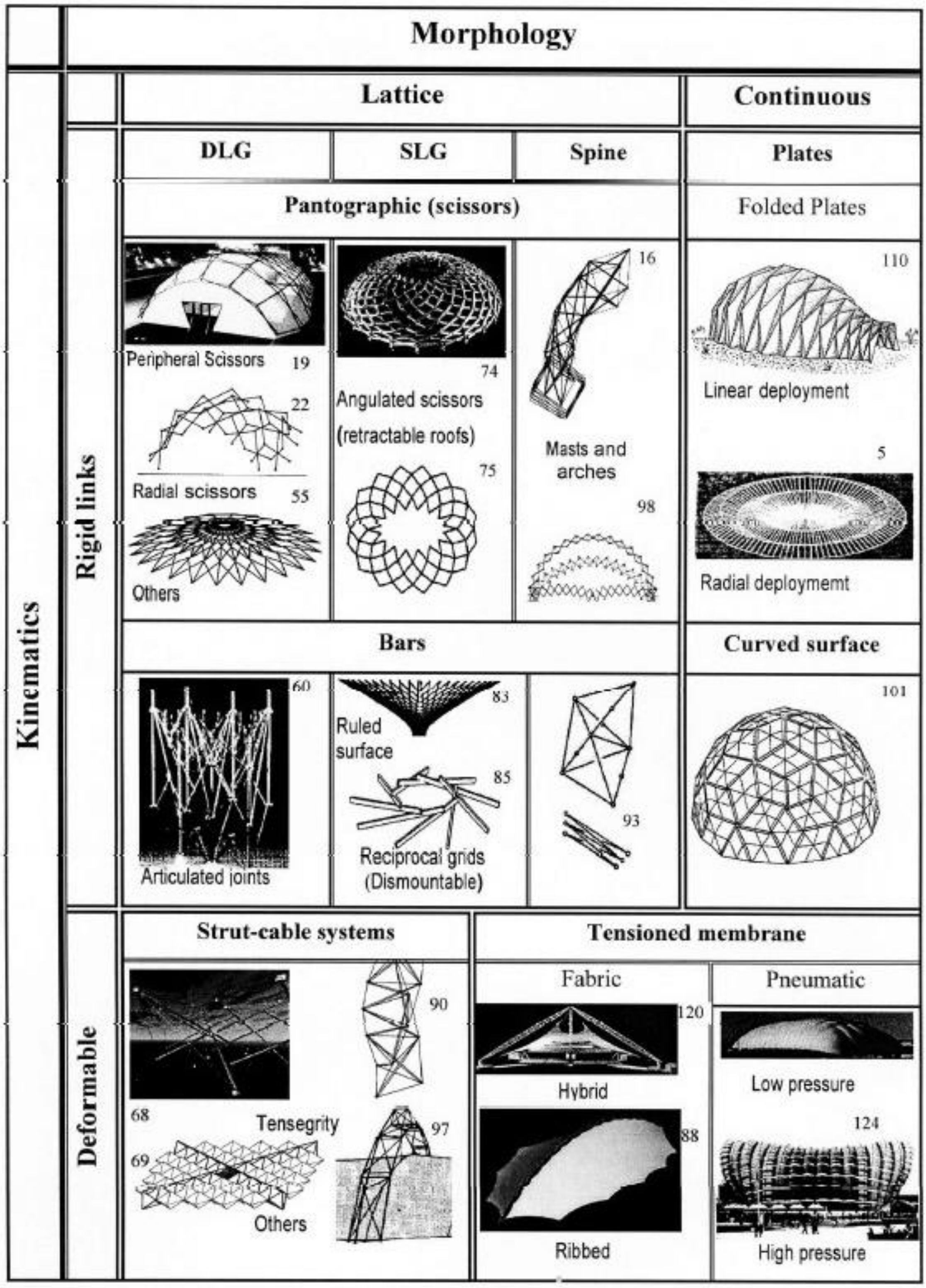


Figure 1.7. Classification of Deployable Structures
(Source: Hanaor & Levy, 2001)

1.2. Aim and Scope of Thesis

The purpose of the current thesis is to reveal the mechanical background of movable designs in art and architecture and propose a novel design based on a technical perspective. The current study aims to examine the principles and examples of pieces that carry mechanisms that generate a motion with rigid links as the primary design strategy component, concerning the corresponding knowledge in the pre and post-industrial periods.

Numerous observers, artists and architects focus on the theory and practice of motion in the pre-industrial period. Examination of various mechanisms and research involving illustrations and technical knowledge presents those designers' mechanism knowledge of the related timeline. Despite involving related information, the scope of the current study should not be perceived as an examination of mechanisms based on historical heritage. The current study includes the examination of outstanding pieces of several architects and designers.

The present study also examines the post-industrial developments, firstly by covering the massive development of mechanism science; then by presenting the basic mechanism design principles and fundamentals with several examples of design applications. Those are analyzed concerning the kinematic structural (type and number) analyses. Kinematic structural analysis processes and methods are similar in kinetic art and architecture with mechanical engineering. Explained kinematic fundamentals and processes include first steps and basic design knowledge. The current study thus serves as a guide on this basis.

After analyses are conducted, a mechanism design process is explained for deployable surfaces that are adaptable to environmental and user requirements. The generation of a design method for single degree-of-freedom (DoF) deployable surfaces that form regular convex polygons in the deployed position is aimed. A unit is designed and subsequently adapted and repeated in polygons to reveal the same DoF. Finally, the Archimedean tilings are selected to assemble these polygon modules in repetition to cover a surface with no gaps or overlaps. Only kinematic designs of these assemblies are presented, but further constructional design is not included in this study.

Examinations include explanations of mechanism types, mobility calculations, technical drawings, modelings and kinematic diagrams using graphical methods.

1.3. Outline of Thesis

The present thesis consists of 6 chapters.

Chapter 1 introduces the research field with basic concepts and usage area as in kinetic art and architecture applications. This chapter is followed and terminated by the scope, aim and outline of the study.

Chapter 2 involves two subheadings related to the pre-industrial period. The first part consists of the examination and evaluation of the nature of motion that makes a significant contribution to the development of mechanism design. The second part presents outstanding projects and development in the field of movable design that are remarkable for architects, engineers, and artists.

Chapter 3 examines the post-industrially developed science of *kinematics of mechanisms* revealing the mechanism fundamentals, types, design and analysis processes on the basis of scientific development with respect to contemporary architectural and artistic applications.

Chapter 4 presents the structural (type and number) analyses of the primary linkage units revealing the overall structures of the selected art and architectural designs.

Chapter 5 describes the case study of a novel design that is capable of creating adaptable surfaces. A method is revealed to design a unit and the repetition of this unit is adapted to deployable polygons. These polygon modules are repeated in an assembly method to be used in Archimedean tilings.

Chapter 6 has the final remarks of the thesis. Also, it includes recommendations for future works.

CHAPTER 2

EARLY USE OF MECHANISMS IN ART AND ARCHITECTURE

2.1. The Historical Basis of Motion Studies

Theoretical and technical studies on movement provide the basis for mechanism design. Motion is a field that was studied long before the formation of kinematics science that is based on the motion studies of the bodies without regard to the forces affecting them. Through history, numerous engineers, artists and architects have wondered, observed and conducted research on the motion of living things, water, air, terrestrial and celestial bodies, as well as gravity and magnetism. The operation principles of machines were also examined. The architect Marcus Vitruvius Pollio (70-80 B.C.-15 B.C.) suggested machinery design to be derived from the firmament and nature, also stated the elements of motion as circular and rectilinear in hoisting machines (Pollio, 2006). The examinations and studies led to the construction of recreational or useful tools and machinery. It is not possible to specify every contributor in this field but the work of Aristotle, Archimedes, Galileo and Newton in philosophy, physics and mathematics, Vitruvius in architecture and Leonardo da Vinci in art and engineering, contributed remarkably to the mechanism science of today.

Even in times when preliminary development stage of scientific knowledge and practice, various methods were used in the research of the nature of motion. Aristotle (348-322 B.C.) defined the scientific method based on observations, measurements and experiments and used it to make effective contributions to the theorization of movement (Laermann, 2011). Aristotle wrote numerous books on the following subjects and more: Physics, philosophy, metaphysics, politics, ethics, etc. In his book *Physica* (Physics), he examined motion in terms of types, the differences between motion and change, and understanding motion with respect to time and space (Aristotle & Barnes, 1992). Aristotle's ideas and theories about motion dominated the developments in this field during the Middle Ages (Buyse, 2019). Some of his ideas and theories, such as that heavier objects would free-fall faster than lighter objects, were corrected centuries later. Galileo and Newton conducted experiments revealing that the free fall velocity did not depend on the object's mass, thus different objects free falling from the same height fall at the same time when air resistance is neglected. Aristotle’s work on in biology shows his perspective about animals to be self-movers that can move on their own; without the help of external sources, by means of their characteristic of having souls (Corcilius & Gregoric, 2013).

The architect Villard de Honnecourt (13^{th} century) was familiar with the Aristotelian science. De Honnecourt's *Perpetuum Mobile* (a self-turning wheel) was not theoretically, but practically an Aristotelian device in terms of focusing on the changing, thus self-regulating characteristics of the bodies (Bugslag, 2001). The device produced infinite continuous pendulum motion that is triggered by a single input motion (Figure 2.1).

Another scientist who studied motion and made his mark on the field is the famous mathematician, physicist, astronomer, inventor and engineer, Archimedes of Syracuse (287-212 B.C.). Besides theoretical analyses and formulations, experimental activity is also remarkable in his machinery design. His geometrical work such as the

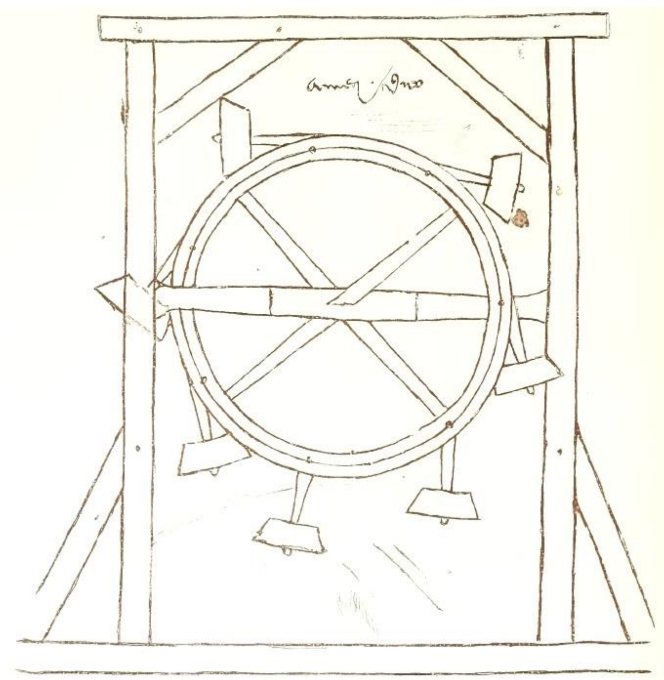


Figure 2.1. *The Perpetuum Mobile* machine drawing by architect Villard de Honnecourt
(Source: Honnecourt, Lassus, & Darcel, 2016)

measurement of a circle in which he calculated the value of the number *pi* and his calculations of area spheres, cylinders, cones, paraboloids, and geometrical figures, all contributed to the development of mathematics. He has been famous with his line “Give me a place to stand, and I will move the earth” in which he referred to the law of lever (Ceccarelli, 2010, p.117). Archimedes conducted remarkable research on the field of balance and equilibrium. He contributed to the theorization of lever, screw (see Figure 2.2) and pulley; and the development of ingenious machinery. Besides developing the fields of statics and hydrostatics, several research on the fields of law of buoyancy and equilibrium of fluids were also conducted by him. As an astronomer, Archimedes' very accurate self-moving model of the solar system in which accelerated eclipses is also quite important. In this model, screws and pulleys that moved globes through several orbits with several timelines were used (Chondros, 2007).

The work of Archimedes also affected the fields of art. In his book *Pneumatic,* Hero of Alexandria (10-70 A.D.) referred to the *floating bodies* of Archimedes. Hero started his book by giving technical information on air, water and fire. He claimed that everything was covered with air, consequently had voids between the air particles, such as in between each grain of sand on the beach. Thus, he suggested that air could be compressed and would be back in the first shape when the pressure was removed (Hero & Hall, 1971). His theoretical studies on compressed air, wind, heated air, water and

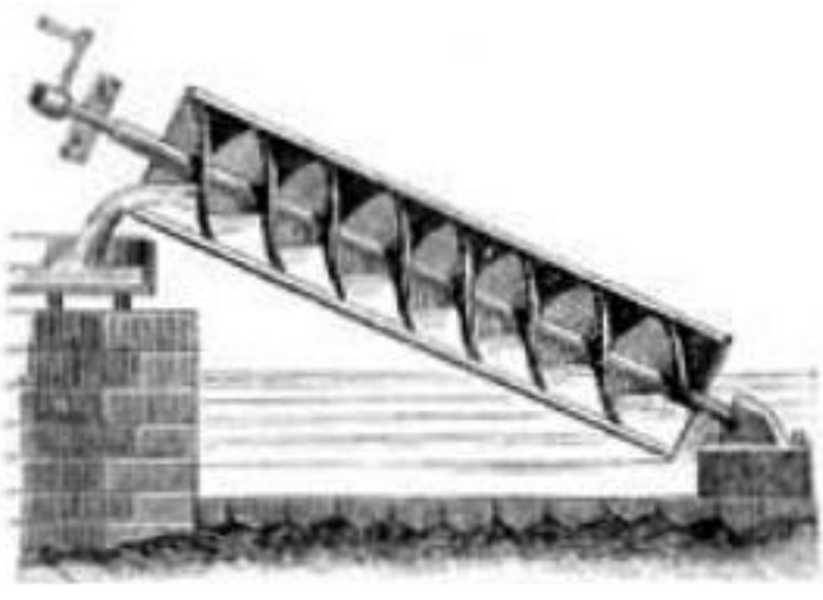


Figure 2.2. The water-rising machine that is called with the *Archimedes screw*
(Source: Lazos, 1995; cited in Chondros, 2007)

fire provided basis for his practical designs. He designed several systems such as automata, vessels, oil lamps, musical instruments, door opening systems and water clocks. Even though he mentioned only the presence of small voids, some of Hero's designs are work based on the principle of void. Hero's work show that the technology of the era was far beyond the related theoretical knowledge. This is probably the result of working not only with theoretical information but also in experimental procedures.

The invention of various tools that facilitate human life and production of recreational forms were enabled by the designation of movement. While motion was sometimes characterized by needs, some designs were inspired by motion itself. Long before the theorization of several ideas, humans started to observe movements of different kinds and made tools, toys, sculptures, objects, art and structures using them. A Greek architect, for example, sculptured a statue floating on the air that was connected with the magnetic force applied onto the roof and walls in the 3rd century B.C. when magnetic force was even not theorized yet (Chen et al., 2015).

The formation of hydrodynamics, which is the combination of dynamics with hydrostatics gained basis with the applied experimental work of Al-Biruni (973-1048) and Al-Khazini (12th century) in which they studied dynamics and statics to use in the field of mechanics (Laermann, 2011).

Leonardo da Vinci (1452–1519) was one of those who contributed to the research of movement of living bodies and machinery production. Da Vinci has numerous works of art, perspective drawing, sculptures, hydraulics, construction machines, anatomy, optics, astronomy and flight. Da Vinci's approach to movement was based on several parameters such as weight, force, movements of water and air, perpetual motions and movements of machines (Leonardo & McCurdy, 1955). Several drawings and notes of him revealed how much he valued and investigated movement in detail. As shown in Figure 2.3, da Vinci's study of the human shoulder region clearly shows the change among the body shape and muscle tissue during movement.

The movement of celestial bodies has always been a point of interest for human beings. It was investigated by a number of artists, architects and engineers. One important astronomer who studied motion both theoretically and practically was Nicolaus Copernicus (1473-1543) who revolutionized the law of motion with his suggestion about the Earth moving around the Sun (Boorstin, 1994). This was the first time that the solar system was formulated in a Sun-centered model. Copernicus' revolution was supported by his very rational and theoretical arguments showing

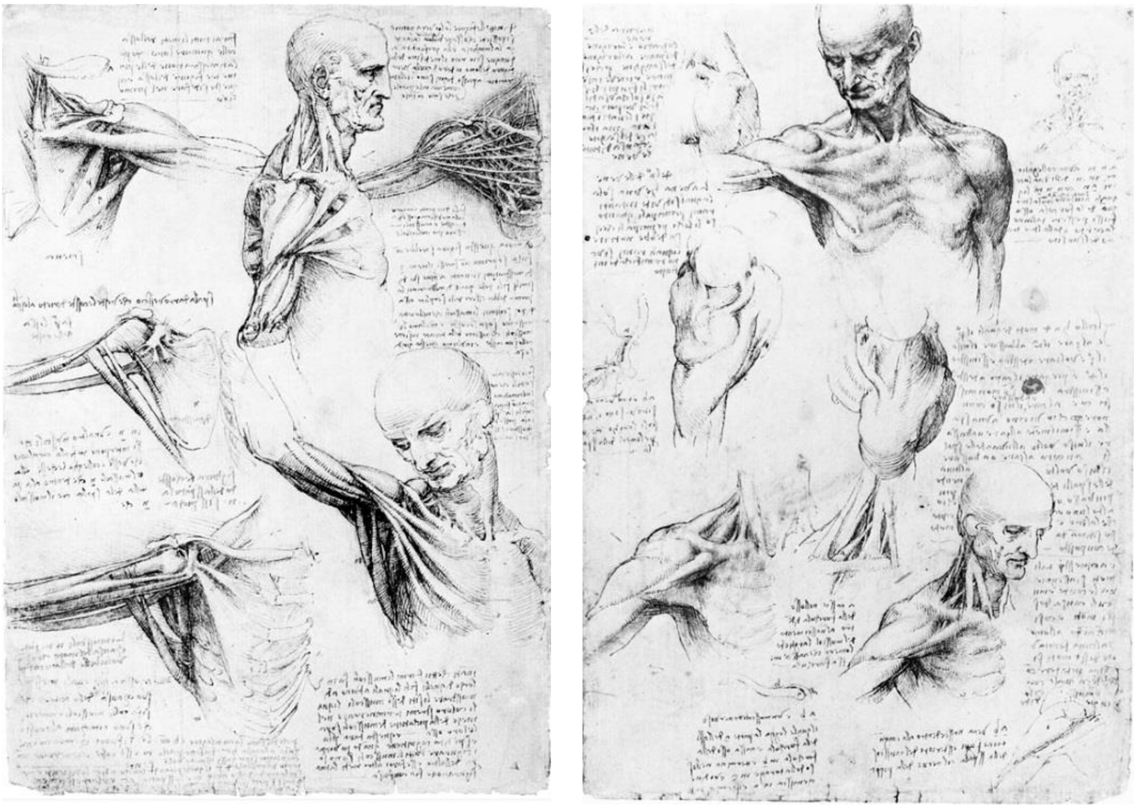


Figure 2.3. Anatomical drawings of human shoulders in several positions
by Leonardo da Vinci
(Source: Vinci, 2012)

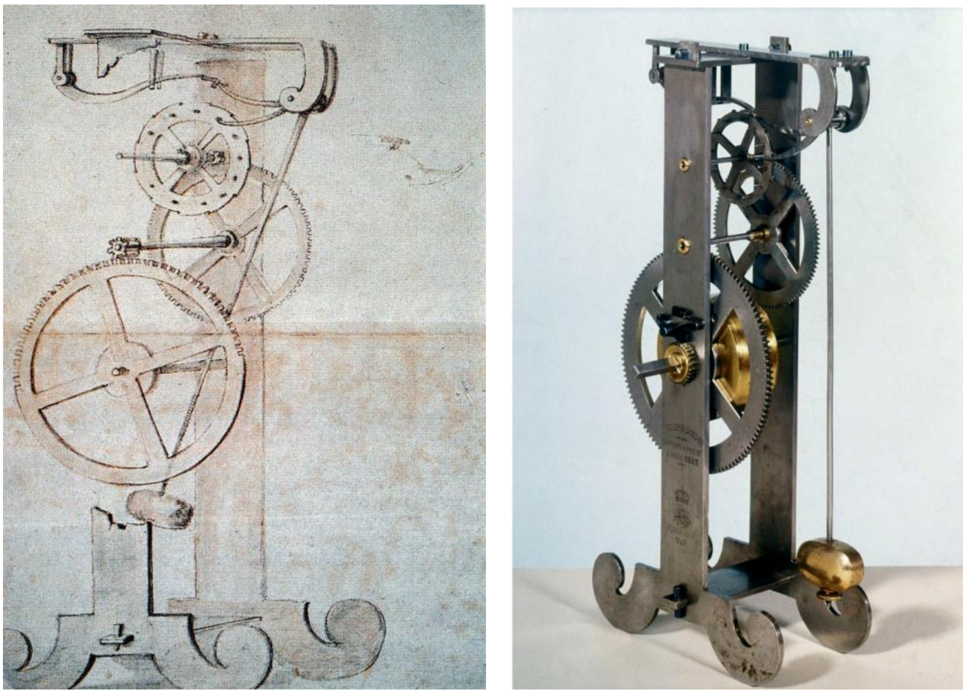
weaknesses of the well accepted geocentric definition of the universe. He was the first one who explained the three motions of Earth. The first one was Earth's rotation which resulted in the presence of day and night, the second one was Earth's ecliptic movement around the Sun which generated the seasons, and the third one was the change in the inclination of Earth's rotation axis in detail (Zielinska, 2007).

Francis Bacon (1561-1626) was the first philosopher who developed an experimental research method that consisted of observation, experimentation and data collection for a clearly defined research question's examination (Laermann, 2011).

Another revolutionist in the field of motion was Galileo Galilei (1564-1642). Galileo studied the mechanics and motion of objects such as falling bodies, lifting weights, equilibrium, floating bodies concerning with the related to forces, velocities and displacements. The first examples of kinematic diagrams are drawn and formulations are used by him to study and analyze various mechanisms such as levers, pulleys, screws and capstans (Ceccarelli, 2006). Galileo's contribution to experimental research in the field of natural sciences is clearly seen in his high attention to detail and hard work on the subject of measurement, he made vigorous efforts to make the unmeasurable measurable (Laermann, 2011). Galileo revealed numerous works on motion such as the concept of a *projection of a projectile* which represents the simultaneous occurrence of two independent motions -one vertical and one horizontal- generating a parabolic curve. Another concept is the *relativity of motion* which points to the perception of motion with respect to a *frame of reference,* thus resulting in the perception of an object to be in motion with respect to a certain reference point while to be in rest with respect to another. The third remarkable work of him was about the parameters that affected the oscillating motion of a pendulum clock (see Figure 2.4). Galileo could not terminate his design of the pendulum clock, but it was Christiaan Huygens (1629–1695) who discovered the pendulum clock synchronization in motion. Galileo's telescopic observations supported the ideas of Copernicus on the Sun centering model, however Johannes Kepler (1571–1630) corrected the misinformation of Galileo who claimed the orbits of planets to be circular rather than elliptical (Buyse, 2019).

René Descartes (1596-1650), a famous philosopher, with his modeling of human bodily functioning *animaux machine* (animals machine) suggested that bones, muscles, nerves, arteries and veins were just as automatic machines working on their own (Tez, 2008). As a result of this perception, the concept of motion was applied in the same mathematical terms to the animated and non-animated (Buyse, 2019). Giovanni Alfonso Borelli (1608-1679), who is accepted as the father of biomechanics, examined the movements of living bodies with the inspiration he got from the Galilean physics (Buyse, 2019). Borelli analyzed the motions of living bodies including actions such as skating, running, swimming, etc. and their physiology including blood circulation, breathing, etc. in his book*, De Motu Animalium, 1681 (On the Movement of Animals)* (Borelli, 1989). The links and joints demonstrated in the legs are shown in Figure 2.5. Along with this, the French medical doctor and philosopher Julien Offray de La Mettrie (1709-1751), who regarded human beings as living examples of continuous movement, in his book *L'homme Machine (Man a Machine)* defined humans as independent self-existent mechanisms. Just as the feet working with muscles, the mind was thinking through muscles (Tez, 2008).

The primary contribution of the scientific revolutionist, astronomer and mathematician Isaac Newton (1642-1727), who developed the law of motion consequently revealed the mathematical principles among mechanics and natural



(a) (b)

Figure 2.4. *Pendulum Clock* design by Galileo Galilei
(a) Galileo's design in 1642, finished and drawn from his design by his son Vincenzo Galilei in 1649 (b) Modeled by Eustachio Porcellotti, Florence, Italy, 1883
(Source: Science Museum Group Collection, 2019)

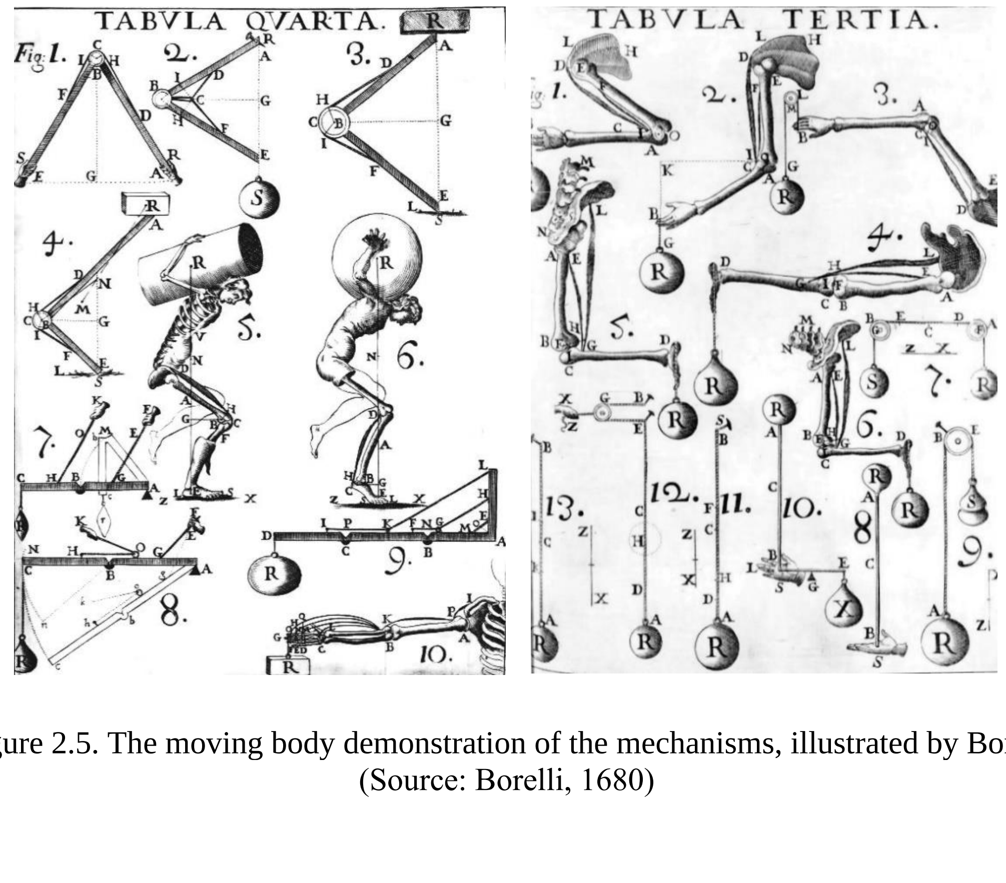


Figure 2.5. The moving body demonstration of the mechanisms, illustrated by Borelli
(Source: Borelli, 1680)

philosophies. Newton stated that the ancient people perceived mechanics as double layered structures: rational and practical. The practical part is stated to be the one related with manual arts that gave name to the present definition of *mechanics* whereas the rational part created the accurate knowledge for that practice. The fact that artisans do not work in perfect accuracy, resulted in the accurate work to be labeled as geometrical and the inaccurate work as mechanical. Contrary to the ancient categorization, he refused to call the products with perfect accuracy as geometric and less accurate ones as mechanic because he argued that problems had mechanical solutions and geometry was not the solution itself, but a tool to be used in the mechanical process. He considered his work as the mathematical aspect of philosophy in which he examined the effect of natural forces such as gravity, levity, elastic force, the resistance of fluids, etc. on motions (Newton, 1846).

Newton's laws of motion are still in use for everyday problems. His well-known three laws of motion for the bodies are summarized in the following. The first law states that a body will keep its status, either moving or resting, unless it is interfered by an external force. The second law states that the force acting on a point mass is equal to the rate of change of momentum of the mass. The third law states that every action creates its equal and opposite reaction. Another remarkable contribution of him is his work on gravity. Development of engineering and invention of various tools enabled the construction of numerous structures standing against gravity. Water-wells, lifting cranes and many attempts to fly are resulted by the struggle against gravitation. The concept of force is known since Aristotle's definition of falling bodies, but it was Newton who analyzed and formulized this force by explaining the underlying reason of bodies falling down. The gravitional force depends on the mass of the bodies and distances between them. Newton claimed that this law of gravity force, resulting with the elliptical movements of the planets, could be applied to everything in the universe (Hawking, 1991).

One of the keystones of the utilization of power was revealed by James Watt (1736-1819) who is a scientist, producer and inventor. He conducted scientific research on the field of thermodynamics and invented several parts of the steam engine. His famous double-acting steam engine's (see Figure 2.6) working principle is based on the straight-line mechanism that produces parallel motion which is also discovered by him (Pennock, 2007). These inventions are some of the fundamentals of the Industrial

Revolution (1760-1840) that is one of the milestones for technology and society in history.

Numerous research are conducted on the evaluation and calculation of movement. The balanced transmission of the force from one point to another is found no less useful for human beings than the ability to stand in balance under the presence of multiple forces. Even centuries ago, motion was studied with the idea of imitating movable bodies in the products and generating qualified machinery with the help of the mathematical research of the field. For the current study, to mention every scientist that studied the science of motion is not possible, nor necessary. Not only are each one of these scientists and their vastly important discoveries in studying and theorizing the field of movement, but several revolutionary technical knowledge and inventions are also conveyed in the research.

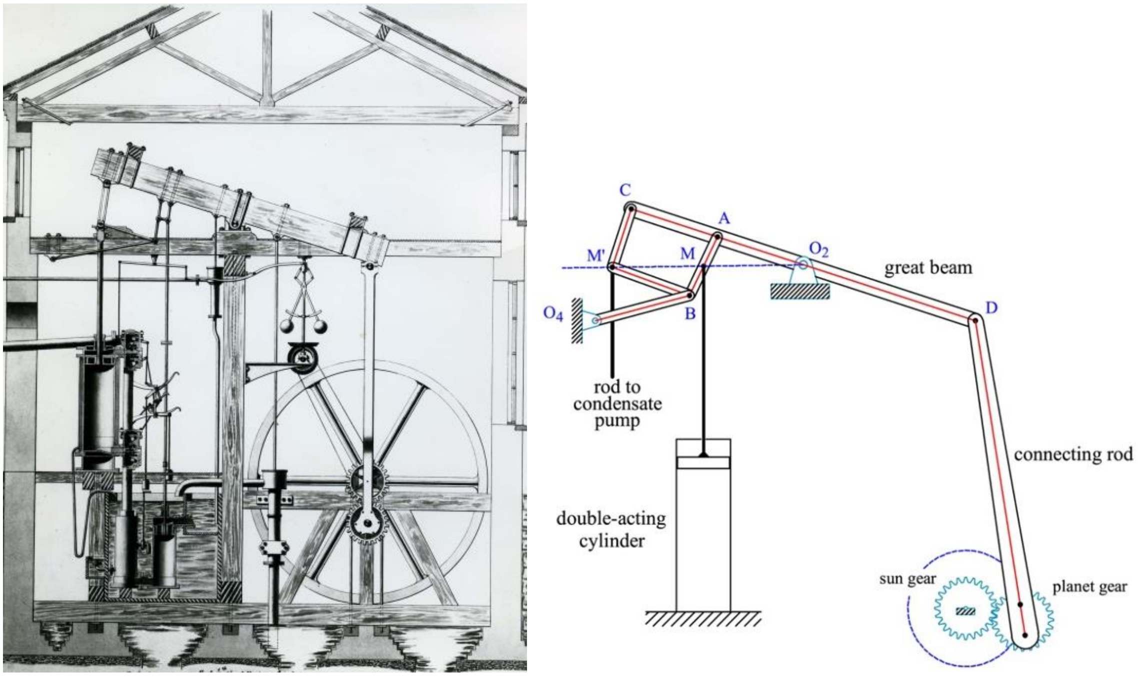


Figure 2.6. Watt’s steam engine
(a) The double-acting steam engine, original drawing (1788)
in the Science Museum, London
(Source: Encyclopædia Britannica, 2020)
(b) Diagram of the parallel motion linkage
(Source: Pennock, 2007)

2.2. First Examples

The experimental and theoretical studies of motion and movable designs have an important role in the fields of architecture, art, and engineering. The improvement of mechanisms changed lives, cities, architecture, artistic expressions, and building techniques as well as allowed people to better understand the universe. Early mechanisms could be produced for recreational purposes or they could be developed for a certain goal.

Starting from the nomadic lifestyle, then transitioning to settle life which then proceeded into city life; mechanisms and movable techniques of architecture were improved. The portable, demountable, adaptable, and transportable solutions for dwellings; the tents, tipis, yurts, and caravans were used and improved by nomadic people. These were not designed by architects but by the nomads themselves. These were highly functional, portable dwellings that were adaptable to climatic changes.

In his extant, *Ten Books on Architecture,* Roman architect and engineer Marcus Vitruvius Pollio explained the use of machines during the construction of a building in detail. These books are accepted as the first literary works on architectural theory. From his point of view, an architect needed to have a wide range of theoretical and practical knowledge on various fields such as drawing, geometry, mathematics, history, mechanics, music, optics, and astronomy. As written in the source, the term of architect had different meaning in terms of job description than today's definition. In that period, architects were mentioned as specialists who worked in several fields such as the aqueducts, water wheels, water clocks, sundials, siege machines, and construction machines (Pollio, 2006). This understanding remained during the Middle Age and Renaissance period as well. This is the reason why architects of that age were seen as developers and masters of several mechanical and technological fields.

Automata were the first mechanical designs with complex systems. Numerous creative designs of self-operating machines and automata displayed their mechanisms concerning the principles like air pressure, the buoyancy of the water, gravity, equilibrium of weights, pneumatics and hydraulics. The design process was based on the passion for constructing imitations of the terrestrial and celestial bodies. Those were significant tools for the development of the machine theory and knowledge, and also provided basis for the development of various mechanisms that work with muscle power and natural powers such as water and wind force.

The improvement of devices such as clocks and waterwheels shaped architectural aspects such as towers and aqueducts that took their place in shaping the cities. Architects, artists and engineers produced movable devices and various products, as well as buildings or building components like automata, fountains, waterwheels, clocks, and construction machines. Rotatable windmill structures, bridges, movable roofs and doors were also designed. The improvement in the field of techniques of machines encouraged architects to build forms and heights that were never used before.

The concept of movement in design fields is improved since early ages. Practical and theoretical studies conducted in the field of mechanisms directly affected the Industrial Revolution which quickly resulted in paramount understanding of machinery design, production, economy, technology, lifestyle, art, and architecture.

2.2.1. Portable Dwellings of Nomads and Retractable Architecture

Tipis, tents, yurts, etc. are the dwellings that are accepted as the first examples of demountable and portable types of architecture. The nomadic lifestyle goes back to the very first appearance of humanity. The mobile life brought mobile and adaptable architecture together. This resulted in the development of homes that were able to be easily and quickly packed up, sometimes portable, lightweight and climatically durable with designs and methods that had accessible and protective materials. Today, the nomadic lifestyle and numerous people who have been living in tents and campervans, led to the appearance of various portable and transportable architectural designs. Starting from the early ages, or even before, steppe and desert nomads developed many different living spaces such as tents, tipis, yurts, or huts. These dwellings were not built by experts or architects, but nomads who needed protection against the environmental elements. Some of the activities done in these tents are housework, cooking, eating, sleeping, daily activities and rituals. Depending on the culture, life-style, geography, weather, the century they belong and the user type they are developed and used by; dwellings may involve different kinds of geometrical plans including rectangular, polygonal, circular, or ovate. Various natural materials were used as covering in different colors with different setup techniques and transportation systems for these dwelling structures.

Nomadism is stated to be the opposing force to a settled state in terms of being out of the control of the social system that is being imposed to the people. This is evaluated to be the reason why states have reached to settle the nomads down and made controllable farmers out of them with the help of changing socioeconomic conditions (Kavas, 2013). Some of the numerous types of dwellings are developed as individual solutions offered by nomads. The three main types of these dwellings are the North American and Indian's tipi, North Africa's and desert nomad's tent, and Asia's yurt. Some of the examples are semi-portable with structure frames that are left at the site and coverings that are carried with animals. Other examples that are not so widespread but interesting for their portable and lightweight characters are the hut of the equatorial Africa and the boat houses of the Far East (R. Kronenburg, 1995).

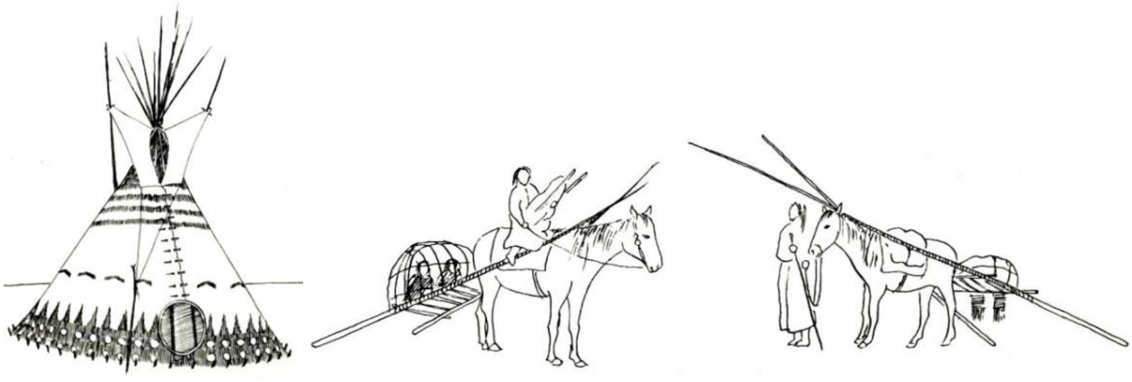
North American and Indian *tipi* has a conical structure that provides resistance against wind and can be quick set up. The Plains Indians strongly believed in the power the circle, thus designed their dwellings in circular shapes. The small covering sheets of the tipis were carried by dogs and the big ones were carried mostly by horses. Each tribe had their own adaptation of tipi design. Figure 2.7.(a) shows a Piegan tipi which is used by the horse-riding culture that colored the coverings. The tipi can be carried in travois or by horseback, the poles can be used to prevent children from falling down or to carry large covers when travelling (Faegre, 1979).

Tents that have a long history about being used by the nomadic desert and semi-desert inhabitants are used in various forms by numerous cultures, yet these were not the first types of dwelling. It was not an easy challenge for humans to make a fully portable dwelling. Generally planned as squares, tents were built in varying forms and structures. They could have square or dome-shaped roof structures with box or arched frames that are strengthened with fasteners and ties. The loomed coverings were made of camel, goat or sheep wool. They could be split into compartments such as a kitchen and a sleeping area. Figure 2.7.(b) shows a Shammar tent which is carried by 2 camels, one carrying the fold and the rolled cover and the second one carrying the poles (Faegre, 1979). Even today, these portable dwellings are used and improved as in the design of Atarer et al. which is a reconfigurable structure to be used as a shelter in post-disaster situations, for public needs or military purposes (2013).

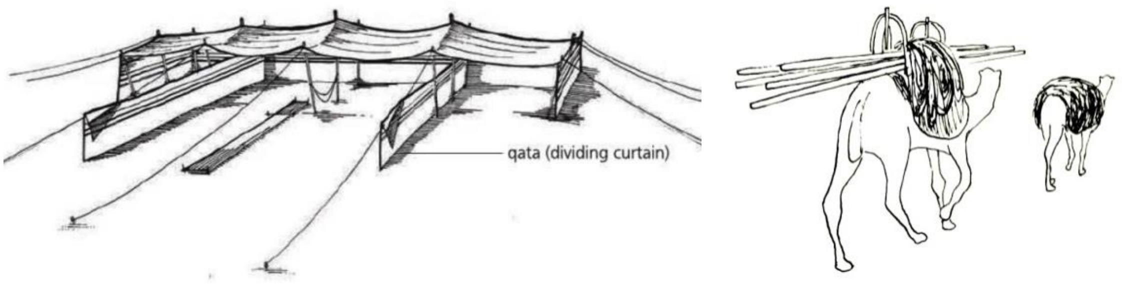
The *yurt* is a circularly planned, lightweight and transportable dwelling. A Mongolian yurt is called a *ger*. The circular structure and dome roof provide stiffness. The foldable and expandable structure provides ease during set up and transportation. The structure's most challenging part is the crown at the top that is made of bending woods (Faegre, 1979). The round roof window that is called the heavenly eye is also used as a chimney. The central pole of yurt symbolizes the axis of Cosmos (Kavas, 2013). It has a lightweight structure that is covered with several layers of felt that provide isolation from cold, wind and rain in winter. Figure 2.7.(c) shows the structure of an Uzbek yurt without covering and examples of transportation: a Kırgız yurt carried by a yak and a Turkmen yurt moved by an ox and wagon (Faegre, 1979).

The nomadic Turkish communities are observed to have a high-mobility culture that is in line with nature, based on climatic cycles. An analysis of the Middle Eastern yurt, especially in the Iranian region, in terms of flexibility and tolerance, durability and maintenance, adaptation to the climate and rigidity, and airflow resistance is conducted by Amirmakhani et al. (2010). The adaptation of the yurt to climatic changes with rigidity and airflow resistance is shown in Figure 2.8. It is a self-supporting structure standing on the frame; no rope is used to hold it still. The roof which is circularly planned in a conical or dome shape has a heavy crown at the top, which both uniforms the distribution of forces and provides rigidity for the structure. The aerodynamic shape of the yurt helps the wind to slip away through the roof with minimal resistance. The shape is also thermally efficient; the felts are raised from the ground for natural ventilation and to let the warm air go up through the roof that results in a cool environment in the summer. These opposing forces are also used for rigidity by balancing the inward and outward pressures. The covering material made of felt is advantageous in terms of providing good insulation from the sun in the summer. The door and the opposite cover are opened in the hottest period and closed again in winter. The yurts face the Sought, thus the sun that enters from the roof opening, provides a circular light that is used as a sundial inside. This sundial is quite useful for the arrangement of the daily routine, for example to determine times for meal preparation. The smoke going through the roof opening in the evening makes the covering more waterproof (Amirkhani, Leylian, Seddigh, Eskandari, & Ablodmaleki, 2010).

Approximately a thousand years after the invention of the wheel, around 3.000 B.C. in Mesopotamia, the chariot was invented by the Sintashta people who used horses to bring the ore down from the Ural Mountains (Jarzombek, 2013). These first wheeled



(a)



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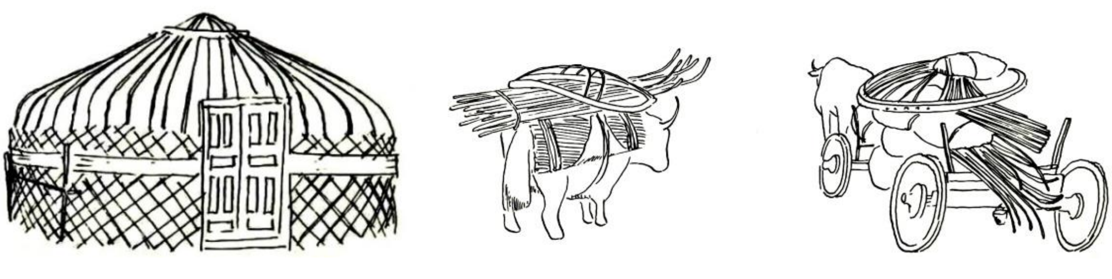


(c)

Figure 2.7. Examples of the nomadic dwellings and their transportation
(a) A tipi of Piegan and travelling with a tipi carried by a horse
(b) A tent of Shammar and travelling with a tent carried by two camels
(c) A yurt of Uzbek, travelling with a Kırgız yurt carried by yak and a Turkmen yurt carried by a wagon and an ox
(Source: Faegre, 1979)

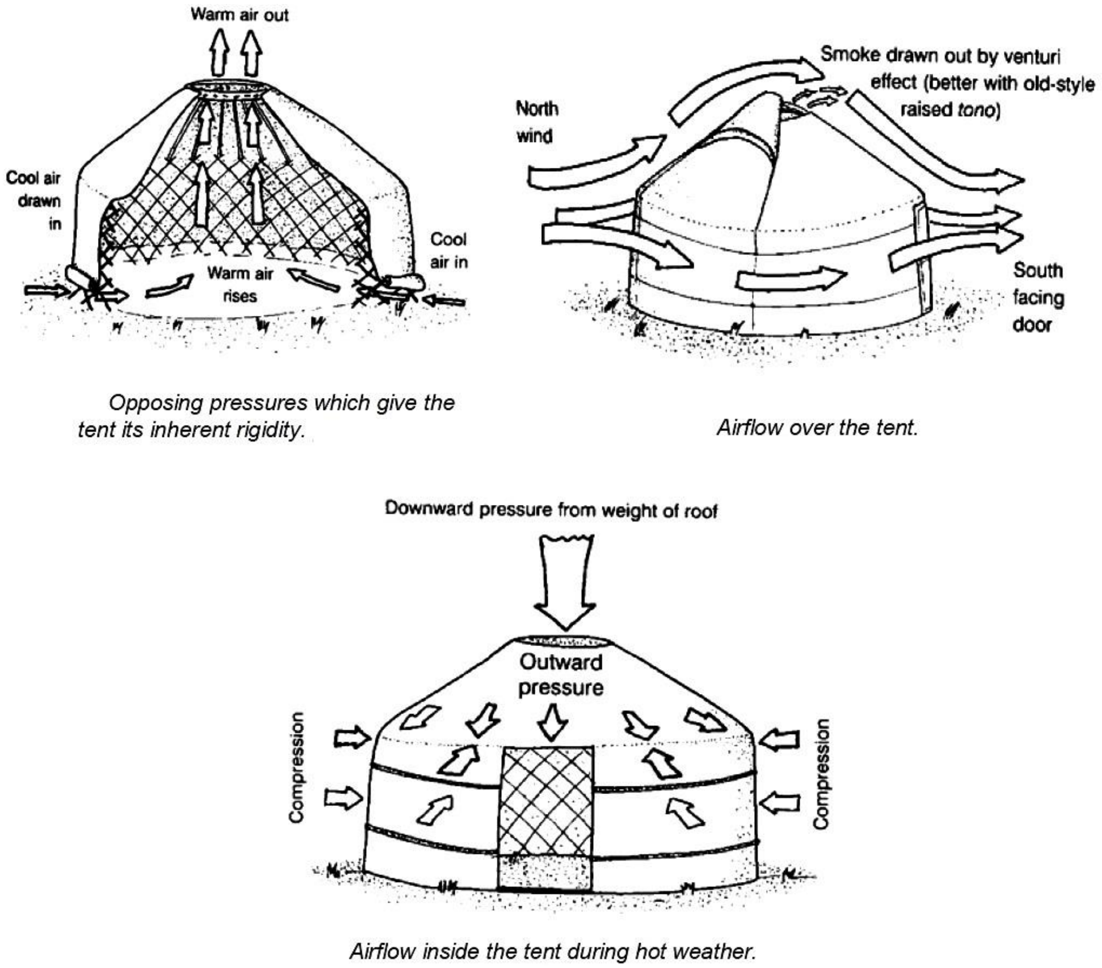


Figure 2.8. The airflow analysis of the Turmen nomadic yurt
(Source: Amirkhani et al., 2010)

wagons were not homes but used as shelters for resting purposes. The sleeping carriages for travelling were made in the 8th century whereas the real caravans were developed in the next century (R. Kronenburg, 1995). Carpine defined the Mongolian mobile homes after his visit in the 13th century. The owners went everywhere with their homes. Some dwellings could be easily dismantled and picked up, whereas some types could not be taken apart but transported on carts. The Tartar huts could be either large or small, depending on the economic status of their owners. They were transported by one or more oxen, depending on their size (Jarzombek, 2013).

Bergeron (1735) drew an elaborative imaginary illustration of William Rubruck’s description of Tartar tent-carts drawn by twenty-two oxen, based on the engraving from the 8th century (Gervers & Schlepp, 1997). Various other types of dwelling-carts such as the four-wheeled square carts driven by oxen and the two-wheeled square carts driven by camels can be seen in the background of Figure 2.9.

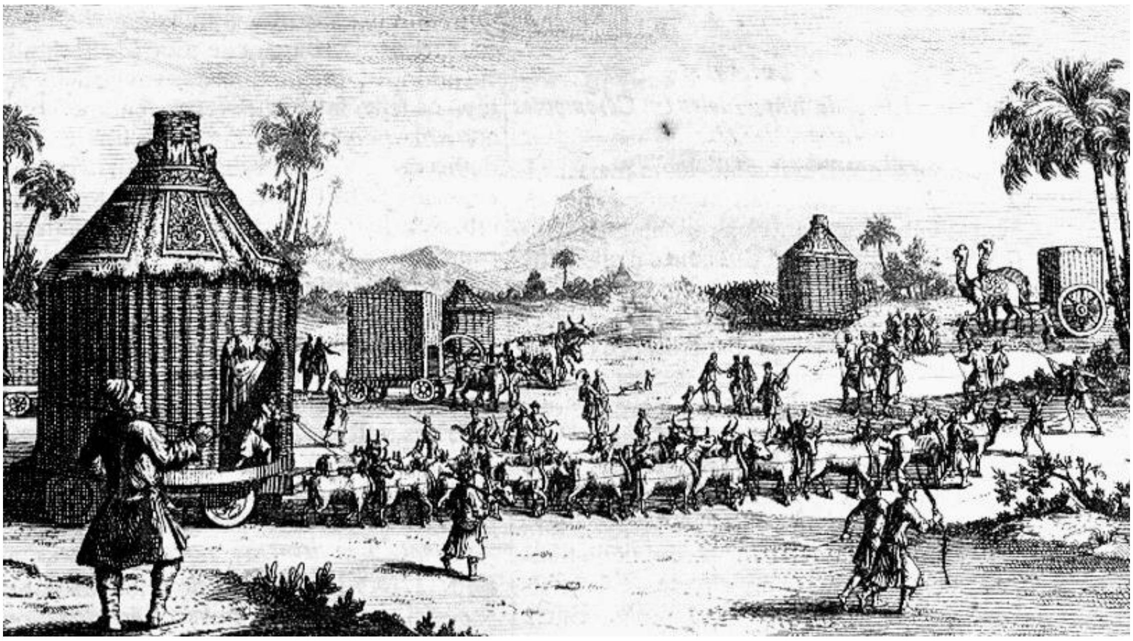


Figure 2.9. Two and four-wheeled dwelling-carts of Tartar
(Source : Bergeron, 1735)

The retractable character of the coverings is applied to the roof of the Roman Colosseum (see Figure 2.10) in the first century with a mechanical system that includes pulleys and removable ropes. The canvas sheets of the roof protected the audience from the strong sunlight. It was the first well-known, large-scale (620 feet by 513 feet), movable ovate roof that was erected and dismantled manually by sailors (Zuk & Clark, 1970). Some other retractable curtains and roofs used, for example, are seen in theaters; however they are not as large as the one in the Colosseum.

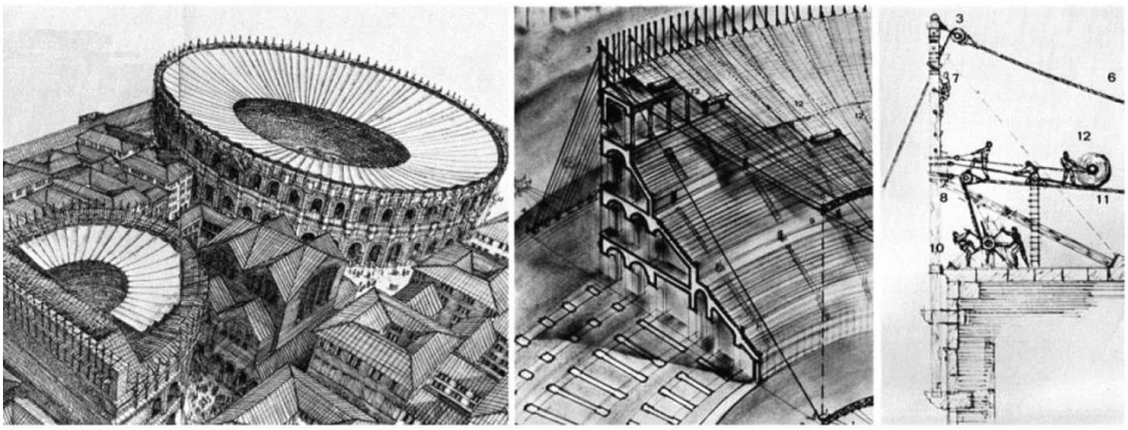


Figure 2.10. The retractable roof of the Roman Colosseum with details
(Source: Graefe, 1979; cited in Masubuchi, 2013)

2.2.2. Automata and Musical Instruments

Numerous mechanical figures such as acrobats, dolls, birds, ducks, swans, elephants, dragons and many other creatures are generated by imitating living bodies using natural materials such as wood, gold, silver and bronze. Mechanical theaters that tell a story, fountains that adorn the squares, clocks that show cosmos with their time-telling systems, robotic servants, magical entertainments etc. are produced by designers. Automata and mechanical toys are underlined to be based on the observed natural laws which point to the very basic human need of understanding the nature of the world.

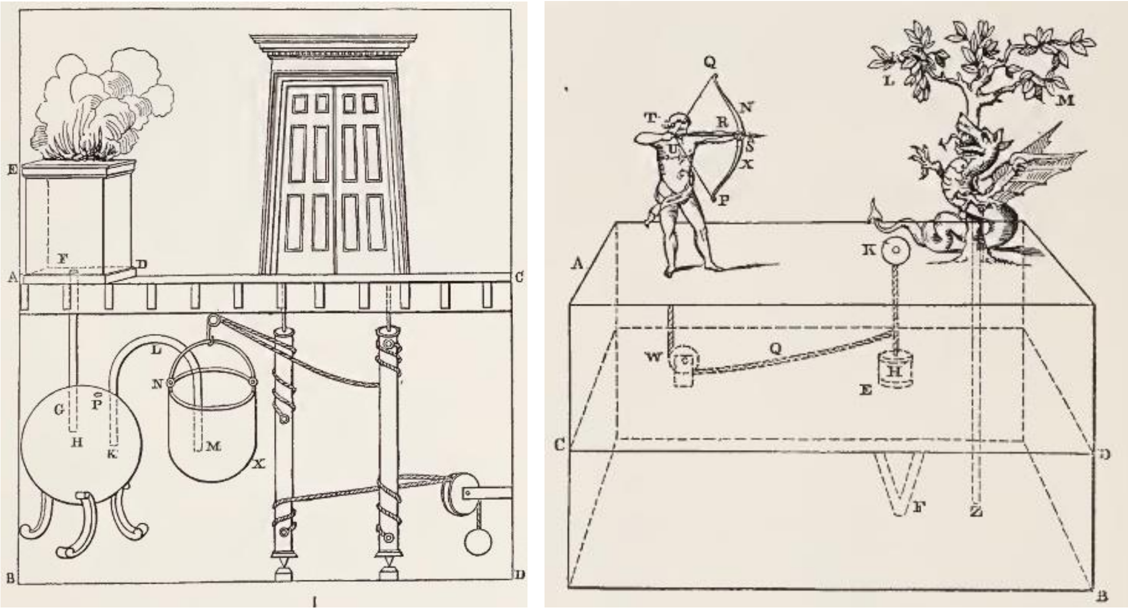
The words *automata and automaton* are originated from the early 17th century Latin word *automatos,* meaning “acting of itself’’ and represent “a moving mechanical in the shape of a person” or “a small robot that can perform a particular range of functions” (Oxford Advanced Learner’s Dictionary, 2020a). Automata from the early ages that are designed with the ability to imitate the movable bodies and work with various mechanical, hydraulic and pneumatic principles, were the first simple machines known. The first automata were activated by the effect of the heated or compressed air; the equilibrium and weight principles, and even the fluidity of water were used in the beginning. Those revealed very complex mechanisms but unlike today, not electrical or motor forces were used. Since each piece was hand made one by one using natural material, they all ended up to be unique design products. These mechanisms that were developed as a result of the analysis of movements of living and non-living beings provided the basis for the development of many complex mechanisms.

The first signs of the idea of automation were dolls that had moving arms and legs found in the ancient Egyptian tombs. Egypt remains to be the outstanding host of the subject with its talking statues that were developed with a mechanism which concealed the trumpets down through their mouths (de Solla Price, 1964). Unique examples of technology had been observed through history. For example, a floating statue was built by a Greek architect for the wife of the Egyptian King Ptolemy II in the 3rd century B.C. An extinct technique, magnetic force application was used on the roof and wall for the statue to float in the air (Chen et al., 2015).

The construction of recreational mechanical devices resulted in gentle spark of art. The engineers of Alexandria such as Ctesibius (285-222 B.C.), Philon of Byzantium (280-220 B.C.), and Hero of Alexandria (10-70 A.D.) revealed mechanical work and automata that had great effect on the Middle Age, Renaissance and the

Baroque period. Hero of Alexandria is known to be the inventor of the first steam turbine and the one who provided basis for the vending machines that are used today (Papadopoulos, 2007). Besides his inventions, Hero had great impact with his written work, *The Mechanics,* in which he explained the principles of motion, statics and balance as well as the basic methods of weight lifting; including the use of the windlass, the lever, the pulley, the wedge, and the screw (Papadopoulos, 2007). Another work of Hero, *Pneumatica*, consists of some controversial information about one hundred mechanical machines. Hero's automata and mechanisms are used and function based on the principles of gravity, water, air and fire. A well-known design of his, a temple door that opens when the altar fire is on, is shown in Figure 2.11.(a). The heated air in the altar expands and passes through the tube and drives out the liquid in the globe. The water passes to the next vessel with the help of a siphon. The vessel goes down with the weight of the water and pulls the strings that are tied up to the cylinders that open the temple door with their rotating motion. The door is closed by the counter-effect of the extinguishing fire (Hero and Hall, 1971). Hero also designed numerous automata for recreational reasons. For example, the automaton of Hercule that shoots a dragon with a bow when the apple that is in front of the dragon is raised by someone is shown in Figure 2.11.(b). The apple is attached to a chain and the other end of the rope is attached to the shooter's arm. The chain is also attached to a weight that covers an underlying hole. The air-tight pedestal is divided into two parts and the upper part is filled with water. The hole is open when the weight rises with the rise of the apple, thus water fills the underside of the pedestal. This system, with the help of the pipe in the underside of the pedestal, enables the dragon to generate the hissing sound (Hero and Hall, 1971).

Various vessels, as well as automata intrigued the interest of designers. El-Jazari revealed numerous recreational vessels that offered various types of beverages while several water flowing automata and fountains were also designed by him (Cezerī & Tekeli, 2002). Fountains designed with various mechanisms were remarkable design elements of their region. For example, the silver *Fountain Tree,* made by Guillaume Boucher at the Mongol court in the 12^{th} century had a mechanical system. The fountain that offered various liquors flowing from the mouths of the snakes simultaneously with the sound coming from the horn of the angle standing above, was considered as a masterpiece of the era (Tatár, 2011). Even though the fountain that was built by Boucher was demolished, it was described in detail in numerous sources such as in the illustration by Pierre Bergeron that is shown in Figure 2.12.



(a) (b)

Figure 2.11. Hero’s designs in his book, *Penumatica*
(a)The *Temple Doors opened by Fire on an Altar* (b) The automaton of the *On an Apple being Liftes, Hercules shoots a Dragon which then hisses*
(Source: Hero & Hall, 1971)

Figure 2.12. An illustration of *The Fountain Tree* of beverage
(Source: Bergeron, 1735)

Producing sounds with mechanisms that work with natural sources attracted the interest of numerous designers. Athanasius Kircher (1602–1680) theoretically analyzed the sound, acoustic designs, music, and instruments in his book, *Musurgia Universalis,* in 1650 (see Figure 2.13). Kircher also published numerous works on several disciplines such as mathematics, optics, magnetism, biology, Egyptology, geology, and medicine. He analyzed the sound and echoes with respect to the acoustic design for architectural applications. The drawings of Kircher's design, in which organ, pipes and automata that are powered with water are shown in Figure 2.13. The falling water turns a wheel that is connected to a cylinder such as the ones used in the music boxes today. This wheel simultaneously acts the organ and the automata (cuckoo and crow) at the top. The melody on the pipe organs is provided by the air that results by the falling water that generated an air pressure in wind-chests (Rose, 2004).

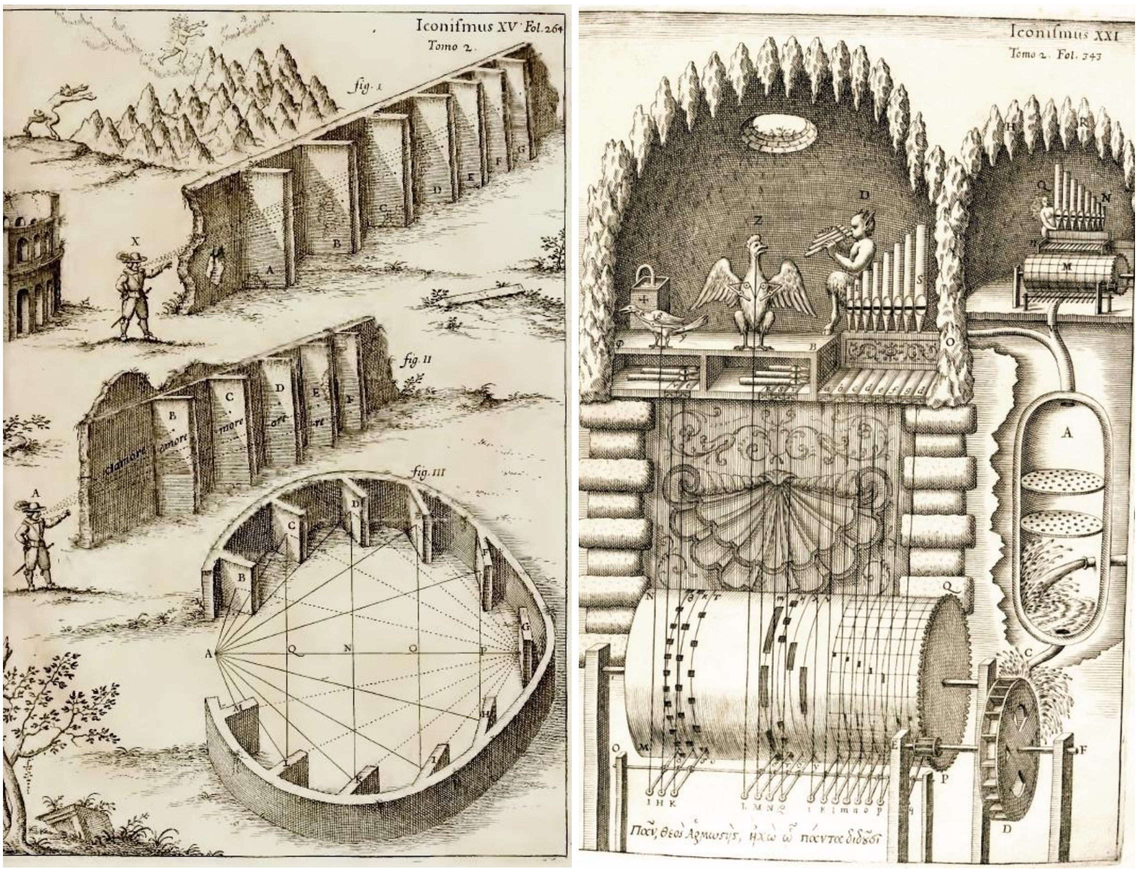


Figure 2.13. Examples of the drawings of acoustic works and a musical instrument by Athanasius Kircher
(Source: Kircher, 1650)

2.2.3. Water Rising Devices, Waterwheels and Windmills

Waterwheels have great economical and industrial impacts on the process of building a city, thus arouse the interest of numerous architects, artists and engineers. Not only these but waterwheels and windmills are revolutionary and have remarkable impact in terms of changing the need for slave labor into mechanical work (Tez, 2005). The very first machines are found to act by human or animal muscle power whereas in the medieval age, they are used with either animal force or the power of natural sources that are essential for that period such as wind or water. The first windmills are the early examples of movable architecture since their rotatable structures provide adaptation to environmental changes. Waterwheels and windmills are suggested to be one of the most important machines in terms of changing the world (Denny, 2007).

Water and wind powered mechanisms have great potential for product design. A wide range of devices like clocks, automata, and musical instruments that are connected to other mechanisms like gears and linkages are designed with power from water and wind. Natural power sources have an essential role in industrialization, just as the usage of waterwheel in textile factories where all mechanisms are activated by a single wheel. The present section, however, focuses on the wheels and water-lifting devices that provide water for the agricultural requirement of towns and cities. Water is raised by the waterwheels (mills) or other water-lifting devices including levers and gears, and is distributed through aqueducts. These masonry aqueducts that are designed by architects and engineers are also remarkable for city-scale designs. Gravity enables water transportation to the long distances. It is one of humanity's oldest needs that extend over the Bronze Age to design water cisterns, canals and wells to harvest water (Yannopoulos et al., 2015). A model of an aqueduct and a waterwheel is shown in Figure 2.14.

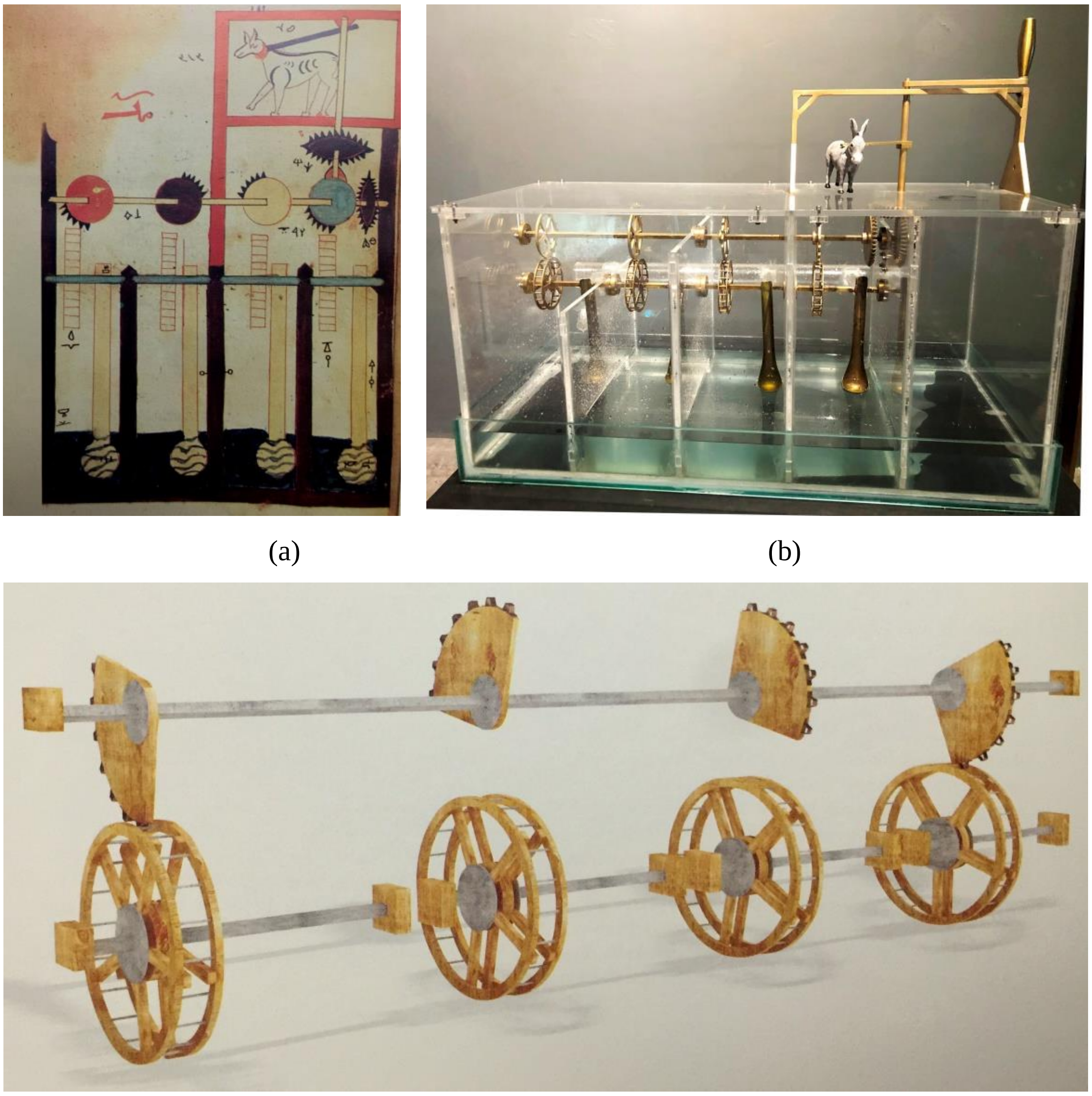
The history of water-lifting devices of which their working principle is based on the balance of the counterweight, goes back to 3000 B.C. Romans use Archimedean screws for water transportation. The Egyptian waterwheel (Noria) is also invented by them around the 1st century B.C. (Yannopoulos et al., 2015). The wooden wheels lift the water in the buckets to transfer the water mostly to pipes or aqueducts. The architect Vitruvius described these systems in detail in the Roman period.

El-Cezeri (A.D. 1136-1206), a well-known designer, engineer, and writer used natural sources like the fluid pressure, buoyancy or rate of flow to develop his

Figure 2.14. A model of a waterwheel and an aqueduct from the *Extraordinary Machines of el-Cezeri Exhibition,* 2019 in Turkey

hydrodynamic auto machines as well as numerous different clocks and automata. El-Cezeri defined the 6 types of water-lifting devices in his book, *El-Cami Beyne'l-İlm Ve'l-Amel En-Nafi Fi Eş-Şınaa Ti'l-Hiyel* in detail. An example of a device designed by him is shown in Figure 2.15. El-Cezeri here used gears to transform the horizontal motion actuated by an animal to vertical motion. The gear is then connected to a bar that carries 4 gears. The reforming part of this work is that gear teeth are partially applied in 90° of each gear (segmented gear). Each corresponding gear worked sequentially, meaning each gear that is connected to a ladle moved respectively. This enabled control of the sequence of motion just as in cams. The animal therefore always carried the weight of only a single ladle but moved 4 ladles up in one full turn (Cezerī & Tekeli, 2002).

A dramatic increase in the number of waterwheels is observed in the Middle Ages (Denny, 2007). Even though both the vertical and horizontal rotary wheels date back to very early ages, the conditions did not let them take an important place until the Western Christian population, in which slave labor had a place, embraced the waterwheels are used in several areas from ones like grinding, oil extraction, in



(a) (b)

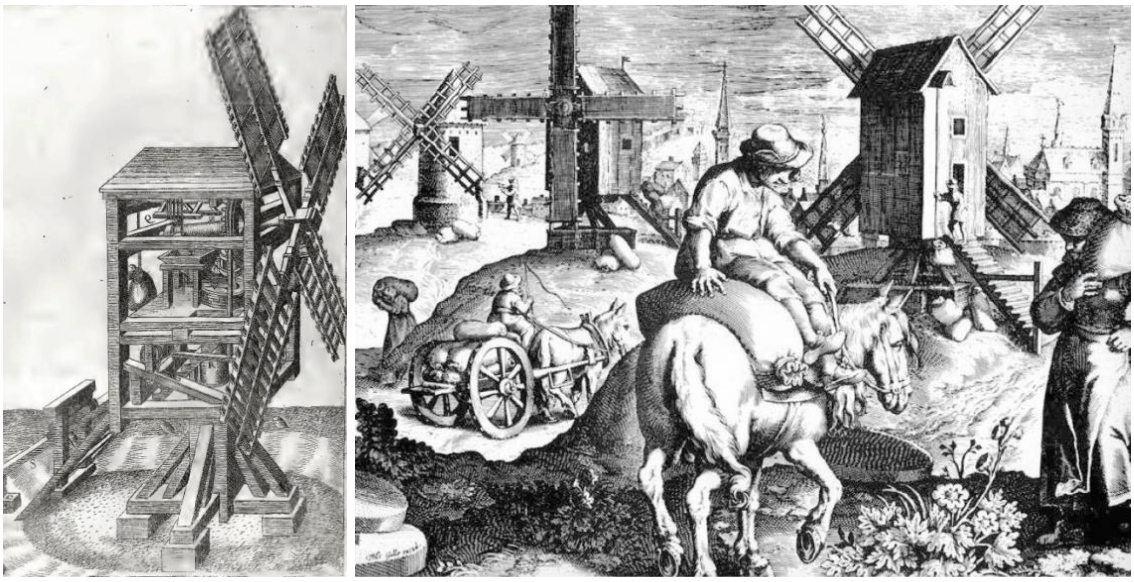
(c)

Figure 2.15. El-Cezeri's The Four Bucket Water Lifting System
(a) El-Cezeri's drawing
(Source: Cezeri & Tekeli, 2002)
(b) A model from the Extraordinary Machines of Cezeri Exhibition in 2019
(c) The gear system
(Source: Çalışkan, 2019)

sawmills or hammering works to the cast-iron work (Tez, 2005). The systematic and scientific improvement of waterwheels by numerous engineers, artists and architects enabled their application as machine drivers that provided power for factories during the early Industrial Revolution.

The windmill, on the other hand, is discovered about 1000 years after the discovery of waterwheels. The invention of windmills was in the 12th century England

and France. Windmills were subsequently spreaded around various regions like Scandinavia, Russia, and the Middle East. The first mills were called *post mills*, some examples are shown in Figure 2.16. The structure was rotated around a wooden center toward the direction of the wind. Using various tools and devices like ropes and windlasses enabled the rotation of these structures with the help of the interior mechanism components just as gears. The structure was elevated from the ground not to damage animals or others around them. Their advantages made them preferred over other human or animal driven machines despite their dangerous characteristic. Furthermore, several methods were developed to be used in case of storms and various related problems. Post mills were developed and quickly spreaded all around the world to fulfill the requirements of changing weather conditions (Randl, 2008). Windmills were then improved with more accurate calculations and experience in usage, thus became more efficient in terms of construction and configuration techniques today. The windmills were always horizontal and many of the tower mills are still represented today.



(a) (b)

Figure 2.16. Post windmills from 16th century
(a) The mill house with grinding machine
(Source: Ramelli, 1588)
(b) An illustration by Johannes Stradanus
(Source: Randl, 2008)

2.2.4. Clocks and Clock Towers

The measurement, announcement or simple observation of time, with no doubt, has major importance in today's life. Not only the measurement, but also the developments of devices that measure time provided an important basis for today's complex machinery design. The design of early time measuring mechanisms that show the locations of celestial bodies as well, improved with the development of astronomical observation. These mechanisms are the astronomical models of the universe. The clock towers in cities were the monuments built for announcing or showing the time. In the Middle Ages, these towers with bells had an informational purpose as they also announced important events for the citizens. Thus today, clock towers are today one of the centers of urban life.

In his book *The Discoverers* (1994), Boorstin revealed the history of time, including the reasons, results and development processes of devices related to it. Time measurement is essential for several occupational groups such as sailors and merchants and was quite important determining working hours. Since the working hours were limited within a period of daylight, the first devices for measuring time were sundials. The first examples of sundials consisted of a calculation system based on the location of the sun's shadow on the ground. As it is seen in several representations of the famous Roman architect Vitruvius, sundials were widely used in the 1st century B.C. One of the extant examples of famous sundials is the octagonal Greek sundial (8 faces) on the *Tower of Winds*, built by the astronomer, Andronikos in Athens. It is designed in a way that each person can see the clock in 3 different faces without regard to their position (Boorstin, 1994).

Water clocks were highly useful for measuring the time in the dark; water can be replaced with other materials such as sand, fire, wax or petrol depending on the climatic and cultural differences. Ctesibius of Alexandria discovered the air pressure and pneumatic principles by examining the design methods of water clocks that were built in the 1st century B.C. (Pollio, 2006). The water clock was probably the most sensitive time measuring device until the invention of the pendulum clock in the 17th century (Boorstin, 1994).

The famous Chinese engineer Su Song's clock tower was built in A.D. 1089 An illustration of the clock tower that was drawn by John Christiansen in 1950 is shown in

Figure 2.17. It was a structure over 10 meters high, with 3 levels. The upper level could be reached through an outside stairway that contained an automatically rotating giant bronze globe with a ring that showed the positions of the stars. The second/middle level had a celestial orb that showed the movements of the heavenly bodies rotating fully in a day. The lower level included all of the wooden mechanisms required. There was a time-telling system similar to a pagoda in front of the tower. There were five stores with doors in each floor for wooden puppets holding gongs and bells to ring at certain intervals. This was an example of systems in which automats were used together with clocks. The huge clockwork was powered by water with an escapement regulator (Bautista Paz, Ceccarelli, Otero, Sanz, 2010).

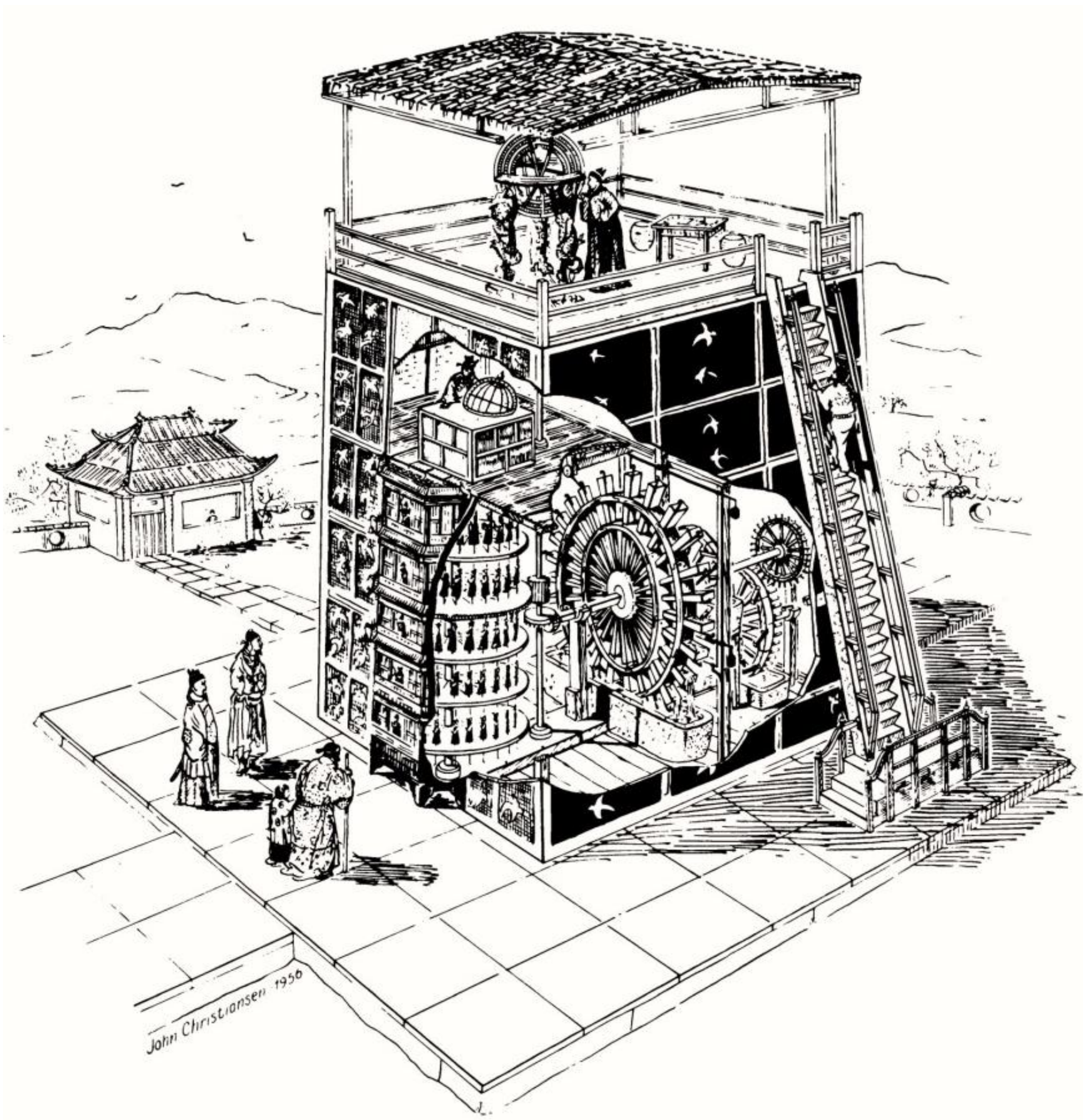


Figure 2.17. An illustration of Su Song's *Astronomical Clock Tower*
(Source: Price, 1959)

The famous giant water clock over the ornate door of the Umayyad Mosque in Damascus, Syria, built by the engineer Muhammad al-Sa'ati in the 12 th century required eleven full-time workers to keep the mechanism working continuously. The clock is shown in Figure 2.18. Two bronze hawk statues hourly dropped bronze balls out of their mouths every hour into two bronze containers day and night times to generate a ringing sound. The container had a bottom hole that allowed the ball to get back to its rest. Above each hawk, there were twelve doors representing each hour, which had unlighted lamps above. Every hour on daytime, the represented hour's door closed up as each two balls dropped out. All of the doors were opened out automatically after the sunset. When it comes to night time, the lamp representing the related hour turned red as each of the two balls dropped. All lamps were turned off after sunrise (Tez, 2008).

Towers with mechanical clocks were designed with the motivation of clergymen to properly execute their responsibilities to God. The mechanical clocks had the aim of announcing the time, thus were developed to vocalize the time rather than to show it. The first mechanical system with the visual representation of time was developed by Jacopo de' Dondi in Italy (1344). Clock or bell towers were quite common and important in the Middle Ages. Bells had the function of delivering messages in significant cases such as a fire, approaching enemies, the birth of a prince, death of the king, or calling for duty (Boorstin, 1994).

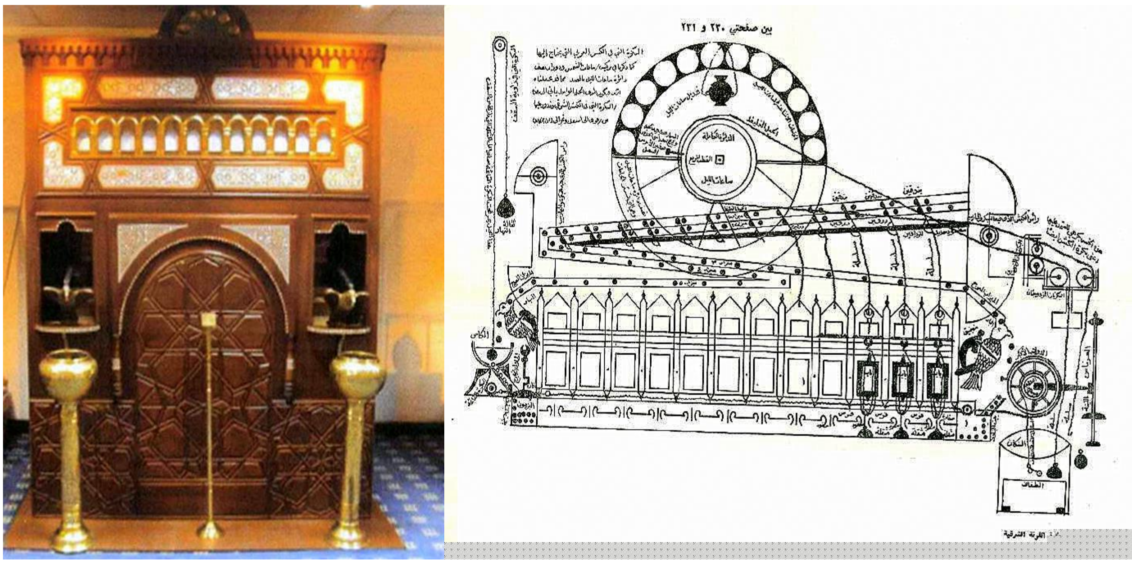


Figure 2.18. The water-clock at the door of the Umayyad Mosque
(a) A model from Cairo Museum (b) Design and drawings by Ridhwan al-Sa’ati
(Source: Al-Jaraki, 2011)

The mechanical clocks have three major features: a *driving force* to run the clock such as hanging weights and the spring, an *indicator* to show the time such as the bells and dials and an *escapement* which is the differentiating element of a mechanical clock that runs regularly by controlling the weights attached to fall through the intervals (Álvarez, 2015). These first all-mechanical clocks consisted of a system in which the hourly visual display was enabled with a rope attached to weight and a clock face connected to a horizontal axle via a gear train that was an essential invention in the field (Denny, 2007).

The invention and widespreading process of the clock has been under the interest of numerous historians. As the clock was quite a popular instrument among philosophers, kings, noble people and elites in the 14th century, it became commonplace in the 15th century with the developing urban lifestyle (Álvarez, 2015). The possibility to add real timelines to the sundials corresponds to the period after the 16th century which was followed by the development of the clock face science that resulted in the trend of carrying pocket sundials (Boorstin, 1994).

The real inaccuracy of medieval clocks is that they were unable to show minutes, so they are considered, in a highly qualitative environment, more as symbolic instruments rather than measuring ones (Álvarez, 2015). The pendulum for the clocks was designed but not completed by Galileo in 1642. Huygens finished the design of the pendulum in 1656. Pendulums convert energy by swinging off a hanging rod. Their swinging time depends on the rod length and gravity. The invention of the pendulum enabled even seconds to be measured.

Today, besides digital clocks, there are still some working clock towers that indicate time with a great deal of historical value. For example, the *Safranbolu Clock Tower*, which was completed in 1797 in Turkey, is still in use (see Figure 2.19). There is also an exhibition about the clock towers of Turkey with their miniature models in the garden of the tower. The clock cannot be seen from every single position due to the uneven landforms in the region, thus it is important to also announce the time. The mechanism of the clock and the bell is on the upper floor of the the square planned tower. Two weights and the pendulum are connected to the gear train from the bottom, allowing both time keeping and bell-ringing mechanisms work. The bell rings every half hour via this mechanism. The maintenance, repair and weekly winder are done by İsmail Ulukaya, today.

Figure 2.19. *Safranbolu Clock Tower* in Turkey
(a) The tower (b) The weights and pendulum (c) The gear train mechanism and the bell

2.2.5. Construction Devices

Marcus Vitruvius Pollio (70-80 BC-15 BC) defined architecture in three departments as construction of machinery, clock making and the art of the building (Pollio, 2006). Vitruvius revealed the period of architecture and various hand-operated hoisting machines that are used for building construction with their usage in detail. Examples of architecture and a hoisting machine examined by Vitruvius are shown in Figure 2.20.

The equipment, devices and tools that are required for construction are also developed by architects during the Medieval Ages. The architect and engineer, Villard de Honnecourt (13^{th} century) for example, is known not only for his architectural and geometrical works, but also for his mechanical work (see Figure 2.21). Various drawings of automata, levers, siege machines, etc. are seen in his extant portfolio (Honnecourt et al., 2016).

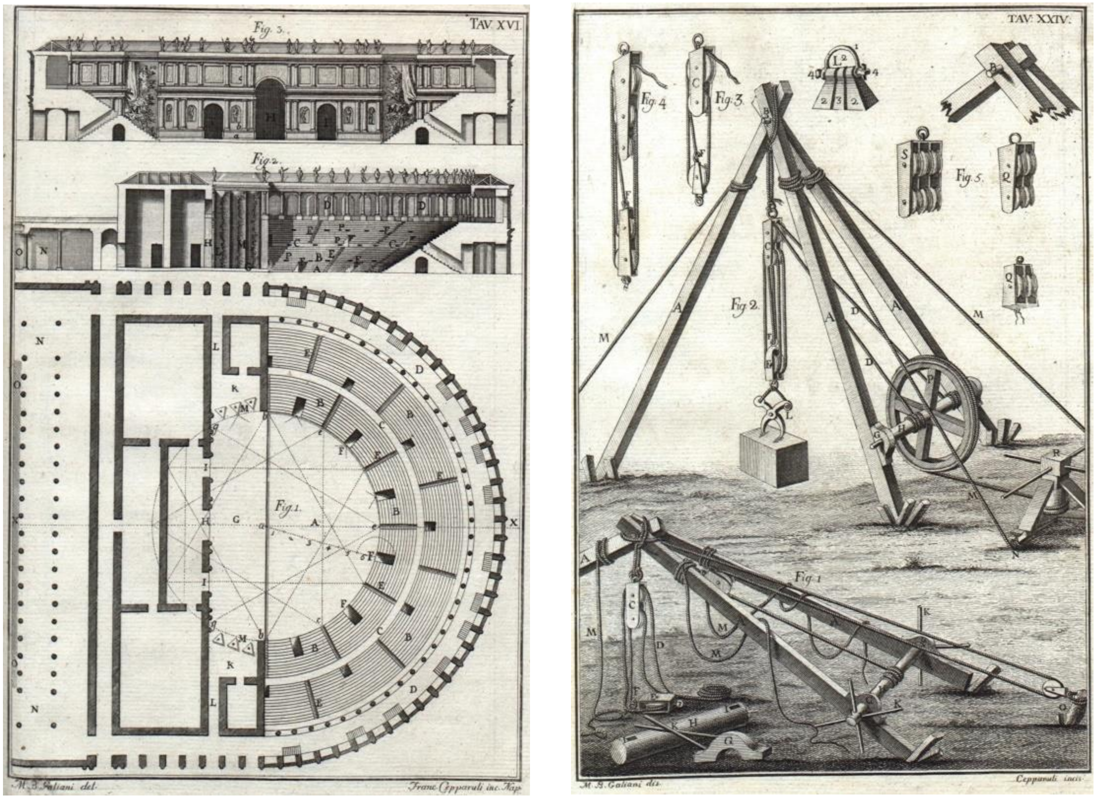


Figure 2.20. Examples of architecture and a machine described by Vitruvius
(Source: Pollio. & Galiani, 1790)

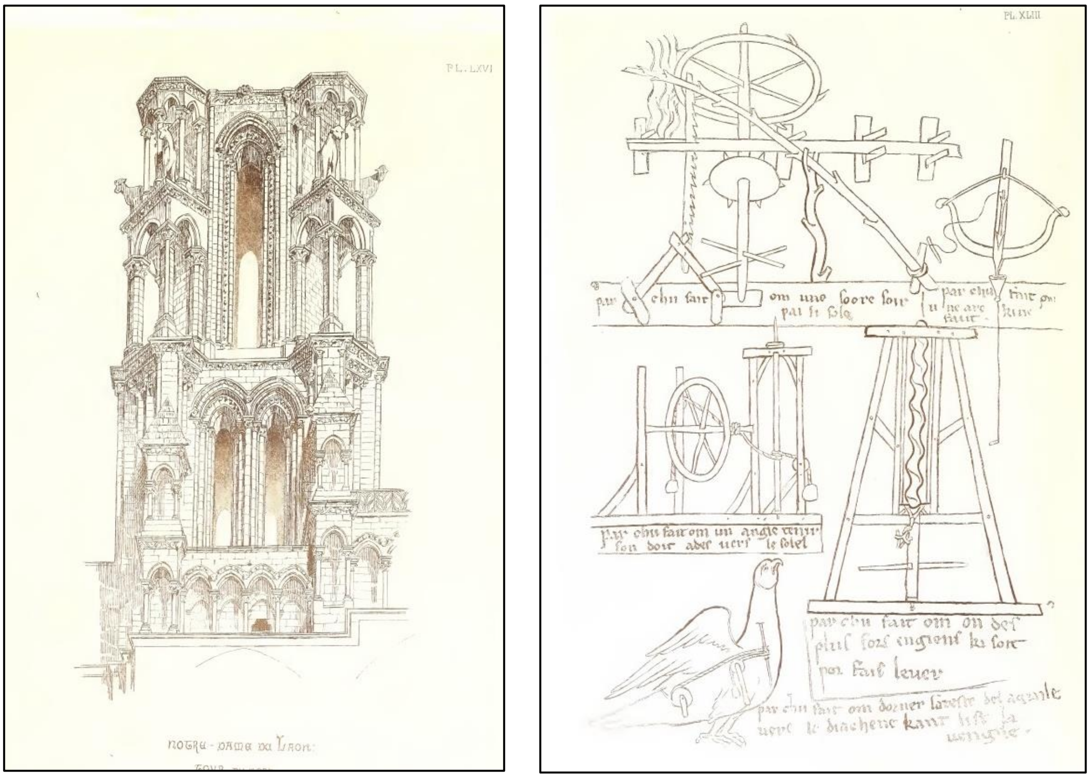


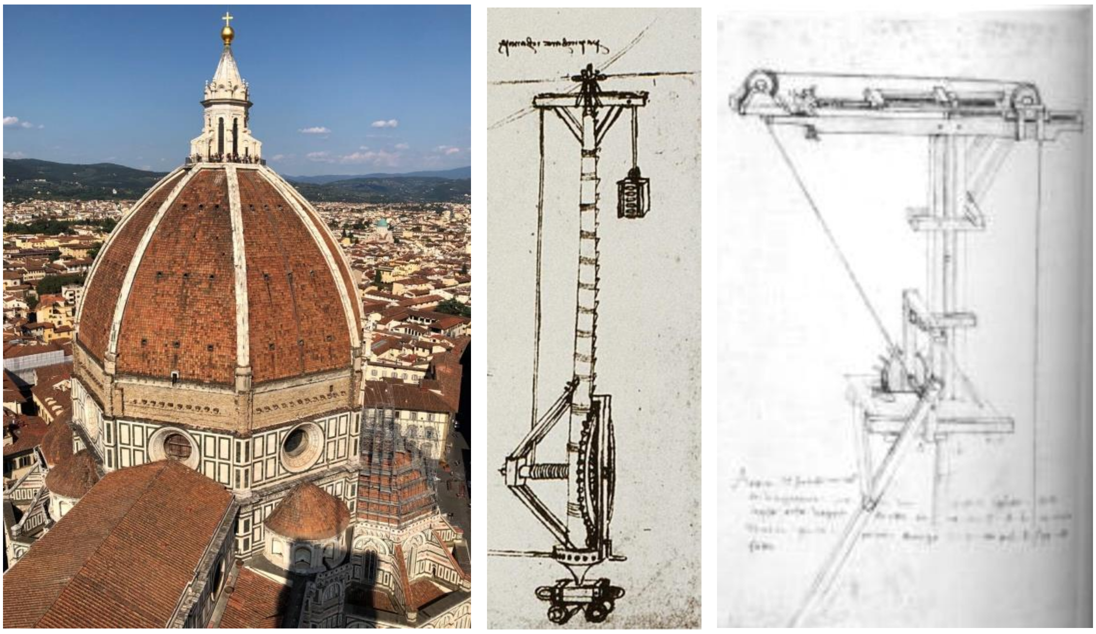
Figure 2.21. Drawing examples of architecture and machine by Villard de Honnecourt
(Source: Honnecourt et al., 2016)

Renaissance engineers were seen and trained to be not only engineers by today's meaning but artists, as “Masters of Arts” as well (Cascini, Romano, & Russo, 2011). Filippo Brunelleschi (1377-1446) was one of those masters, known by his architecture, sculptures and engineering. One of his contributions is the rediscovery of the drawing principles of the linear perspective. *The Dome of Santa Maria del Fiore* (see Figure 2.22) was a well-known piece of early Renaissance architecture that is built in Florence in 1420–1436. Since no drawing or writing by Brunelleschi survived, today architects and engineers try to rediscover the construction techniques, tools and machines for this high dome of the related period.

Massimo Ricci and his team tried to understand by reconstructing this dome. They described the octagonal vault as a self-supporting structure that is totally constructed through masonry herringbone brickwork. They examined the stable and movable rope lines to obtain a guide to construct the brickwork to generate its geometry (Jones, Sereni, & Ricci, 2010). The design of cranes and weight lifting devices are also essential for this unique and huge dome. Brunelleschi applied his knowledge of mechanisms and gears which he acquired by clock making in his youth, to the machines he used for building construction. The works of Leonardo da Vinci, Giuliano da Sangallo and Bonaccarso Ghiberti are analyzed with hope to rediscover the construction machines, Brunelleschi’s unrecorded systems (Cascini et al., 2011). Two of the cranes that are possibly used by Brunelleschi in the construction of this dome are shown in Figure 2.22.(b) and Figure 2.22.(c).

Leon Battista Alberti (1404-1472) was an Italian architect, artist, sculptor, writer, mathemetician of the Renaissance period. The working principles of wheels, pulleys, levers, screws and cranes were explained with their parts, sizes, and figures in his book, *Della Architettura (The Architecture)* in 1452. Alberti stated balance as the key to these mechanisms' working principle. The division of weight was examined in detail and drawn with figures especially for pulleys and ropes (Alberti et al., 1726). A pulley system designed for weight carrying and a machine designed to carry heavy weight, drawn by di Giorgio Martini is shown in Figure 2.23.

Francesco di Giorgio Martini (1439-1501) was well-known by his mechanical works as well as his architectural works (see Figure 2.24). Various architectural drawings with plans, elevations and oblique views; water lifting devices, hydraulic machinery including waterwheels and wind mills, construction machines for architecture, siege machines etc. are seen in his extant book *Trattati di Architettura*



(a) (b) (c)

Figure 2.22. The Dome of Santa Maria del Fiore, Florence, 1420–36
(a) The dome by Filippo Brunelleschi
(Source: Sokolov, 2019)
(b) The crane drawing by Leonardo da Vinci
(Source: Cascini et al., 2011)
(c) The crane drawing by Bonaccorso Ghiberti
(Source: Cascini et al., 2011)

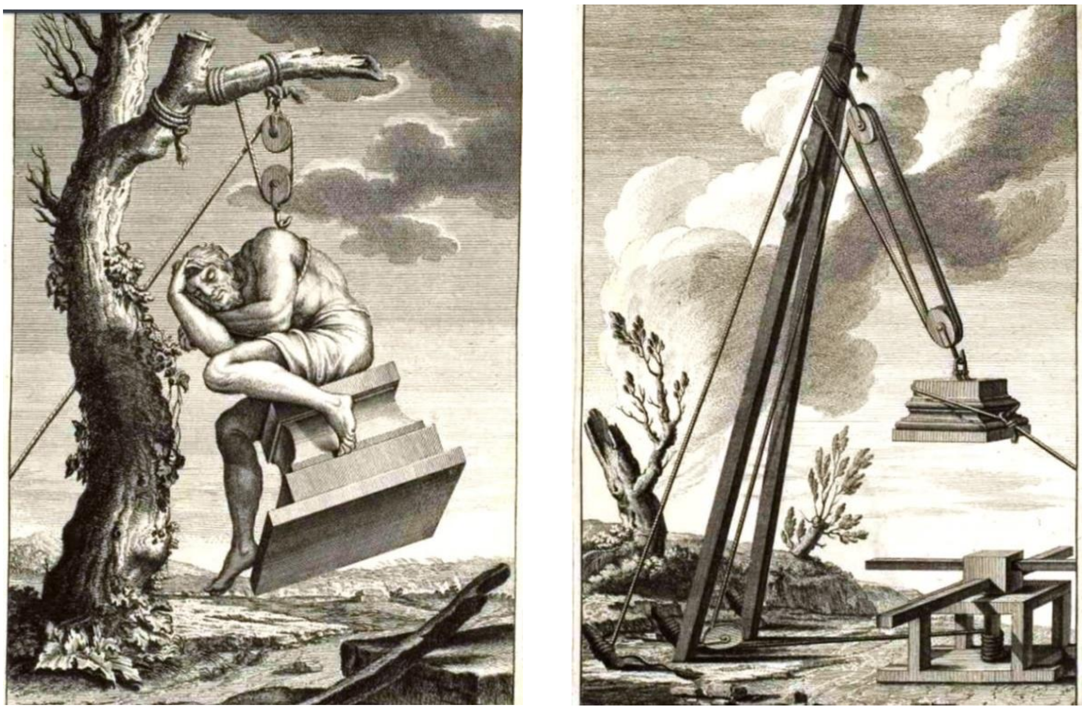


Figure 2.23. Drawing examples of pulleys and weight lifting devices
by Leon Battista Alberti
(Source: Alberti et al., 1726)

Ingegneria e Arte Militare (*Treatise of Architecture)* written in 1477 (Martini & Maltese, 1967).

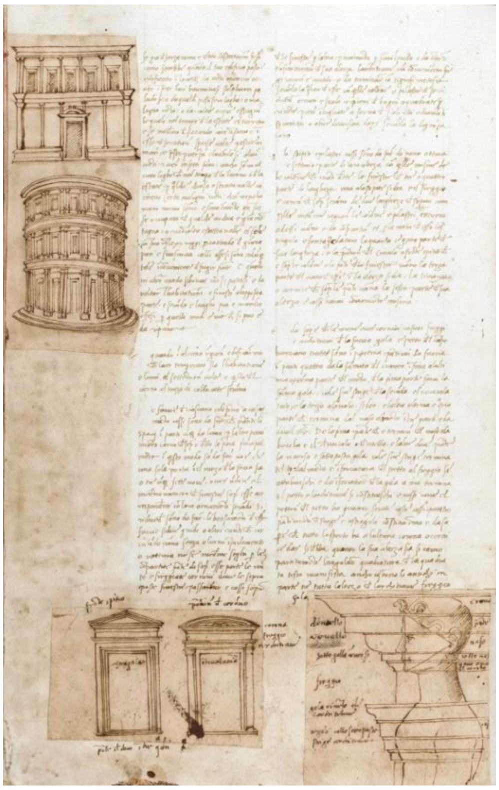
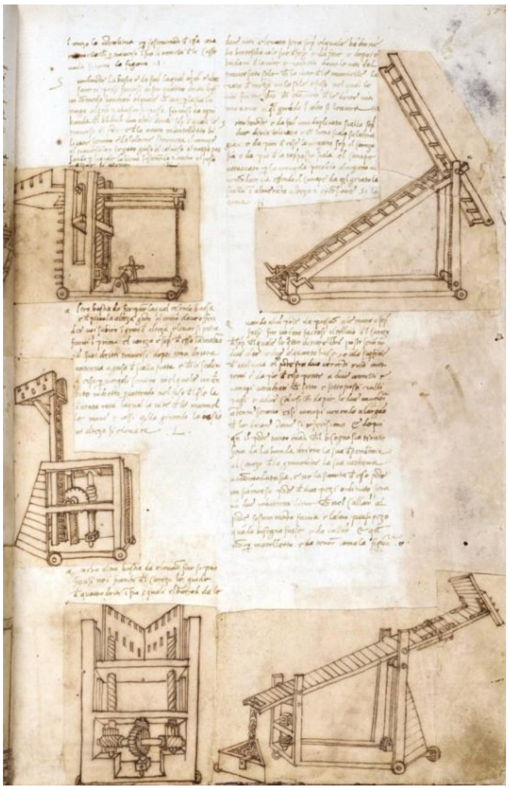
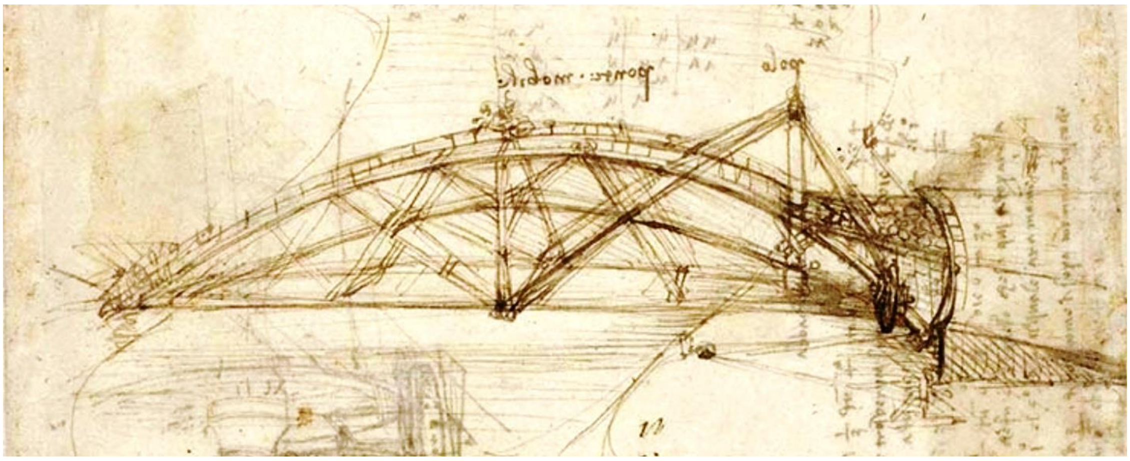
 

Figure 2.24. Samples of architecture and machine sketches
by Francesco di Giorgio Martini
(Source: Martini & Maltese, 1967)

2.2.6. Movable Bridges

Movable bridges are designed and recorded since ancient times. Various strategies are used to obtain their capability of positional change. Some ancient and medieval movable bridges were designed for defensive purposes of castles. Some were designed to provide passage in channels to regulate both pedestrian and water traffic (Hovey, 1926). For example, da Vinci's sketches in the *Atlantic Codex* included several movable bridges (1487-1489). Figure 2.25 shows da Vinci's drawing of a movable bridge with the hand-operated mechanism that consisting of winches and wheels that is capable of 90° rotation, allowing the boats pass.

The remarkable development of the design of movable bridges during the Renaissance was in line with the development in art, architecture and engineering literature. Otis Ellis Hovey, in his book *Movable Bridges*, besides modern bridges, examined the ancient, Renaissance and early modern bridges in detail on a historical basis (1926). Various types were retractile (horizontal translation), swing (rotation in a vertical ax) and drawbridge or bascule (rotating in a horizontal ax) bridges (Hovey, 1926). The portcullises, which are vertically sliding doors, were commonly used with the drawbridges in medieval castles for security related purposes. The portcullis carried specific mechanisms with pulleys. The most commonly seen drawbridges were movable defensive systems that were used in the entrances of castles and forts over moats (deep ditches filled water surrounding the castle).

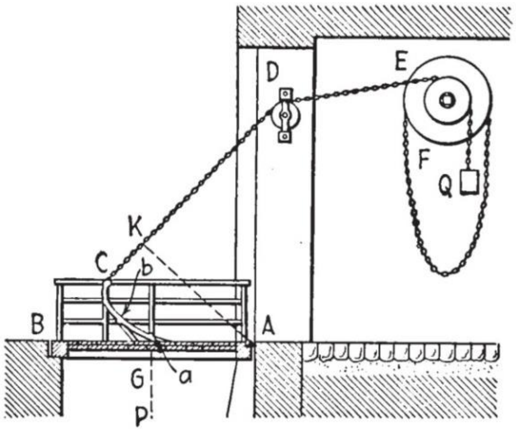


(a)

(b)

Figure 2.25. A Movable Bridge of Leonardo da Vinci
(a) The skech by Leonardo
(Source: Da Vinci, 1486)
(b) A model of the bridge
(Source: Xpo Factory, 2020)

Figure 2.26 shows two drawbridge examples. Several mechanisms are used to design drawbridges. A simplified version of the earlier drawbridge mechanisms proposed by Jean Victor Poncelet (1788-1867) is shown in Figure 2.26.(a). The curved track in the platform was connected to the chain and another end of the chain was connected to a counterweight (Hovey, 1926). Another drawbridge in the entrance of the Bishop's Palace that is built in the 14th century and is still in use at Wells in England is shown in Figure 2.26.(b).



(a) (b)

Figure 2.26. Drawbridge
(a) The mechanism drawing of a drawbridge by Poncelet
(Source: Hovey, 1926)
(b) The drawbridge at the Bishop's Palace, Wells in 14th century
(Source: Buck, 1991)

Numerous books in the field of engineering were written by Bernard Forest de Bélidor (1698-1761). De Bélidor used integral calculus in the solution of technical problems. He had four books on *Architecture hydraulique* including waterwheels, mills, pumps, harbours, bridges etc. One of his drawbridge sketches is shown in Figure 2.27. In its original titles, Figure 1 shows the exterior elevation of the door that the drawbridge is applied to, Fig. 2 shows the section of the bridge in closed position, Fig. 3 is the section drawing of the open position. Other sections, elevations and top view of the drawbridge are also shown in the drawings (Bélidor, 1737). As it is shown in Fig. 3, the bridge is working with a lever principle. The system that was connected from the point P to the platform N with chains was hand-operated to be closed. The platform was

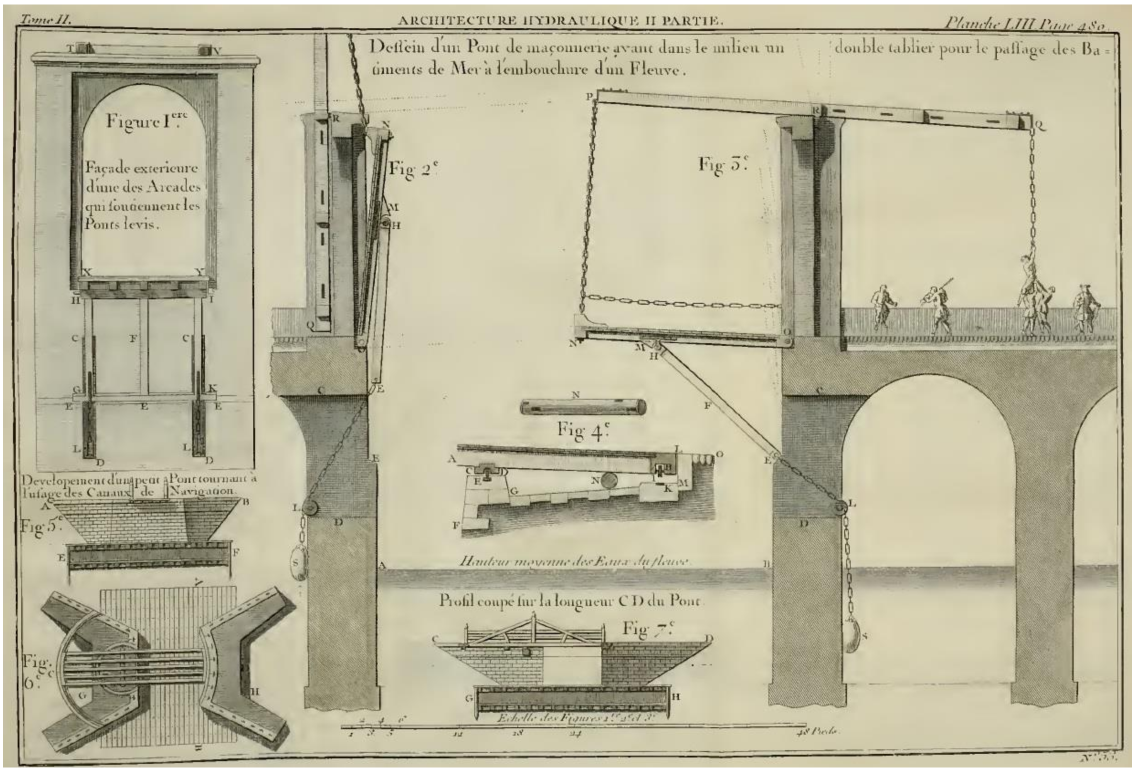


Figure 2.27. The drawings of a drawbridge
(Source: Bélidor, 1737)

(a) (b)

Figure 2.28. The bridges with similar mechanism principles from recent centuries
(a) *Langlois Bridge* in France (firstly constructed in 1835)
(Source: Zengerling, 2014)
(b) *Thieu Drawbridge* in Belgium (1891)
(Source: Merzagora, 2018)

also supported from the bottom by a slider mechanism and was opened with gravity. The mechanism of the bridge generated motion with the platforms that were connected to the rotatable upper spans that provided balance between counterweights. Numerous examples are in use and new movable bridges are designed with this principle. These bridges are not developed for protective purposes such as those in the castles; but they allow pedestrian, bicycle or vehicle passage, and regulate boat or ship traffic. Figure 2.28 shows two examples of bridges with mechanism principles similar to Bélidor’s. The Langlois Bridge is one of the well-known examples by virtue of the oil painting of Vincent Van Gogh (1888).

CHAPTER 3

KINEMATICS OF MECHANISIMS

Mechanism is defined in the International Federation for the Promotion of Mechanism and Machine Science (IFToMM) Dictionary as the “constrained system of bodies designed to convert motions of, and forces on, one or several bodies into motions of, and forces on, the remaining bodies”. M*echanism and machine science* is the “branch of science, which deals with the theory and practice of the geometry, motion, dynamics and control of machines, mechanisms and mechanism elements and systems thereof, together with their application in industry and other contexts,” stating that “related processes, such as the conversion and transfer of energy and information, also pertain to this field.” (IFToMM, 2014, no.0.3, no.0.1).

3.1. Kinematics

Architectural and artistic designs of motion are directly affected by both mechansim science and design techniques and tactics. Mechanical, geometrical and mathematical principles are used by architects in several parts of the design process while many designers have produced pieces in line with natural, biological and astronomical observations. The underlying science, *mechanics* which is interested in effects of force, time and motion, consists of 2 main branches: *statics* (no effect of time) and *dynamics* (effect of time) (Uicker, Pennock, & Shigley, 2003).

It is shown in Figure 3.1 that the science of mechanics is studied in two branches; statics and dynamics, where dynamics is also divided into two disciplines: *kinematics* and *kinetics*. Kinematics is defined as the study of motion without regard to forces and effects caused by those while kinetics studies the forces, moments and motion (Norton, 2004). Kinematic and kinetic analysis and design of mechanical systems involve well established theories today.

Despite the dramatic change triggered by several aspects of technology in the field of mechanical engineering, Newton's laws of motion seem to be the remaining

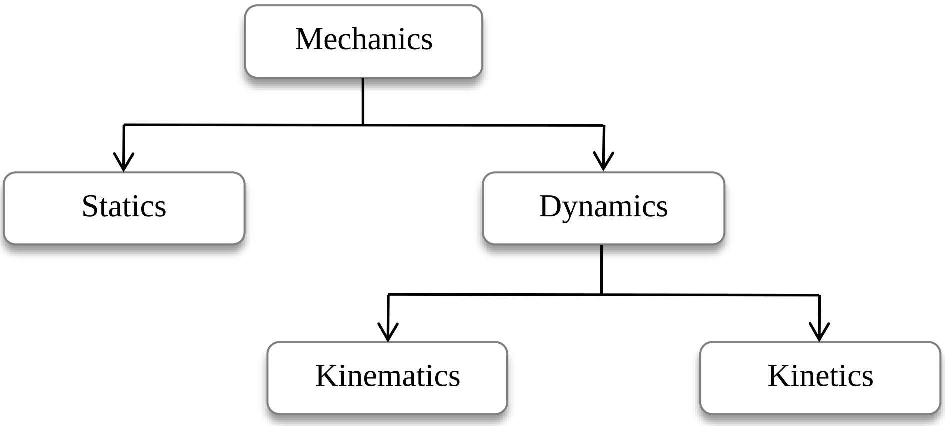


Figure 3.1. The underlying disciplines of Mechanics
(Redrawn by author from: Uicker et al., 2003)

principle of mechanisms required for the study of motion and forces (Söylemez, 2000). Mechanism science, which keeps maintaining its place in design, is formed and developed in the 19th-20th centuries. The earliest mentioning of kinematics was found in Euler's observational work *Novi Commentari Academiae Petrop* in 1775. Franz Reuleaux, on the other hand, who is accepted as the father of modern kinematics published his *Theoretische Kinematic* in 1875. It wasn't until the late 19th century that *kinematic machinery design* is approved as a scientific discipline of mechanical engineering rather than simply artwork. Kennedy from England and Chebyshev from Russia are some of the main conributers. Ferdinand Freudenstein along with his students are accepted as the ones making the final touch to *modern kinematics* in America so far. There are currently several international institutions working for development of mechanism science including IFToMM, which has the main purpose of supporting the fieldwork of machines and mechanisms theoretically, experimentally and practically (IFToMM, 2020).

3.2. Mechanism Design

Design, is defined as “a creative decision making process” (Yan, 1998, p.3). It is basically the process of creating something new based on imagination and experience, is mostly focused on providing solutions for basic or complex human needs. The word *design* is derived from the Latin word *designare,* meaning *work out* (Yan, 1998). The definition is made as a plan of an object that is not produced yet (Oxford Advanced Learner's Dictionary, 2020b). Design takes part in a range of disciplines including architectural design, structural and mechanical engineering, industrial design or art depending on the specific design process, aim and effect of that specific object.

Mechanisms reveal a basis for facilitators in the solution of everyday problems such as machines, tools and devices. The main purpose of mechanical design is to use the movement obtained from natural energy sources in the most effective way to achieve a goal by producing the functional piece stated as mechanism (Akçalı & Mutlu, 2014). The essence of the machinery design process is usually generated by the geometry of motion in mechanisms (Phillips, 2007).

Link and joint types, the number and type of members and the junction procedure are seen to be determinant factors of the occurring motion. Mechanism design is thus mostly concerned with planning every movement that will be obtained between every single part of a mechanism to achieve an aimed motion or sequence of motion (Yan, 1998). Determination of the numbers and types of links and joints are basic steps of the mechanism design process. Understanding mechanism design provides a basis for mechanical engineering, kinetic architecture and kinetic artwork. The relationship between design, kinetic architecture design, kinetic art design, machine design and mechanism design is shown in Figure 3.2.

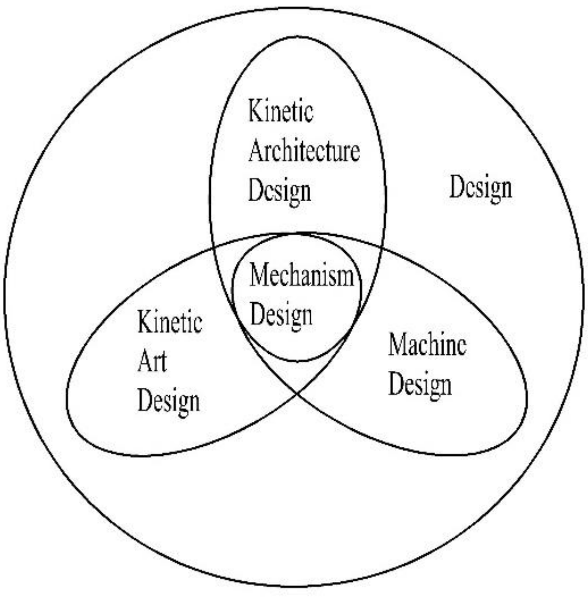


Figure 3.2. In between relationships among different design procedures

A *machine* is a “mechanical system that performs a specific task, such as the forming of material, and the transference and transformation of motion and force (IFToMM, 2014, no.0.2). They need to hold a power unit, an adequate control system and a work output. The main difference between machines and mechanisms is that while machines are designed for a certain purpose, mechanisms are much more general pieces in terms of purpose, therefore a mechanism can be observed in different machines. Machines are mostly examined for their function and several mechanisms are designed to fulfill the machine's requirements. Architectural and artistic design processes are quite similar in this sense. A single mechanism can be used in various size, form, material and speed, thus presenting various design products. Development of an existing mechanism and use of different mechanisms together are some strategies preferred by designers.

The slider-crank mechanism that involves 4 links connected with 4 joints is an example for the use of a mechanism in several design products (see Figure 3.3). As shown in Figures 3.4 and 3.5, besides being used in the umbrellas, it is used in a door design of the *Ernisting Warehouse* project by Santiago Calatrava. The slider-crank mechanism is seen to be developed by Choe U-Ram to produce his kinetic sculpture of a blooming flower (see Figure 3.6), *Una Lumino Portentum*. Development of an existing mechanism and use of different mechanisms together are some strategies preferred by designers. In the *Ernisting Warehouse* (1985) door design, 73 slider-crank mechanisms are connected in series and 6 slider-cranks radially connected around a center are used in the *Lumino Portentum* whereas 8 slider-cranks are radially connected around the handle in the umbrella. The slider-crank mechanism is used in both designs, no matter how different their functions are.

Such kinematic chains with at least one fixed link generate mechanisms in the presence of at least two other links that retain mobility. On the other hand, designs with no remaining mobility are called structures. While mechanisms are in motion, structures are not. Structures are immobile systems that consist of combinations of mechanical members with joints. Formation of mechanical devices and differences among mechanism and structure is shown in Figure 3.7. While both motion and force are transmitted in mechanisms, only force is transmitted in structures.

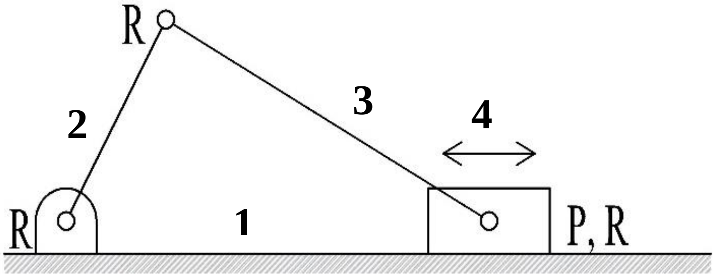


Figure 3.3. The basic *slider-crank* mechanism diagram

Figure 3.4. The *slider-crank* mechanisms of an umbrella

Figure 3.5. The slider-crank mechanisms of Calatrava's Ernstings Warehouse project (Source: Calatrava, 2020)

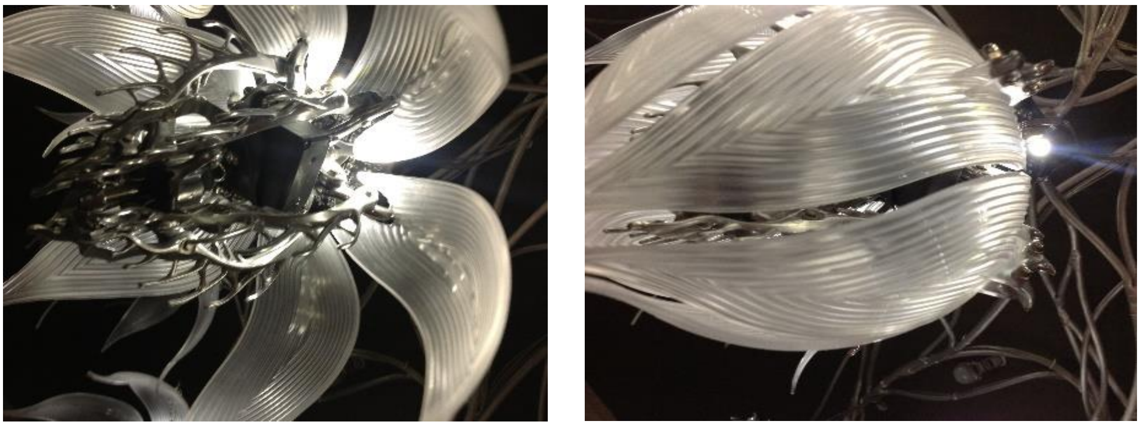


Figure 3.6. The slider-crank mechanisms of U-Ram's Una Lumino Portentum, 2009

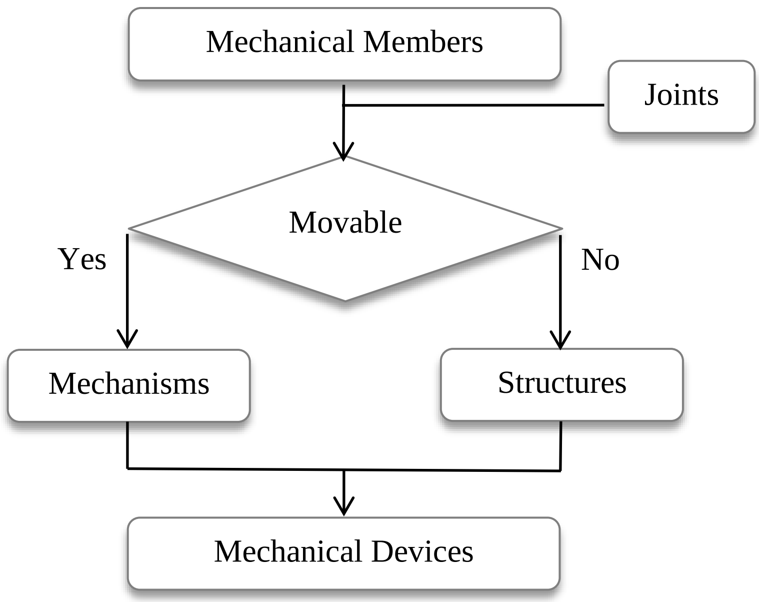


Figure 3.7. Formation of mechanical devices
(Redrawn by author from: Yan, 1998)

3.3. Motion

As William Zuk and Roger H. Clark state in their book Kinetic Architecture, “Life itself is motion, from the single cell to the most complex organism, man. When motion ceases, life ceases.” (1970, p.14). Motion, thus is continuously observed and experienced in human daily life. Motion is seen in different concepts and acts such as growing up, adaptation to different circumstances, walking, flying, swinging, and many others. Gravity can be targeted as one of the main determinants of human body and motion. The limits of gravity have always been pushed by both the human body and products (see Figure 3.8).

Figure 3.8. Human body in motion
(Source: Eaton, 2018)

In line with developing observation and study, motion had been turned into a subject of curiosity, examination and research for ages. Observation of nature and examination of biological movements of living beings is one efficient tool of design. Reuben Margolin's kinetic sculpture design *Double Raindrop* (2007) which is based on his observations of nature is shown in Figure 3.9. It is inspired by two raindrops landing near each other. Raindrops are represented with hexagones rather than circles. A connection of 500 pulleys and a mile of cable are used to mechanically move the interference pattern (Margolin, 2020b).

Another example is the one built by Kresling, by whom studies on living organisms are conducted. A beetle's hind-wing analysis of him is shown in Figure 3.10. The design proposal of deployment mechanisms involving folding membranes is based on the flapping movement in the aforementioned analyis (Kresling, 2000).

As well as kinetic designs in which motion itself is the focal point, designs in which movement is used to derive a functional final product are also observed. Scientific development in the field of mechanism science contributed to shaping the process of movable and functional product design by the forming required methods.

There are two types of motion significant in this field: Translation and rotation. The simultaneous combination of these movements is termed as complex motion. Position of the body during pure *rotation* (R) is pictured as follows, “the body poses a line (axis of rotation) that has no motion with respect to the 'stationary' frame of reference. All other points on the body describe arcs about that axis. A reference line drawn on the body perpendicular to the rotation axis changes only its angular orientation.” (Norton, 2004, p.26). A rotation movement (R) from the first position with respect to a reference point to a second position with an angle of theta (ϴ) is shown in Figure 3.11.

The movement of pure *translation* (T) is also described by Norton, “all points on the body describe parallel (curvilinear or rectilinear) paths. A reference line drawn on the body changes its linear position but does not change its angular orientation.” (2004, p.24). *Curvilinear translation* is the movement that occurs in case curvilinear pathways are drawn by points of the translatory object. *Rectilinear translation* is the movement seen to occur in case rectilinear pathways are drawn by points of the translatory object. An object's transitions from position 1 to position 2 through curvilinear and rectilinear translations and in between paths are shown in Figure 3.12.

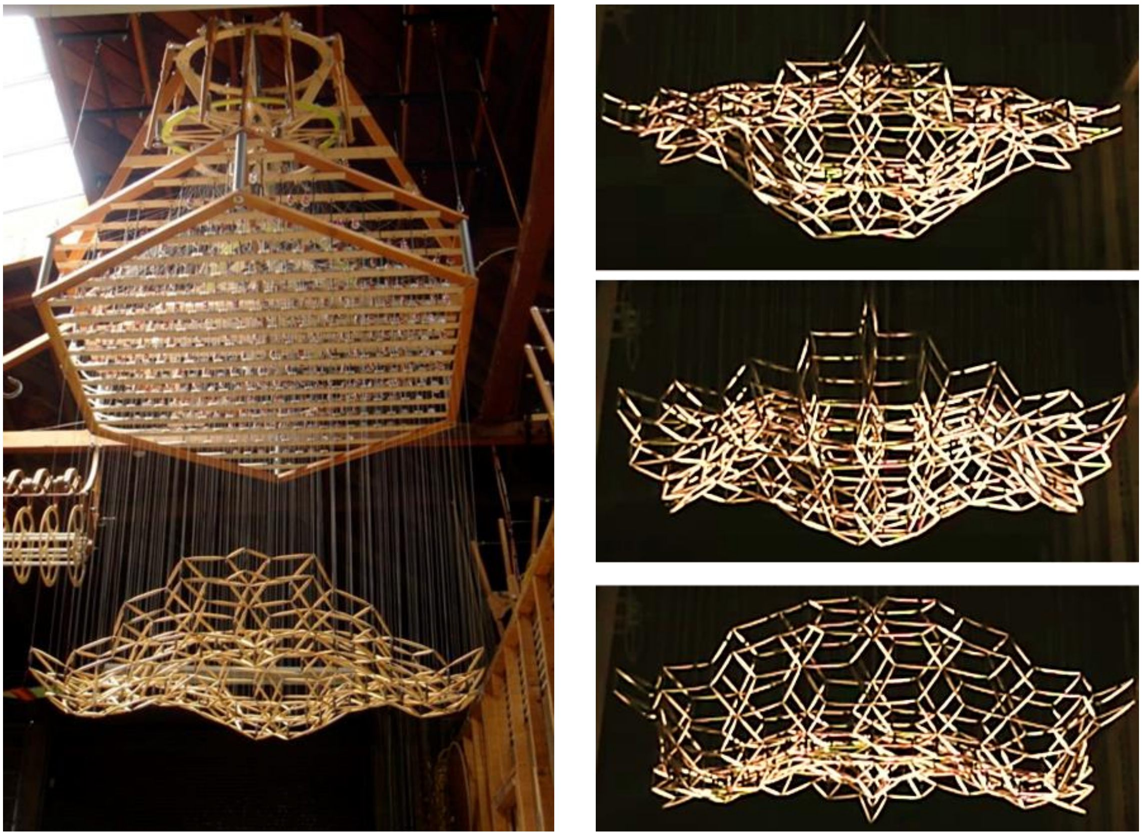


Figure 3.9. Kinetic sculpture, *Double Raindrop*, 2007, inspired by motion in nature (Source: Margolin, 2020b)

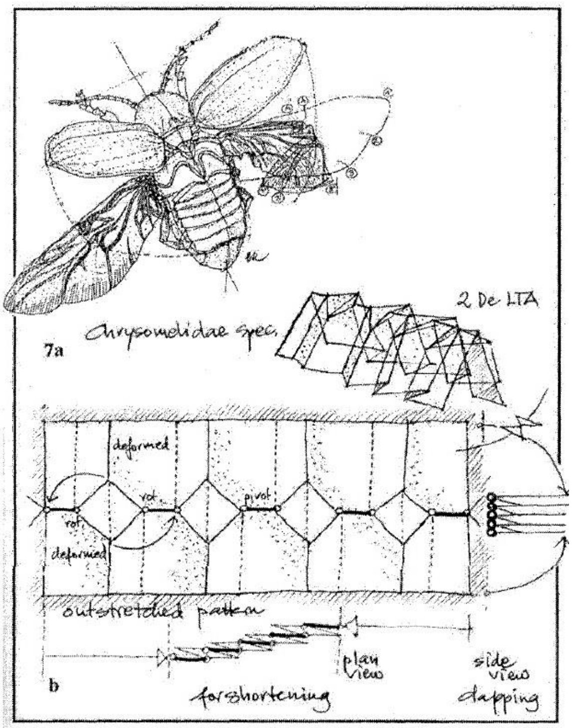


Figure 3.10. Kresling’s deployable structure model inspired by a beetle’s hind-wings (Source: Kresling, 2000)

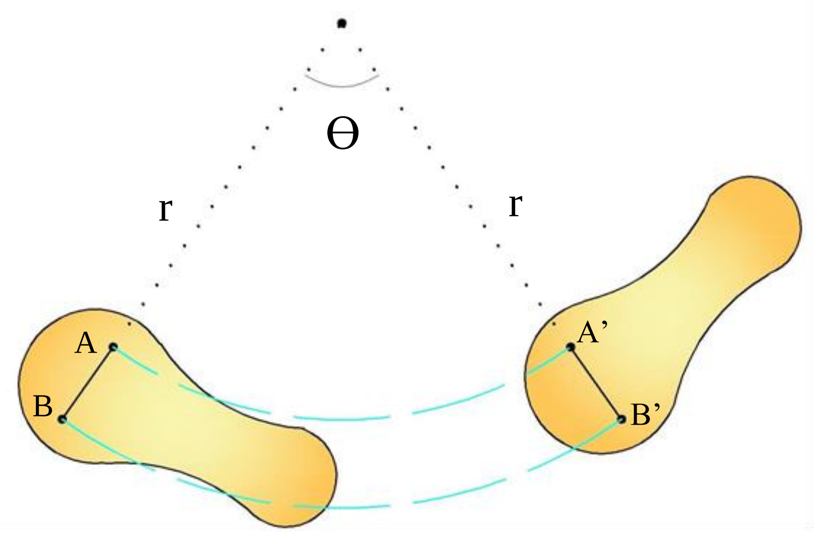


Figure 3.11. Rotation

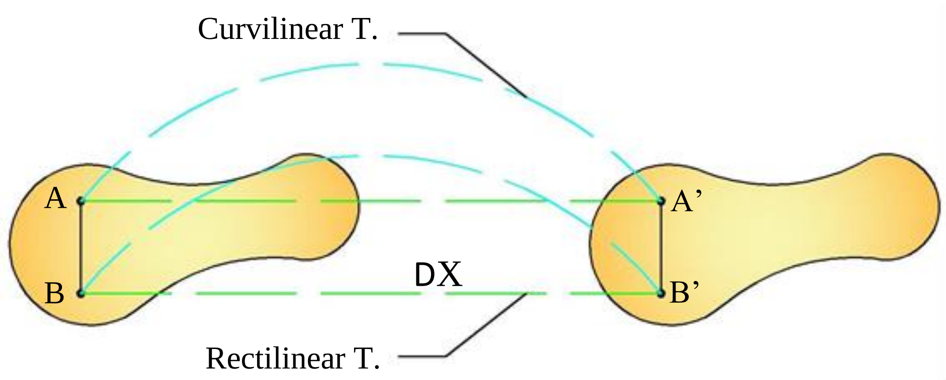


Figure 3.12. Curvilinear and Rectilinear Translations

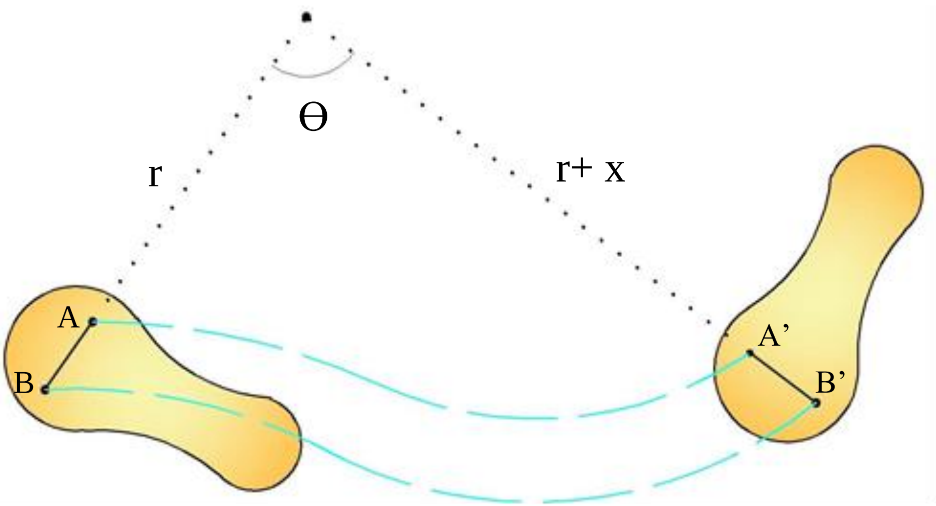


Figure 3.13. Complex Motion

The description of *complex motion*, is seen in the abovementioned study of Norton as “a simultaneous combination of rotation and translation. Any reference line drawn on the body will change both its linear position and its angular orientation. Points on the body will travel nonparallel paths, and there will be, at every instant, an axis of rotation, which will continuously change location.” (2004, p.26). An object passing from the first position to the second executing a complex planar motion consisting of the combination of a translation of x and a rotation of theta (Ө) with respect to a reference point and related pathways are shown in Figure 3.13.

Six independent motions ($\lambda = 6$), 3 rotations (R) and 3 translations (T) can accordingly be observed on an object (see Figure 3.14).

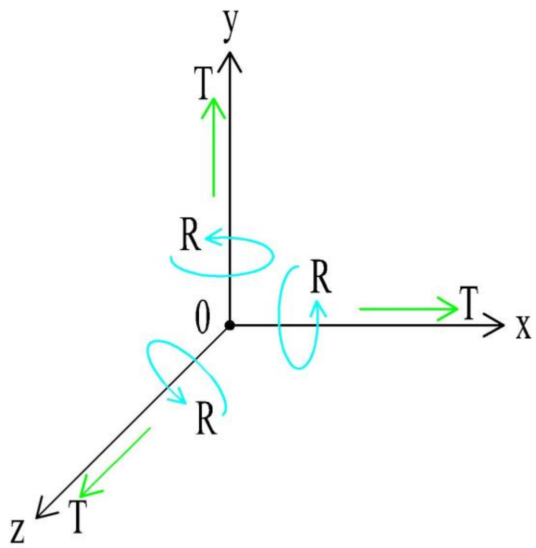


Figure 3.14. 3 rotations and 3 translations on the Cartesian Space

3.4. Links

The term link is used to “name a component of a mechanism with any form (bar, cam, gear, etc.)” (Gogu, 2008, p.11). All links are considered to be rigid in the present study. The purpose of a rigid link is to maintain the spatial relationship that is constant between joints.Motion is transmitted from the input link to the output link through connected joints in a mechanism. An *input link* is defined as a “link for which at least one of the position components is considered as an independent variable” (IFToMM, 2014, no.1.1.3).

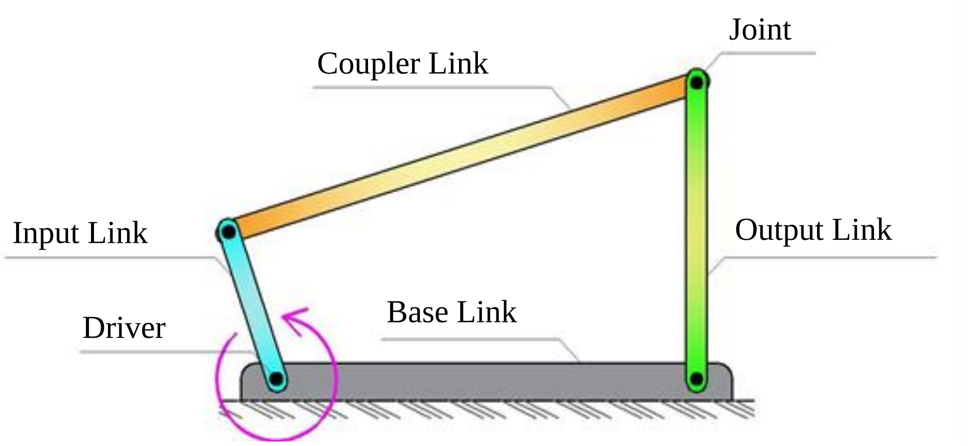


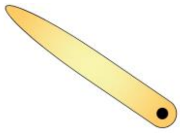
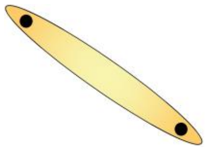
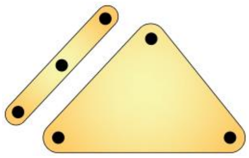
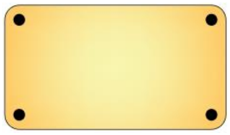
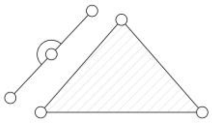
Figure 3.15. Four-bar mechanism components

An *output link* is defined as a “link performing the required motion or force as intended for the design of the mechanism” (IFToMM, 2014, no.1.1.4). A *base (frame) link* is defined as a "link of a mechanism deemed to be fixed.” (IFToMM, 2014, no.1.1.5). A *coupler link* is defined as a “link that is not connected directly to the frame” (IFToMM, 2014, no.1.1.9). The 4 bar-mechanism with a base link, an input link, a coupler link and an output link connected by joints is shown in Figure 3.15.

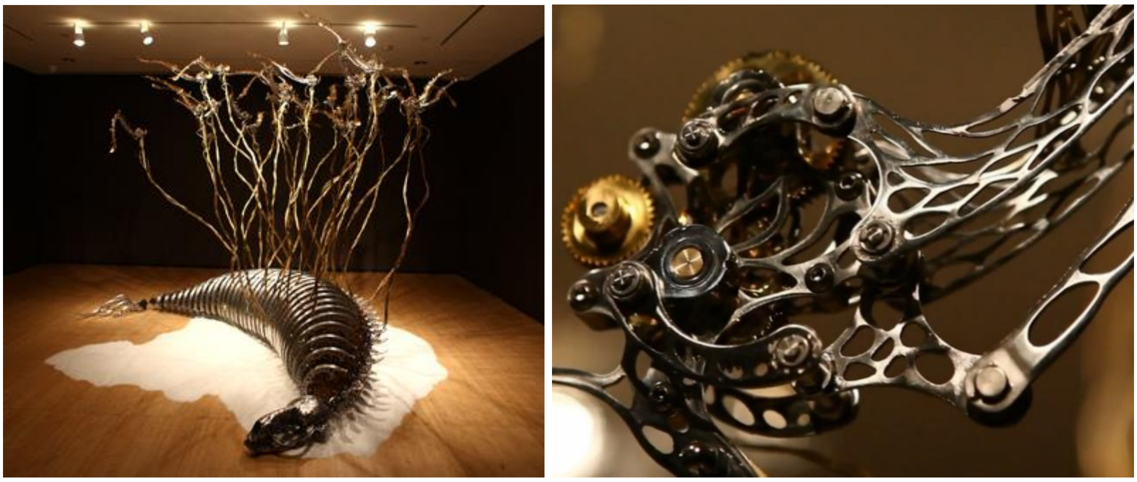
Relative motion and energy is obtained by input links through drivers. Input links must be driven by actuators that either use natural resources such as gravity, wind, water force or are manually controlled by human or motors (Myszka, 2012). Two types of motion are generated by motors: the first is rotation such as in the one provided for the input links by rotary motors, the second is translation such as in the one provided for the input links by hydraulic and pneumatic cylinders.

Classification of links, without respect to their shape, is based on the number of joints that they are connected with. Links that are connected with 1 joint are called monary link, links that are connected with 2 joints are called binary links, links that are connected with 3 joints are called ternary links, those that are connected with 4 joints are called quaternary links, etc. Classification of links with 1, 2, 3 and 4 joints including kinematic representations and number of joints for each are shown in Table 3.1. A ternary link, for example, can be designed in several shapes such as a circle, a triangle, a square or completely free form. No matter what form it has, the proper name is ternary link as long as it has 3 joints.

Table 3.1. Classification of links

	Monary Link	Binary Link	Ternary Link	Quaternary Link
Link				
Kinematic Represent				
Joint Number	1	2	3	4

The metallic kinetic sculpture of Choe U-Ram, *Custos Cavum*, meaning "guardian of the hole" in Latin is shown in Figure 3.16.(a). A detail from *Custos Cavum* where various components like bars and gears designed in several geometrical shapes with several combinations of links such as binary and ternary types is shown in Figure 3.16.(b).



(a) (b)

Figure 3.16. Combined use of binary and ternary links in different shapes
(a) The kinetic sculpture, Custos Cavum (b) Link detail from Custos Cavum
(Source: U-Ram, 2011)

3.5. Joints (Kinematic Pairs)

Joints are the components that allow possible relative motion between links of mechanisms. A *kinematic pair* is defined as the “connection between two links restricting their relative motion” while *joint* is stated to be the “physical representation of a kinematic pair” (IFToMM, 2014, no.1.2.3, no.1.2.2). “It is important to see that a kinematic chain is just as much a system of joints linked by links as it is a system of links joined by joints.” (Phillips, 2007, p.16)

Types of joints used in a mechanism and the *Degree of Freedom* of these joints are the key features of a mechanism (Söylemez, 2000). *The degree of freedom of a kinematic pair* is defined as the “number of independent coordinates needed to describe the relative positions of the links involved with the kinematic pair” (IFToMM, 2014, no.1.2.5). A kinematic pair's degree of freedom (DoF) that is calculated between 1 and 5 is essential for generation of motion, meaning a DoF of 0 reveals no motion. While constraining the motion of joints provides a DoF between 1 and 5, an object has 6 DoF in space. On one hand, joints generate motion in mechanisms, however on the other hand, they constrain an object that is capable of expressing 6 motions to a maximum DoF number of 5, thus provide control over the 5 possible motion. It can, therefore, be said that joints are rather constraining than allowing in terms of the motion.

Kinematic pairs are categorized by Reuleaux (1876) into *higher* and *lower pairs* (Gogu, 2008). Higher pairs are the ones that have a line or point contact between its elements, whereas lower pairs are have surface contact between pairs. A mechanism with only lower kinematic pairs is called a linkage.

3.5.1. Lower Pairs

The *lower pair* is a “kinematic pair that is formed by surface contact between its elements” (IFToMM, 2014, no.1.2.9). Revolute (R), prismatic (P), screw (H), cylindrical (C), spherical (S) and flat (planar) (E) pairs are lower pairs (see Figure 3.17). The R and P pairs are the basic building blocks of all other pairs that are combinations of those (Norton, 2004). The motion combinations of lower pairs with symbols, mobilities, contains and relative motion of those are shown in Table 3.2.

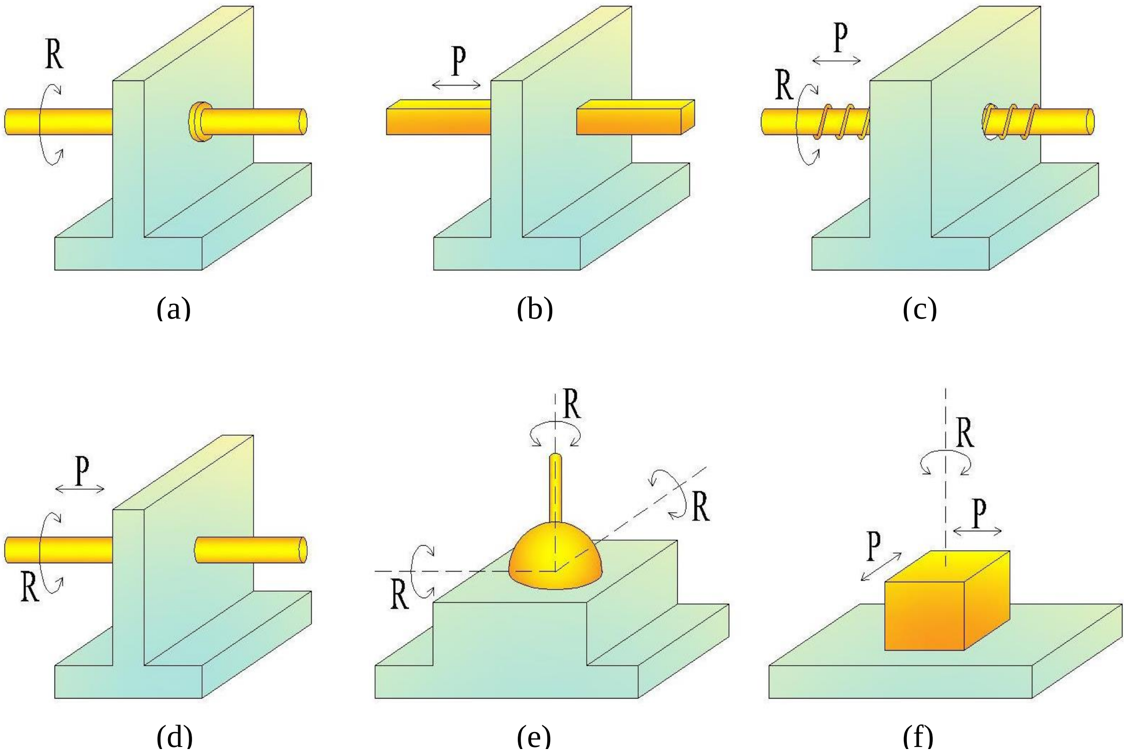


Figure 3.17. Lower pairs
(a) Revolute pair (b) Prismatic pair (c) Screw pair
(d) Cylindrical pair (e) Spherical pair (f) Flat pair

Table 3.2. Properties of lower pairs

Pair	**Symbol**	**DOF**	**Contains**	**Relative Motion**
Revolute	R	1	R	Rotation
Prismatic	P	1	P	Rectilinear translation
Screw	H	1	RP	Helical
Cylindrical	C	2	RP	Cylindrical
Spherical	S	3	RRR	Spherical
Flat	E	3	RPP	Planar

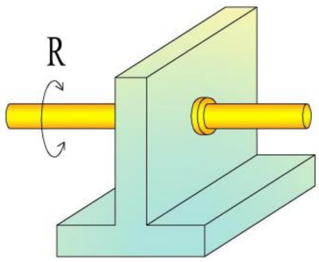
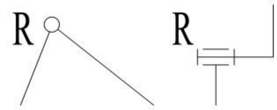
The primary advantage of using lower pairs rather than higher pairs is that they are capable of maintaining the lubricating grease in between surfaces and therefore have a longer life span (Norton, 2004) and also there are lower stresses on the corresponding links due to joint reaction forces.

3.5.1.1. Revolute Pair

A *revolute pair (hinge)* is defined as a “pair that allows only rotary motion between two links” (IFToMM, 2014, no.1.2.11). It is denoted by R and consists of a rotary or circular motion that has 1 DoF. Thus, it can be concluded that there are 5 remaining types of motion that are restricted. Kinematic properties of revolute pairs are shown in Table 3.3. As it is shown in Table 3.3, scissors are an everyday example of R.

Having 1 DoF is one of the main factors that influence the very common use of revolute pairs in art and architecture. For example, various link types such as ternary or quaternary links are connected with revolute joints in Hobberman’s movable *Olympic Arch* design that is designed to be used in the 2002 Winter Olympics stage curtain shown in Figure 3.18.

Table 3.3. Kinematic properties of revolute pairs

		Typical Form	**Example**
Symbol	R		
DOF	1		
Contains	R		
Relative Motion	Rotary		
Kinematic Representation			

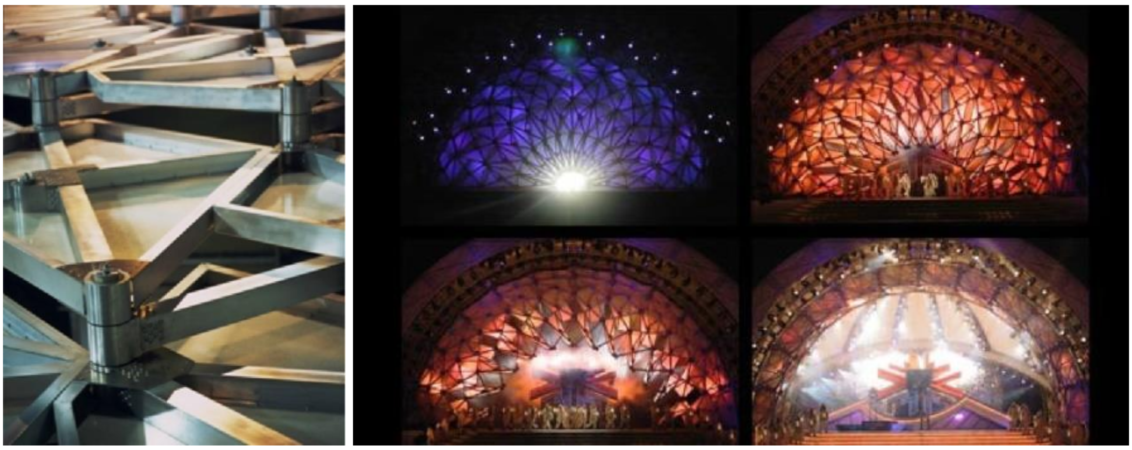


Figure 3.18. Use of revolute joint in the *Olympic Arch*
(Source: Hoberman Associates, 2002)

3.5.1.2. Prismatic Pair

A *prismatic pair* is defined as a “pair that allows only rectilinear translation between two links.” (IFToMM, 2014, no.1.2.12). It is denoted by P and contains 1 DoF thus inferring that the 5 remaining types of motion are restricted. Kinematic properties of prismatic pairs are shown in Table 3.4. An umbrella's opening and closing movements is an everyday example.

An example of movable structures is the kinetic Planetarium/IMAX theater in the city of Valencia in Spain. Inspired by the form of an eye, the building is designed by Santiago Calatrava at Ciudad de las Artes y de las Ciencias Project (2009). The movable part's design consists of an input link that is driven by a hydrolic actuator. Translation motion is transmitted by actuators through prismatic joints. The opening motion permits views accross the pool (see Figure 3.19).

Table 3.4. Kinematic properties of prismatic pairs

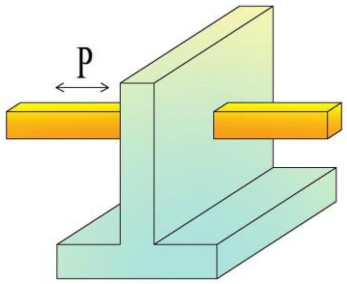
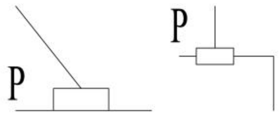
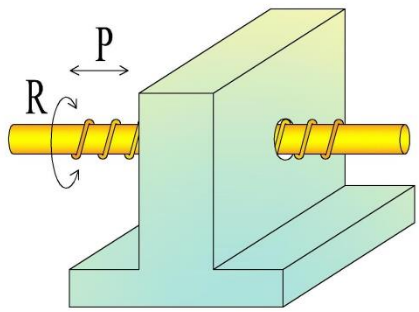
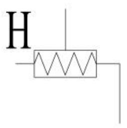
		Typical Form	**Example**
Symbol	P		
DOF	1		
Contains	P		
Relative Motion	Rectilinear Translation		
Kinematic Representation			

Figure 3.19. Use of prismatic joint in Ciudad de las Artes y de las Ciencias (Source: Calatrava, 2009)

3.5.1.3. Screw (Helical) Pair

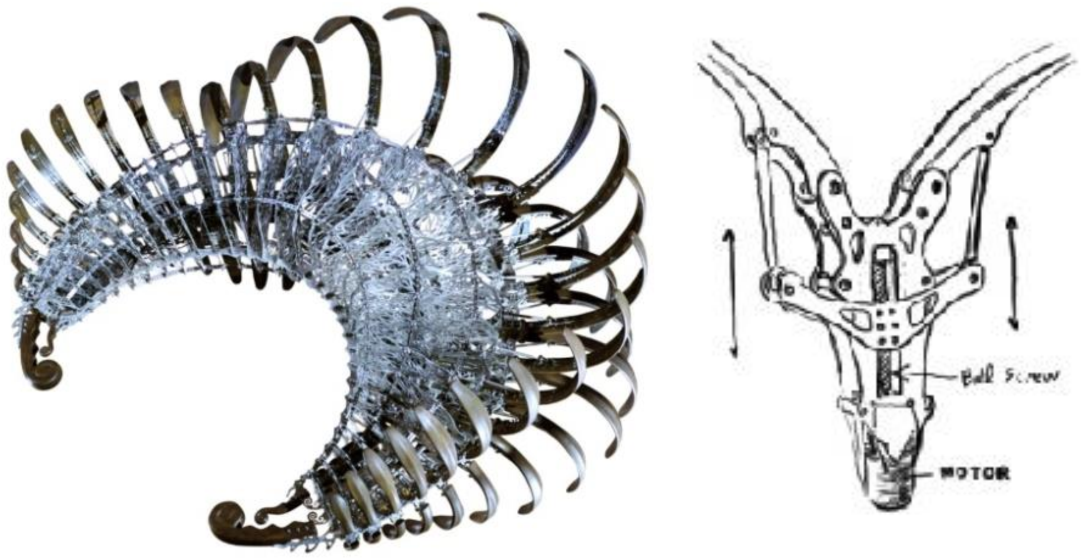
A *screw (helical) pair* is defined as a “pair that allows only screw motion between two links.” (IFToMM, 2014, no.1.2.13). It is denoted by H and contains 1 DoF. The screw pair is actually capable of generating 2 types of motion (rotation and translation) but it has 1 DoF because motions are interdependent, meaning one cannot occur without the other (Uicker et al., 2003). Kinematic properties of helical pairs are shown in Table 3.5. They are used in arrangement of the distance between compasses we use in daily life (see Table 3.5).

Table 3.5. Kinematic properties of screw pairs

		Typical Form	**Example**
Symbol	H		
DOF	1		
Contains	RP		
Relative Motion	Helical		
Kinematic Representation			

Choe U-Ram's drawings of his kinetic sculpture *Opertus Lunula Umbra* (*Hidden Shadow of Moon, 2008*) in which a belt screw is used are shown in Figure 3.20. The motion that is generated by the motor is transmitted through screw joints.

As shown in Figure 3.21 the screw pair is used in the kinetic facade of the entrance of the Digital Gallery in Theme Pavilion Expo Yeosu project (2012) designed by Soma Architects. Lights conditions are controlled by kinetic lamellas that are supported on the top and bottom edges of the facade. Lamellas are manipulated by actuators that are screw spindles activated by servomotors (McManus, 2020).



(a) (b)

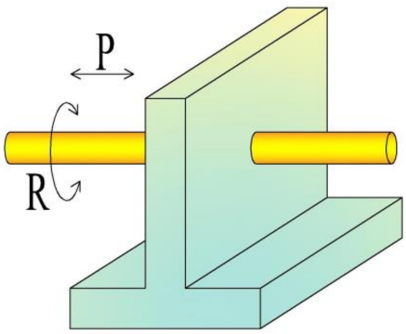
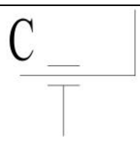
Figure 3.20. Use of screw joint in *Opertus Lunula Umbra*
(a) Kinetic sculpture
(Source: U-Ram, 2014)
(b) Drawings
(Source: U-Ram, 2008)

Figure 3.21. Use of screw joint in Theme Pavilion Expo Yeosu
(Source: Rutzinger, 2013)

3.5.1.4. Cylindrical Pair

A *cylindrical pair* is defined as a “pair for which the degree of freedom is two and that allows a rotation about a particular axis together with an independent translation in the direction of this axis.” (IFToMM, 2014, no.1.2.14). It can thus be concluded that 4 remaining types of motion are restricted. It is denoted by C and contains R and P. Kinematic properties of cylindrical pairs are shown in Table 3.6. The joint of the bolt locks which both translates and rotates is given as an example from daily life (see Table 3.6). For example, a kinetic umbrella that provides shelter from both rain and sun was designed by Koray Korkmaz (2005) using several links and joints such as cylindrical and revolute is shown in Figure 3.22.

Table 3.6. Kinematic properties of cylindrical pairs

		Typical Form	**Example**
Symbol	C		
DOF	2		
Contains	RP		
Relative Motion	Cylindric		
Kinematic Representation			

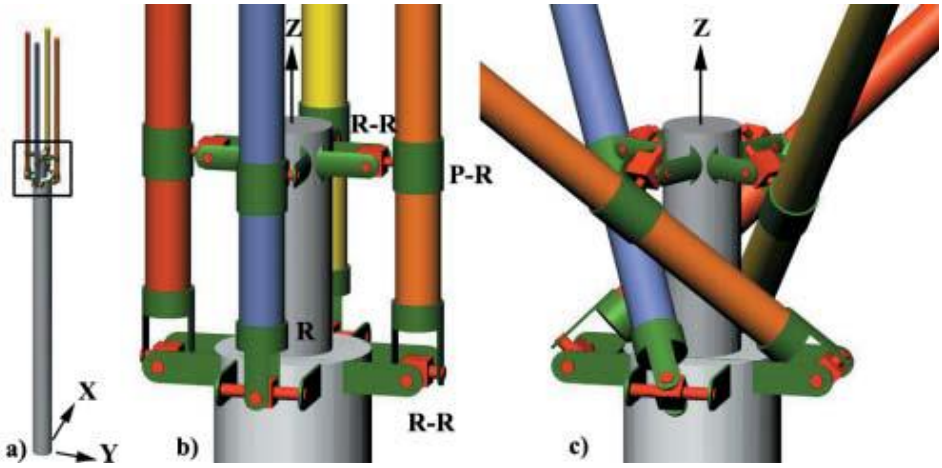


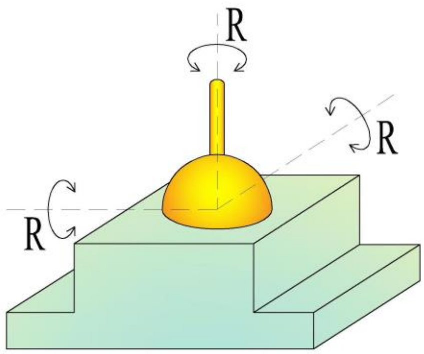
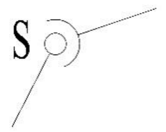
Figure 3.22. Use of R and C joints in the kinetic umbrella design
(Source: Korkmaz, 2005)

3.5.1.5. Spherical (Globular) Pair

A *spherical pair* is defined as a “pair for which the degree of freedom is three and that allows independent relative rotations about three mutually orthogonal axes” (IFToMM, 2014, no.1.2.15). It can thus be concluded that 3 remaining motions consisting of translations are restricted. It is denoted by S. Kinematic properties of spherical pairs are shown in Table 3.7. The use of the spherical pair is illustrated with the arm mechanism of a kinetic sculpture *Poseable Arm* design by Rob Ives (2019).

Another example of the spherical pair is shown in Figure 3.23. The spinning of the hula hoop is provided by spherical pair used in the lumbar region of the kinetic sculpture designed by Paul Spooner.

Table 3.7. Kinematic properties of spherical pairs

		Typical Form	**Example**
Symbol	S		
DOF	3		
Contains	RRR		
Relative Motion	Spheric		
Kinematic Representation			

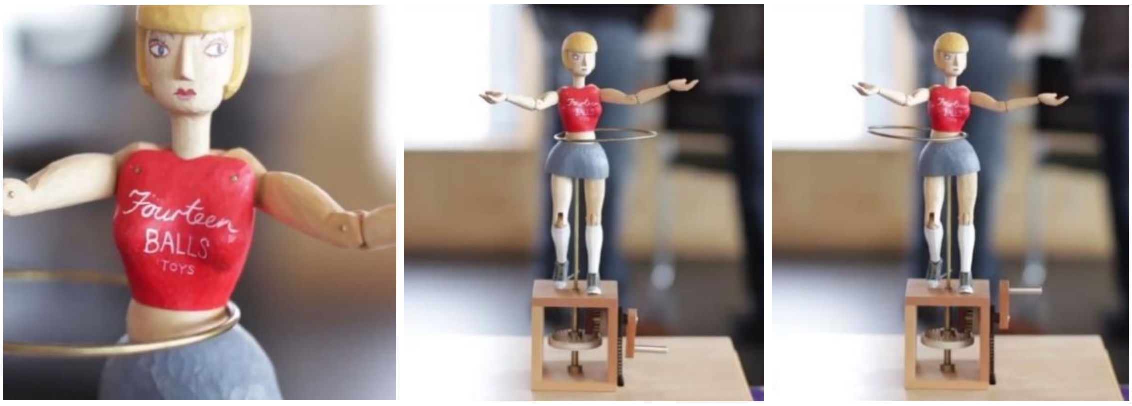
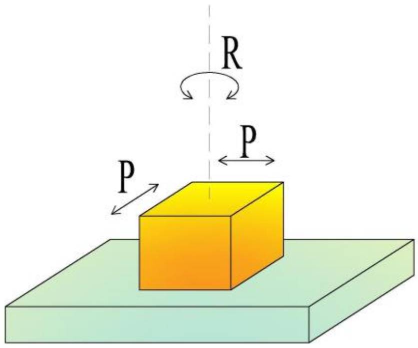
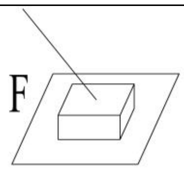


Figure 3.23. Use of spherical joint in *Hula Hooper*
(Source: Pier, 2018)

3.5.1.6. The Flat (Planar) Pair

A *flat (planar)* pair is defined as a "pair for which the degree of freedom is three and that allows relative motion in parallel planes." (IFToMM, 2014, no.1.2.16). It can thus be concluded that the 3 remaining types of motion are restricted. It is denoted by E and comprises RPP motions. Kinematic properties of flat pairs are shown in Table 3.8. However, the use of this pair is quite rare due to its "undisguised form" (Uicker et al., 2003).

Table 3.8. Kinematic properties of flat pairs

		Typical Form
Symbol	F	
DOF	3	
Contains	RPP	
Relative Motion	Planar	
Kinematic Representation		

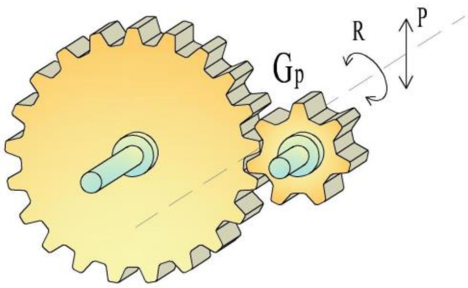
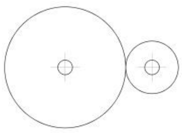
3.5.2. Higher Pairs

A *higher pair* is defined as a "kinematic pair that is formed by point, or line conract between elements." (IFToMM, 2014, no.1.2.10). Every pair apart from lower pairs are stated to be higher pairs (Uicker et al., 2003). Gear and cam pairs will be discussed as the most common higher pairs in the present study.

Gear pair is defined as a "higher kinematic pair formed by successively contacting elements of two links" (IFToMM, 2014, no.1.2.20). It is connecting through their meshing teeth. It is denoted by Gp and has 2 DoF (see Figure 3.24). Gear pair is a higher-order joint, the complex motion is generated between the gear links with the help of meshing teeth (Myszka, 2012). Characteristics of gear pairs are shown in Table 3.9. The joint of the manuel drill is given as an example from daily life (see Table 3.9).

As it is shown in Figure 3.24, four gears are used to acquire the movement through the gear joints in Hoberman's *Transforming Tetrahedron* that is exhibited in Papagayo Children's Museum (2005) in Mexico.

Table 3.9. Kinematic properties of gear pairs

		Typical Form	Example
Symbol	Gp		
DOF	2		
Contains	RP		
Relative Motion	Rotation and translation		
Kinematic Represent			

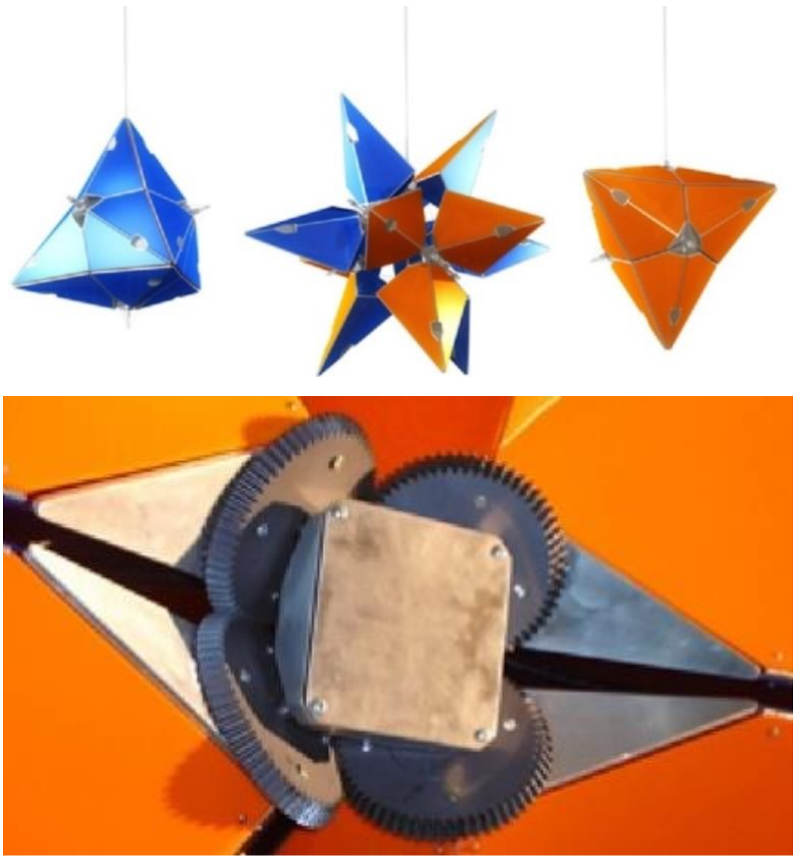
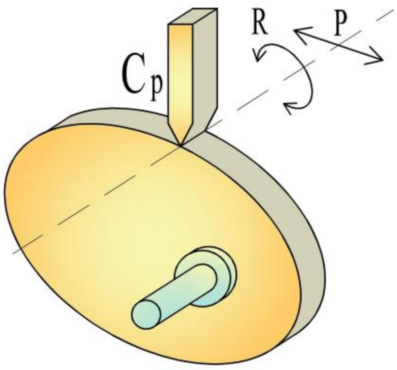
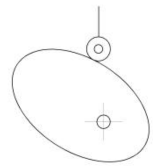


Figure 3.24. Use of gear pairs in *Transforming Tetrahedron*
(Source: Hoberman Associates, 2016)

A *cam pair* is defined as a “kinematic pair consisting of a cam and a follower in direct contact.” (IFFToMM, 2014, no.1.2.17). It is denoted by Cp and has 2 DoF. A cam pair is a higher-order joint, a complex motion of rotation and sliding is revealed between combined links. Characteristics of cam pairs are shown in Table 3.10.

Table 3.10. Kinematic properties of cam pairs

		Typical Form
Symbol	Cp	
DOF	2	
Contains	RP	
Relative Motion	Rotation and translation	
Kinematic Represent		

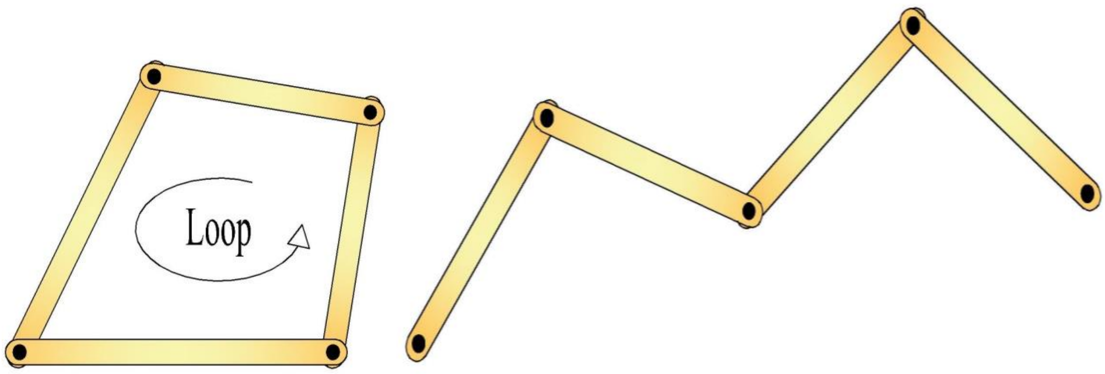
Higher and lower pairs have their own advantages and disadvantages. The reduction of the number of components used in a mechanism is an advantage of higher pairs while their contact stresses are unpreferable for power mechanisms in which high magnitude forces are transmitted.

3.6. Kinematic Chains and Kinematic Inversions

The combination of links and pairs with no determined frame (base link) is called a *kinematic chain* (Uicker et al., 2003).

Kinematic chains are a formation of movable links that are connected with joints. Kinematic chains are used in examinations of the interconnection system and mobility of a mechanism.

Kinematic chains can be categorized as open and closed-loop chains. A kinematic chain is referred to as a closed-loop chain in case all of the links are connected with a minimum of 2 other links (Uicker et al., 2003). A basic representation of a four bar closed-loop kinematic chain is shown in Figure 3.25.(a). Open chains are those that comprise at least one link with only one joint. A basic representation of a four-link open kinematic chain is shown in Figure 3.25.(b).



(a) (b)

Figure 3.25. Kinematic chains
(a) Closed-loop kinematic chain (b) Open kinematic chain

Scales and seesaws are examples of open chains. Several open kinetic sculptures are based on principles of equilibrium. Numerous mechanisms with open kinematic chains are designed by Alexander Calder who is known mostly with his kinetic sculptures and toys. As shown in Figure 3.26, different abstract geometrical shapes in monary and binary links connected with kinematic pairs allow rotary motions. The sculpture hangs from a single point of the ceiling. The links turn around with the effect of air circulation in a very smooth and balanced way. This equilibrium is carefully allowed by the arrangement of center of gravity of the whole assembly.

An example of closed-loop kinematic chain is the origami octagon star (ninja star) with an anonymous shape that is reproduced by the author in different color patterns (see Figure 3.27) Eight links are connected with only prismatic joints to each other to reveal a closed-loop kinematic chain. The shape of the star is formed by manually sliding of the links towards each other.

A kinematic chain including a fixed link (frame) is referred to as a mechanism. A basic representation of a four bar closed-loop mechanism is shown in Figure 3.28.

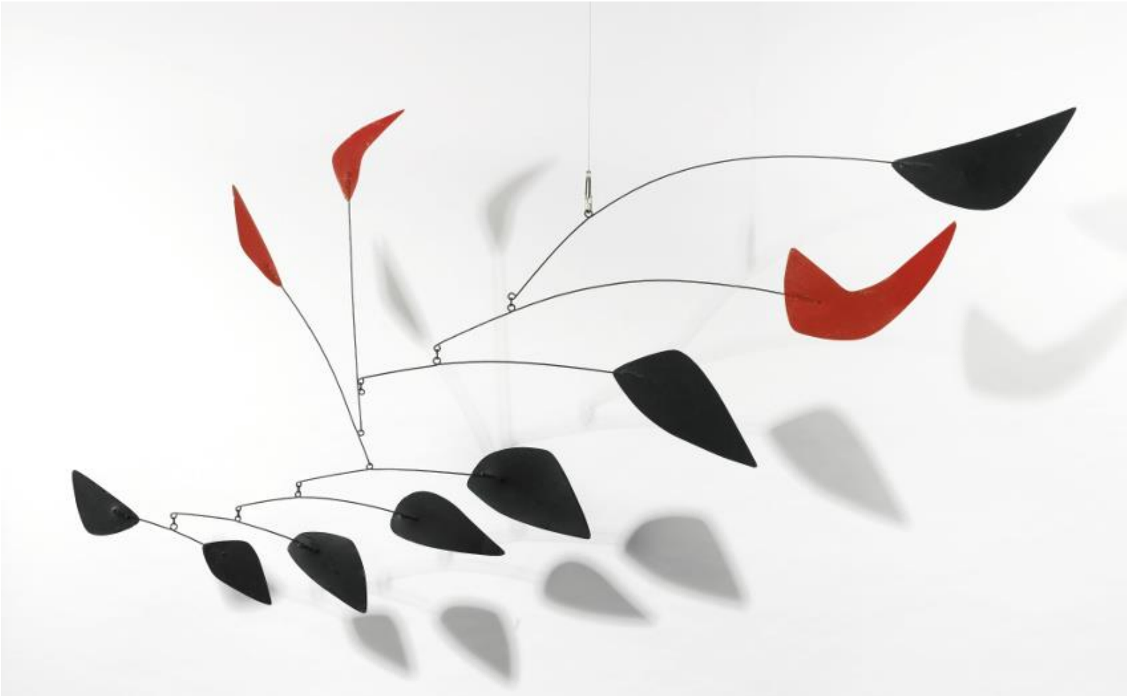


Figure 3.26. Open kinematic chain design in kinetic sculpture
(Source: Sotheby’s, 2020)

Figure 3.27. Closed-loop kinematic chain in origami octagon star
reproduced and drawn by author

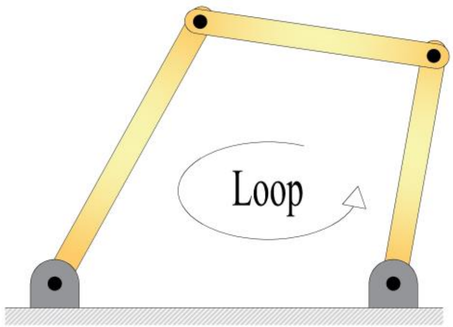


Figure 3.28. Closed-loop mechanism

Kinematic inversions are procedures to examine relative motion of links in kinematic chains with respect to a suppositional frame in place of the existing frame (Söylemez, 2000). Dramatic change in absolute motion can occur where no change in relative motion is observed in the process. Generation of new mechanisms and analyses of existing mechanisms are enabled by kinematic inversions. As it is shown in Figure 3.29, derivations of three other four-bar mechanisms are based on an original four-bar mechanism. These are crank-rocker, double-crank and double-rocker four-bar mechanisms. The crank which is capable of a rotation of 360°, the rocker which is oscillating and the coupler which is not connected to the base link and the base link that can be fixed or grounded are shown in Figure 3.29.

The relationship between link lengths of a four bar linkage and their movements (rotatability) is predicted by *the Grashof condition* (Norton, 2004). A four-bar linkage with at least one link that is capable of making a full revolution with respect to the ground plane is called a Grashof linkage (Norton, 2004). Grashof condition for 4-bar mechanisms:

$$s + l \ \leq \mathrm{p} + \mathrm{q}$$

$s = the\ shortest\ link$

$l = the\ longest\ link$

$p = the\ lenght\ of\ the\ remaining\ link$

$q = the\ other\ remaining\ link$

Analyses of the formula in two conditions ($s + l < p + q\ and\ s + l = p + q$) are revealed in the current section. Four kinematic inversions of which 3 are independent inversions of a given linkage with respect to the Grashof equation is shown in Figure 3.29.

Condition 1: $s + l < p + q$ possibly generates 3 linkage types (crank-rocker, double-rocker and double-crank). A crank-rocker mechanism is generated in case the shortest link (s) is adjacent to the fixed link (q or l), resulting with one link (s) that make a full rotation while another link (p) oscillates (see Figure 3.29.(a) and Figure 3.29.(b)). A double-rocker mechanism is generated in case the shortest link (s) is opposing the fixed link, resulting with two oscillating links (l and q) and one rotating shortest link (s) (see Figure 3.29.(c)). A double-crank mechanism is generated in case the shortest link (s) is fixed, resulting in two links (l and q) making full rotations (see Figure 3.29.(d)).

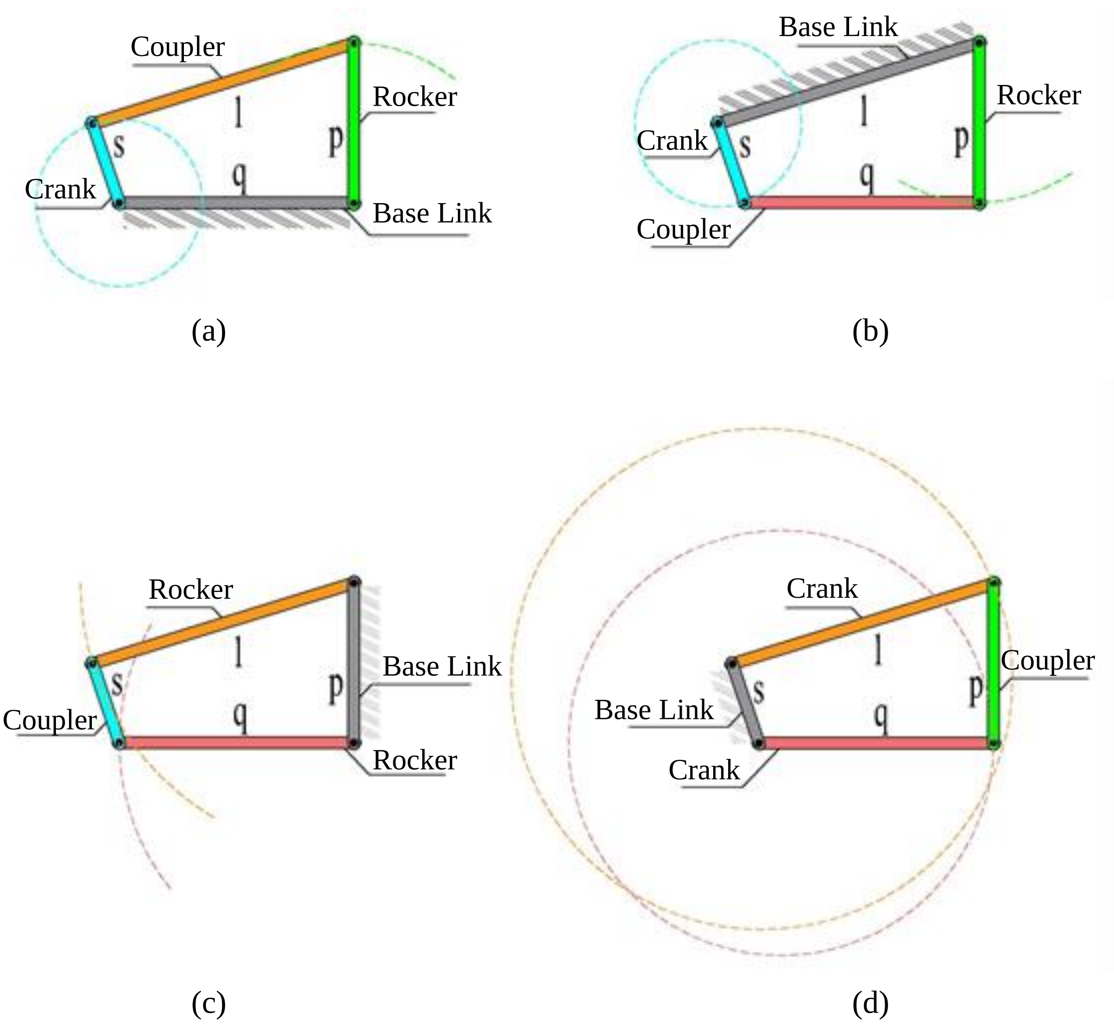


Figure 3.29. Kinematic inversions of the Grashof four-bar linkage
(a) A crank-rocker mechanism (b) A crank-rocker mechanism (c) A double-rocker mechanism (d) A double-crank mechanism

Condition 2: $s + l = p + q$. For example, a parallelogram mechanism with equal parallel link lengths is generated by links (s and p) that make full rotations (see Figure 3.30).

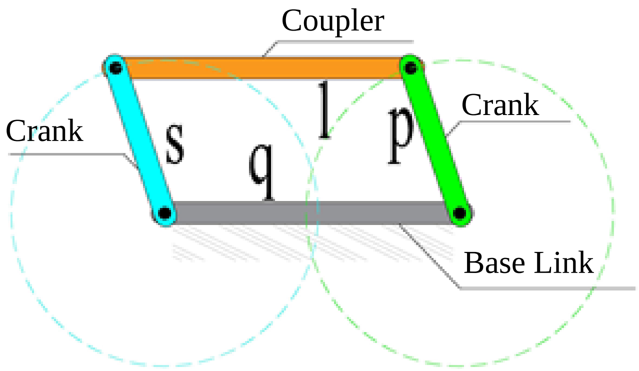


Figure 3.30. Parallelogram mechanism

In cases $s + l > \mathrm{p} + \mathrm{q}$, no link will be able to make a complete revolution. Every link except the base link will oscillate (see Figure 3.31).

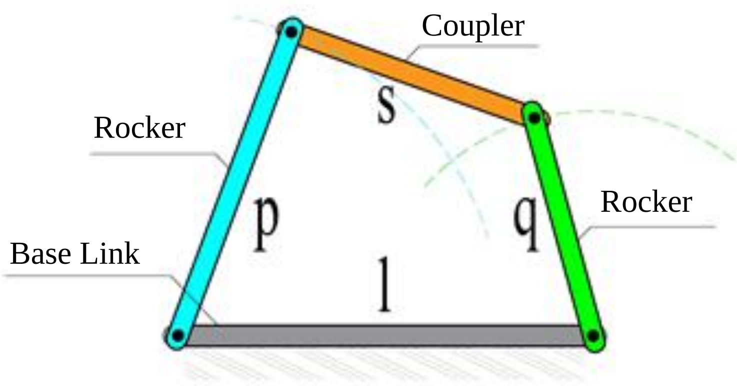


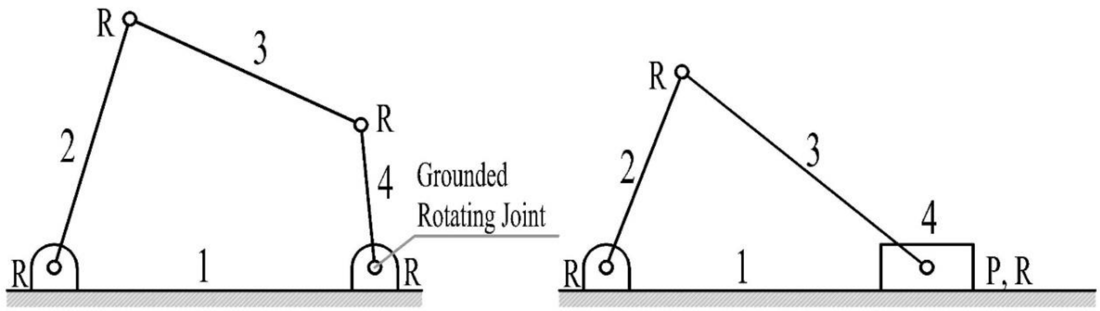
Figure 3.31. Double-rocker mechanism

3.7. Kinematic Diagram

Kinematic diagrams are simple, schematic and scaled representations of a mechanism's overall geometry that consist of links and joint types.

Notation of the frame link and mobile links is essential for the kinematic diagram to be clear (Norton, 2004). Binary links of any form are represented by a line between two joints in a kinematic diagram. The solidity of a link such as ternary and quaternary links is shown by shading or crosshatching. A kinematic diagram is supposed to be properly scaled with respect to the original mechanism. Joints are notated with letters where links are numbered starting from the base link number 1 in kinematic diagrams.

Kinematic diagrams of four-bar and slider-crank mechanisms are shown in Figure 3.32. Both mechanisms contain 4 links. The four-bar mechanism's links are connected with 4 revolute joints (see Figure 3.32.(a)) whereas the slider-crank is connected with 3 revolute joints and 1 prismatic joint (see Figure 3.32.(b)). The links are sequentially denoted with numbers and joints are shown with symbols of their motion. Generally fixed link is denoted as link 1.



(a) (b)

Figure 3.32. Kinematic diagram examples
(a) A four-bar mechanism (b) A slider-crank mechanism

Choe U-Ram used kinematic diagrams in his wing shaped mechanism's design process. The artist’s sketching including the kinematic diagrams are shown in Figure 3.33.

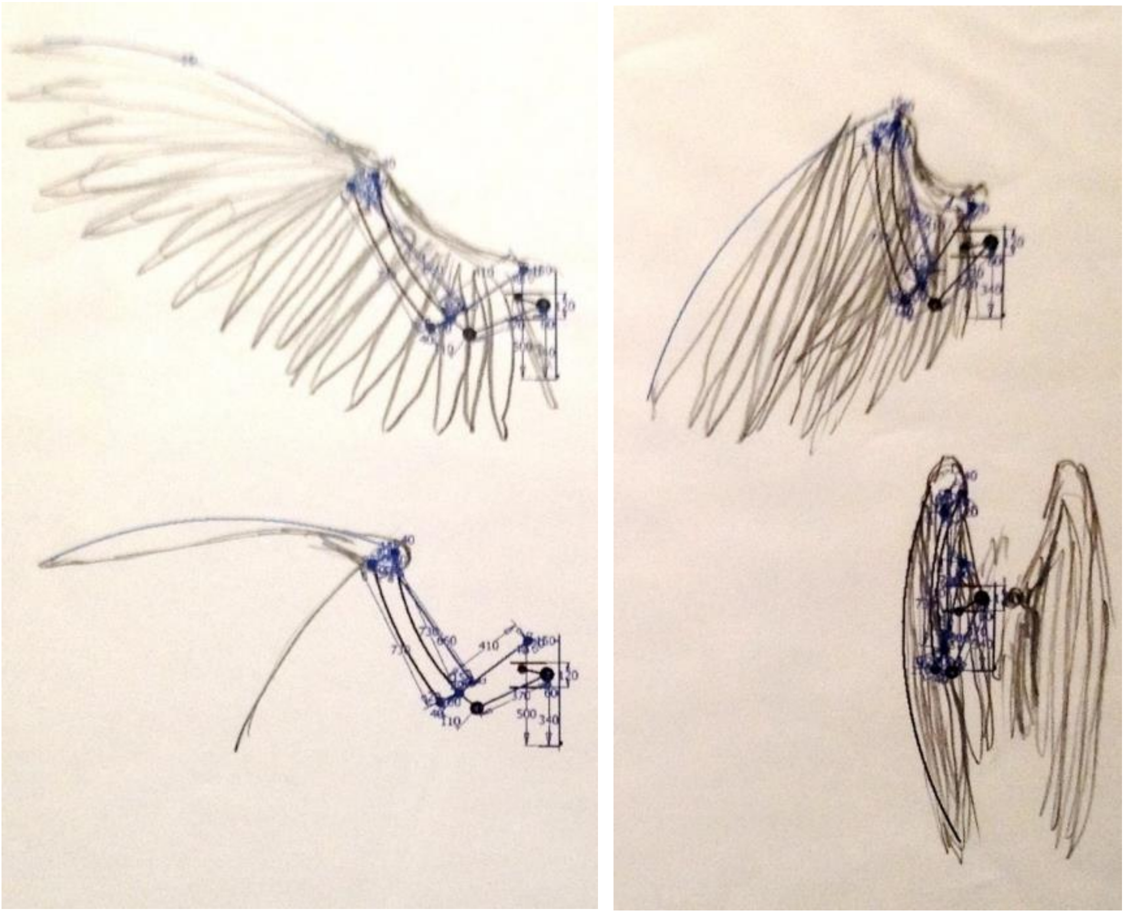
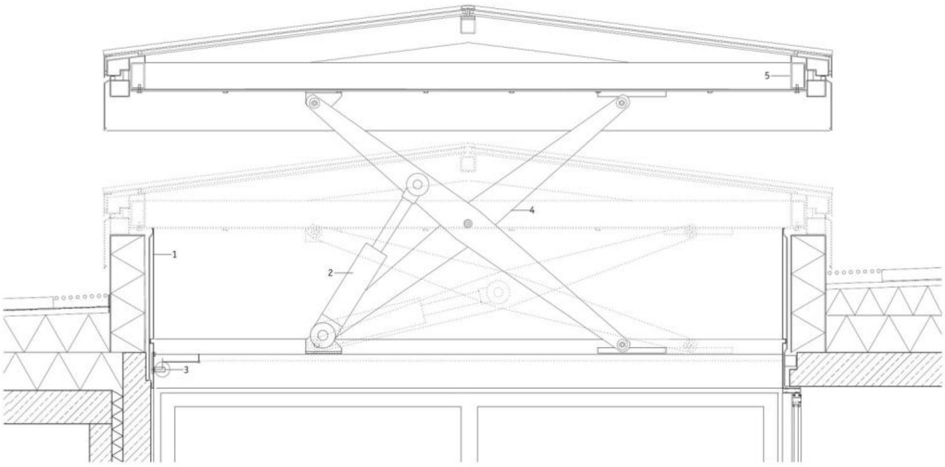


Figure 3.33. Use of kinematic diagram in kinetic sculpture drawings by Choe U-Ram, from his exhibition, *Anima* (2013), in İstanbul

The photo and drawing of elevating skylights over the interior patios of the Rebgaässli Housing Development building in Allschwil that is built by Amrein Giger Architecten in 2004 is shown in Figure 3.34 (Schumacher, Schaeffer, & Vogt, 2012). Kinematic diagram of a mechanism that is required to open and close a ceiling window is shown in Figure 3.35. Folding doors are one of the frequently used movable systems in architecture. The kinematic diagram and technical drawings (plan, section, elevation) of a 300x300 cm. folding door opening into two sides controlled by two points using a motor is shown in Figure 3.36.

Elevating skylights over the interior patios



Section

Figure 3.34. Skylight detail of *Rebgaässli Housing Development* building (Source: Schumacher et al., 2012)

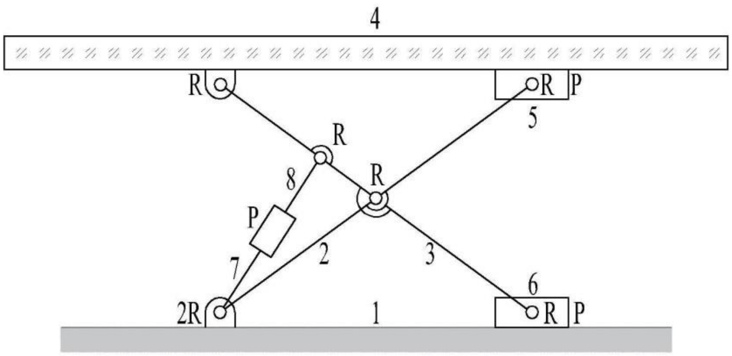


Figure 3.35. Kinematic diagram of a ceiling window mechanism

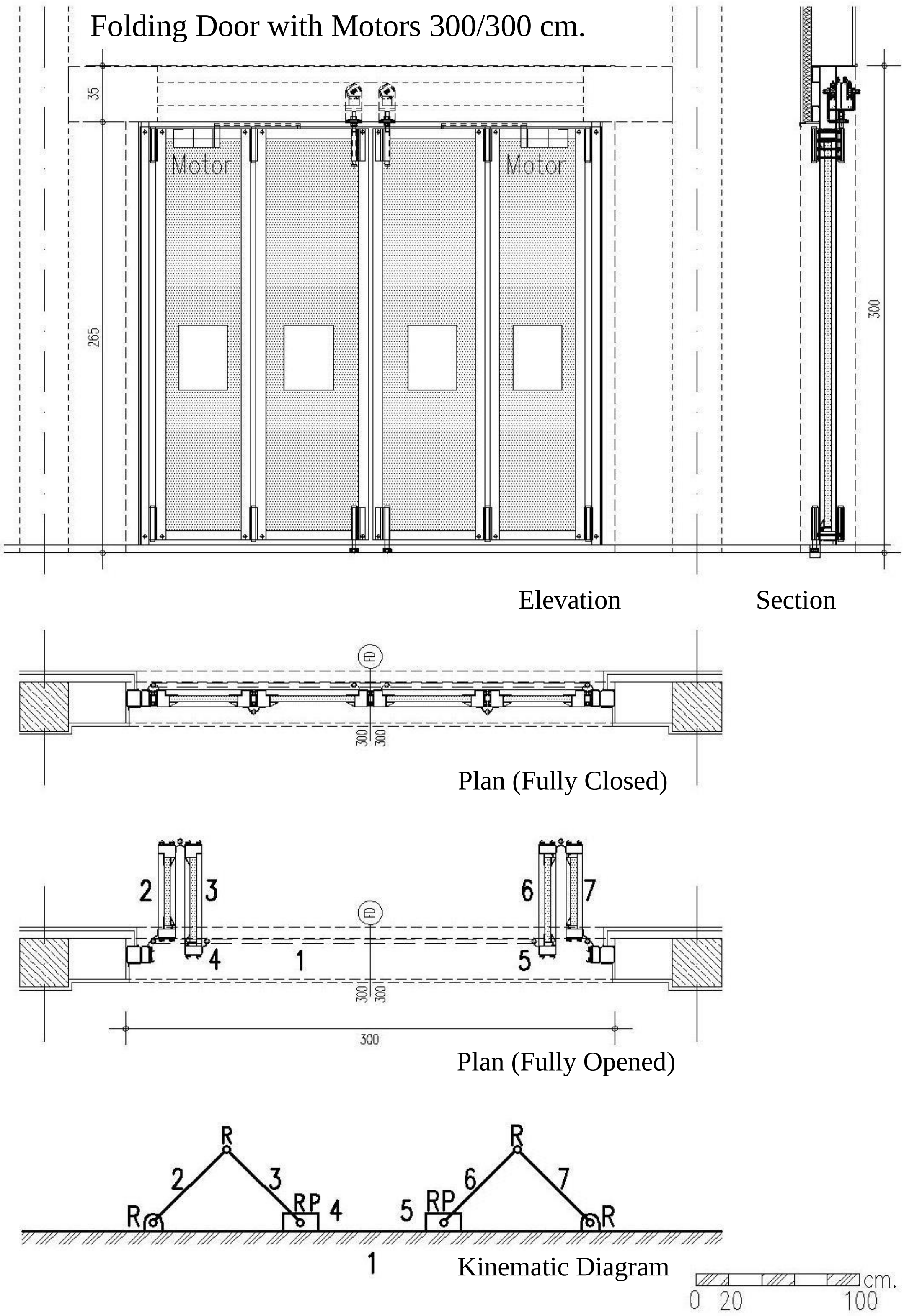


Figure 3.36. Drawings and the kinematic diagram of a folding door

3.8. Mobility (DoF)

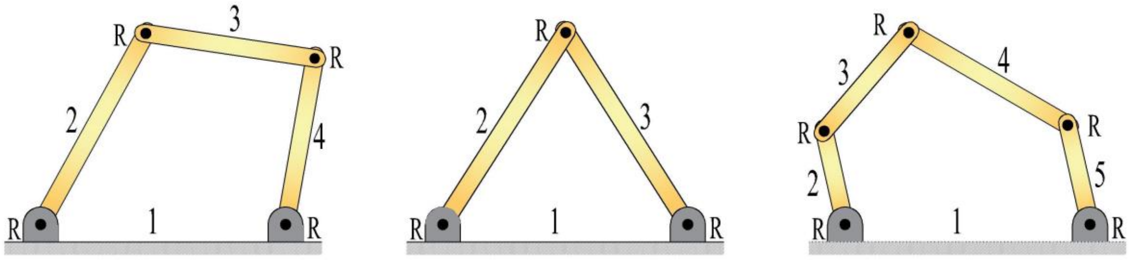
Mobility is the “number of independent variables that must be considered for input motion” (IFToMM, 2014, no.1.3.11). A body in the 3-dimensional space is capable of generating 6 types of motion: 3 independent translations and 3 independent rotations. The degrees of freedom (DoF) of a mechanism depend on the number and design of links and joints of a mechanism. The number of actuators required for a mechanism to work is revealed by mobility analysis (Myzska, 2012). Mobility is neither affected by these operators (motor or manual) nor by the material of the links, the number of teeth of a gear, the velocity, accelaration, force and stress of the mechanism.

Mobility analyses are an essential part of mechanism design. *Degrees of freedom (DoF)* or *mobility* which is denoted by M is the main structural parameter of a mechanism design and analysis.

If the mechanism has $M=1$ means, the mechanism can be operated by a single actuator and generates the same motion in response to any affecting force. Most of the mechanisms are designed to have 1 DoF.

If $M \leq 0$, the design is *immobile*. Despite the movable designs with kinematic pairs, every possible motion is restricted by the connection type of the pairs. A system with a DoF of 0 or less is called as a *structure* or *locked mechanism.*

A mechanism with *multi-DoF* occurs when $M \geq 2$, which means various motions, can be generated. The mechanism can thus be operated by two or more actuators. Two input motions are required for the production of constrained motion in a mechanism with 2 DoF. Open-loop mechanisms designed with purposes of reaching and positioning, such as robotic arms and backhoes contain mechanisms with multi-DoF (Myzska, 2012). Intelligent systems provide predictably variable output motions in multi-DoF mechanisms driven by as many actuators as the number of DoF values. Since the main objective of art and sculpture designs are shape alteration or aesthetic meaning rather than usability, multi-DoF mechanisms are also designed by artists. A 1 DoF with 4 binary links connected with 4 revolute joints (Figure 3.37.(a)), a structure with 3 binary links connected with 3 revolute joints (Figure 3.37.(b)) and a 2 DoF mechanism with 5 binary links connected with 5 revolute joints (Figure 3.37.(c)) are shown in Figure 3.37.



$n = 4 \;\; j_p = 4 \;\; M = 1$ (a) $n = 3 \;\; j_p = 3 \;\; M = 0$ (b) $n = 5 \;\; j_p = 5 \;\; M = 2$ (c)

Figure 3.37. The mobility of two mechanisms and a structure
(a) A single DoF mechanism (b) A structure/ locked mechanism (c) A multi-DoF mechanism

General mobility criterion with respect to the topology of an assembly is generated by Gruebler (1921) and Kutzbach (1929) (Phillips, 1984; Chen, 2003). The *Gruebler and Kutzbach* mobility formula is:

$$M = \lambda\,(n-1) - \sum_{i=1}^{\lambda-1} (\lambda - i)\, j_i$$

Where M is the mobility, λ is the number of independent motions in space or subspace ($\lambda = 2,3,4,5,6$), n is the total number of links in a mechanism, $(n-1)$ is the number of moving links, j_i is the number of i DoF joints.

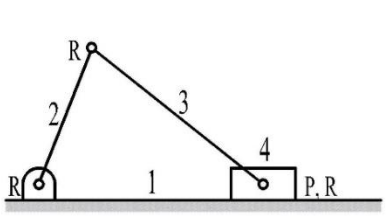
Spatial mechanisms have 6 possible independent movement ($\lambda = 6$) whereas planar and spherical mechanisms are capable of generating 3 independent movements ($\lambda = 3$). The mobility formula for *spatial mechanisms* is:

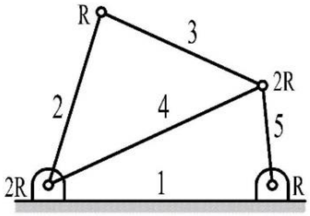
$$M = 6(n-1) - 5j_1 - 4j_2 - 3j_3 - 2j_4 - j_5$$

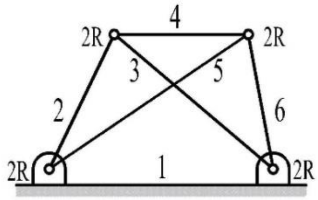
The mobility formula for *planar* and *spherical mechanisms* is:

$$M = 3(n-1) - 2j_1 - j_2$$

Where j_1 is the total number of 1 DoF joints (revolute, prismatic or screw joints), j_2 is the total number of 2 Dof joints (cam, gear, cylindrical joints, etc), j_3 is the total number of 3 DoF joints (spherical, flat joints, etc), j_4 is the total number of 4 DoF joints and j_5 is the total number of 5 DoF joints. The examination of several mechanisms and structures with respect to the given equations is shown in Figure 3.38.







$n = 4 \;\; j_1 = 4 \;\; M = 1$

$M = 3(4-1) - 2x4 = 1$

(a)

$n = 5 \;\; j_1 = 6 \;\; M = 0$

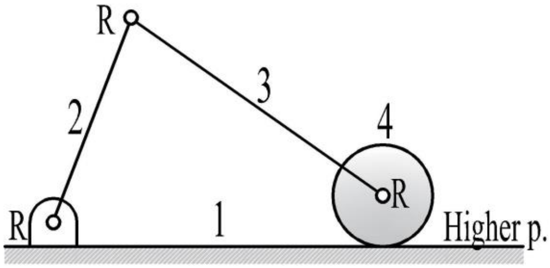
$M = 3(5-1) - 2x6 = 0$

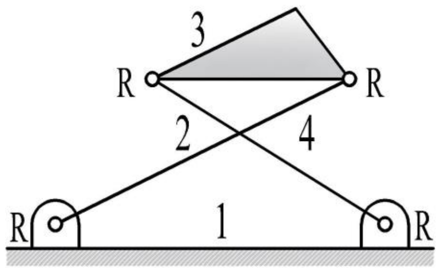
(b)

$n = 6 \;\; j_1 = 8 \;\; M = -1$

$M = 3(6-1) - 2x8 = -1$

(c)





$n = 4 \;\; j_1 = 3 \;\; j_2 = 1 \;\; M = 2$

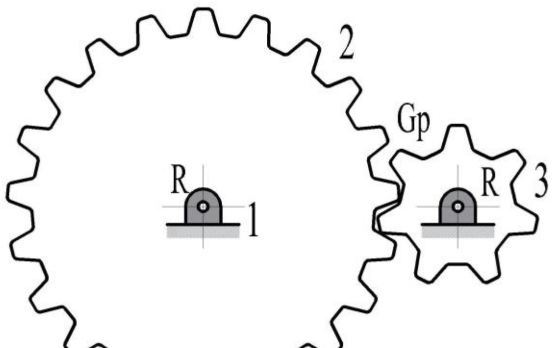
$M = 3(4-1) - 2x3 - 1 = 2$

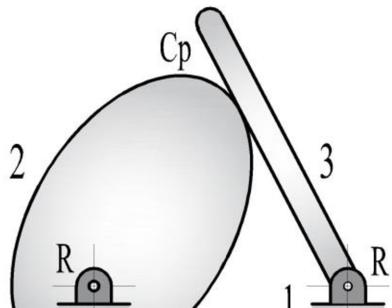
(d)

$n = 4 \;\; j_1 = 4 \;\; M = 1$

$M = 3(4-1) - 2x4 = 1$

(e)





$n = 3 \;\; j_1 = 2 \;\; j_2 = 1 \;\; M = 1$

$M = 3(3-1) - 2x2 - 1 = 1$

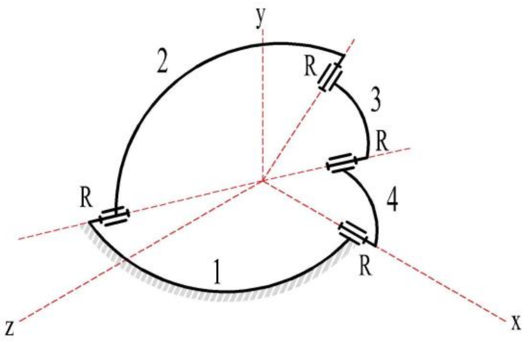
(f)

$n = 3 \;\; j_1 = 2 \;\; j_2 = 1 \;\; M = 1$

$M = 3(3-1) - 2x2 - 1 = 1$

(g)

Figure 3.38. (cont. on next page)

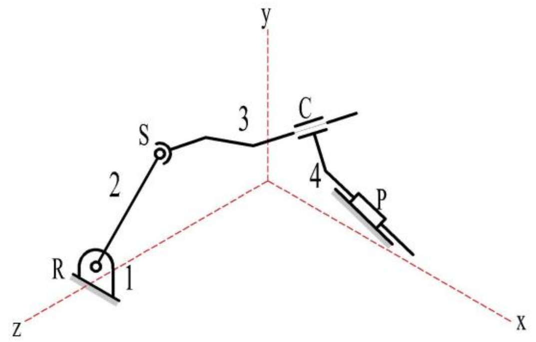


A spherical 4-bar mechanism

$n = 4 \quad j_1 = 4 \quad M = 1$

$M = 3(4 - 1) - 2x4 = 1$

(h)



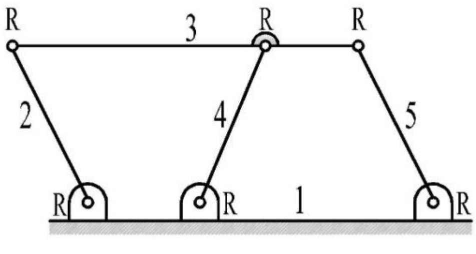
A spatial mechanism

$n = 4 \quad j_1 = 2 \;\; j_2 = 1 \;\; j_3 = 1 \; M = 1$

$M = 6(4 - 1) - 5x2 - 4x1 - 3x1 = 1$

(i)

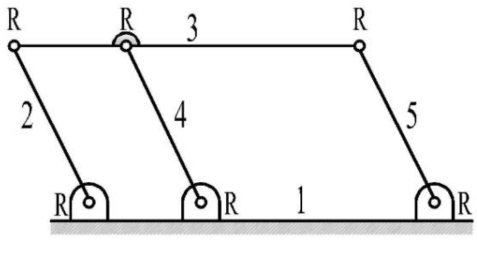
Figure 3.38 (cont.). Mobility analyses of several mechanisms
(a) A 1 DoF slider-crank mechanism
(b) A five-bar structure
(c) A six-bar structure
(d) A 2 DoF mechanism with a higher pair
(e) A 1 DoF four-bar mechanism
(f) A 1 DoF gear mechanism
(g) A 1 DoF cam and follower mechanism
(h) A 1 DoF spherical four-bar mechanism
(i) A 1 DoF spatial four link mechanism



$n = 5 \quad j_1 = 6 \;\; M = 0$

$M = 3(5 - 1) - 2x6 = 0$

(a)



$n = 5 \quad q = 1 \quad j_1 = 6 \;\; M = 1$

$M = 3(n - 1) - 2\, j_1 + q$

$M = 3(5 - 1) - 2x6 + 1 = 1$

(b)

Figure 3.39. Determination of excessive links
(a) A five-bar structure
(b) A 1 DoF five-bar mechanism

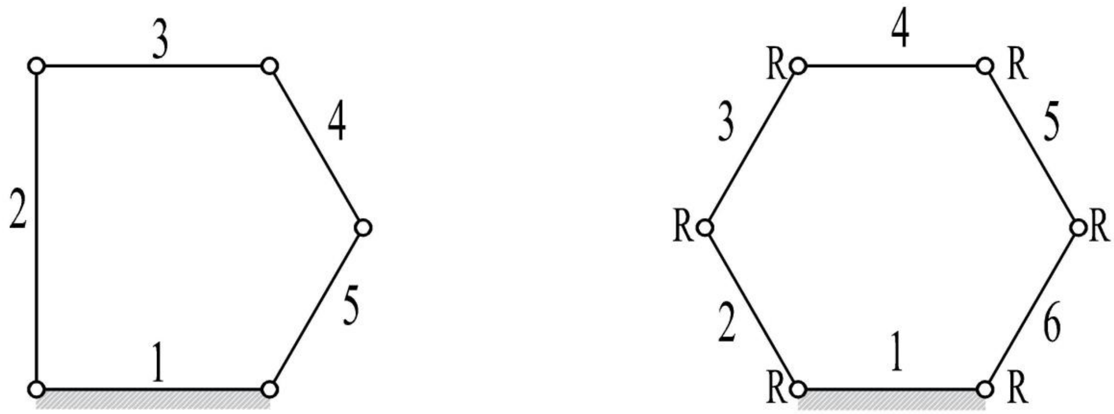
Mobility analyses of different mechanisms are shown in Figure 3.39. It is shown in Figure 3.39.(a) that the system is immobile in case link number 4 is connected to the mechanism, thus no effect on motion is expected. On the other hand, geometric condition of parallelogram mechanisms where links number 2, 4 and 5 have equal lengths and links number 1 and 3 have equal lengths and are parallel is shown in Figure 3.39.(b). No effect of link number 4 on motion is generated. Links that have no effect on the final motion are called excessive link. Excessive links are symbolized by q and added to the formula as the q parameter (see Figure 3.39.(b)). Excessive links are used for their contribution to the strength of the mechanism or the balance of the motion as well as for aesthetic reasons.

An object that has 3 DoF, can either be controlled by 3 actuators or turned to a mechanism in which M=1 (can be controlled by single actuator) by changing link or joint numbers or connection types. This decision is made with respect to the design project. As an example, a planar mechanism with 4 bars and 4 revolute joints has 1 DoF, where 5 bars and 5 revolute joints has 2 DoF (see Figure 3.40.(a)) and in the case of 6 bars and 6 revolute joints, the mechanism has 3 DoF (see Figure 3.40.(b)).

Six-bar mechanisms, by changing link types and increasing joint numbers, can be constructed as mechanisms with 1 DoF as seen in the Steffenson and Watt mechanisms. Steffenson and Watt chains consist of 2 ternary and 4 binary links connected with 7 single-DoF joints. Ternary links are directly connected to each other with a joint in the *Watt chain* (see Figure 3.41.(b)) whereas ternary links are not directly connected to each other in the *Steffenson chain* (see Figure 3.41.(a)). Mobility analyses of the Steffenson and Watt chains are shown in Figure 3.41.

3.9. Types of Mechanisms

Mechanisms are categorized with respect to several variables that put emphasis on various similarities and differences among them. Various categorization types that are based on the number of links used, number and type of joints used or DoF values of the mechanism are revealed in literature. The current study examines mechanism categories with respect to the *pair variable* (linkage, cam, gear mechanisms) and the *motion space* (planar, spherical, spatial mechanisms).



$n = 5 \quad j_1 = 5 \quad M = 2$

$M = 3(5-1) - 2x5 = 2$

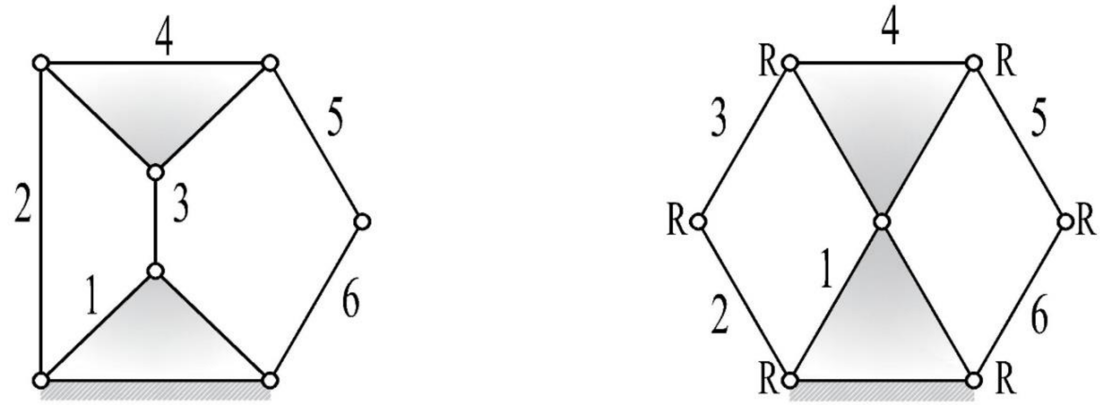
(a)

$n = 6 \quad j_1 = 6 \quad M = 3$

$M = 3(6-1) - 2x6 = 3$

(b)

Figure 3.40. Mobility Analyses of some multi-DoF mechanisms
(a) A 2 DoF five-bar mechanism
(b) A 3 DoF six-bar mechanism



$n = 6 \quad j_1 = 7 \quad M = 1$

$M = 3(6-1) - 2x7 = 1$

(a)

$n = 6 \quad j_1 = 7 \quad M = 1$

$M = 3(6-1) - 2x7 = 1$

(b)

Figure 3.41. Mobility analyses of Steffenson and Watt chains
(a) A Steffenson chain (6-bar, 1-DoF)
(b) A Watt chain (6-bar, 1-DoF)

3.9.1. Mechanism Types with Respect to the Kinematic Pairs

Mechanisms are categorized by Releaux, for the first time with a scientific approach to mechanisms, in 6 titles: screw chain, gear chain, crank chain, cam chain, ratchet chain, pulley chain. Releaux's classification system, which is partly based on joint types, is applicable to simple mechanisms whereas quite insufficient results are inevitable with today's complex mechanisms (Söylemez, 2000). Three types of mechanisms that are most commonly used in art and architecture with respect to the pair variable are analyzed in this section.

3.9.1.1. Linkages

Systems, design and terminology of linkages are forestated in the current study. Linkages are advantageous in terms of providing a considerable number of options for the resulting output motion such as linear, nonlinear, circular or complex motion (Pucheta & Cardona, 2008). Linkages are the most widespread type of mechanisms that are applied in architecture. Since rigid bars are durable against heavy loads, lower pairs and bar links can be used as well as plate links that provide convenient covering can be used in architectural design.

Bar mechanisms are generally named after the number of bars they carry. Four-bar linkages, five-bar linkages, six-bar linkages can be given as examples. Lever and scissors are the most well-known and commonly used 2-bar linkages. Assemblies of several scissor linkages form four-bar loops. Some configurations of a scissor-hinge structure generated as a planar assembly of scissor linkages used for a transformable exhibition space's adaptive roof design proposal are shown in Figure 3.42 (Akgün, 2010).

The four-bar linkage, which has a frame and three moving bars that are connected by revolute joints, is the most useful and simplest closed-loop linkage. Another effective option is the slider-crank mechanism which is also a four link mechanism. In cases that requirements of the design are not fulfilled by a 1 DoF four-link mechanism, a 1 DoF six-bar linkage (either a Watt chain or a Stephenson chain) which are well-known by virtue of their common use, is mostly used (Erdman, Sandor, & Kota, 2001).

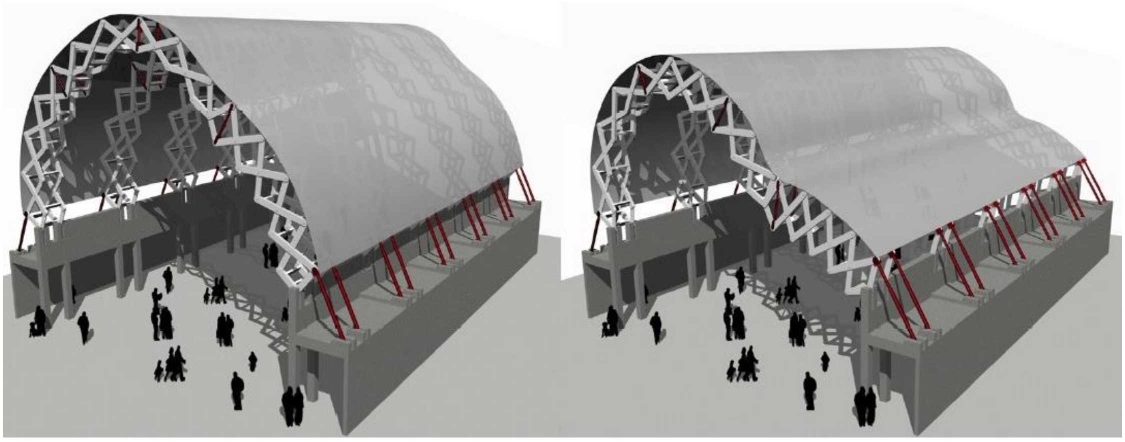


Figure 3.42. Scissor linkages connected in the application proposal of a planar scissor-hinge structure for an adaptive roof
(Source: Akgün, 2010)

Single DoF linkages can also be designed as a combination of several loops. For example, Ten Fold Engineering's relocatable Tree House that can fold to smaller size through deployable structures not only makes transportation far less difficult but also creates a smaller space for storage (see Figure 3.43). The planar linkages consist of bars and revolute joints. They are 1 DoF mechanisms that are driven by a single actuator (Ten Fold Engineering, 2018).

The modular approach of designers provide them versatility and flexibility. As shown in Figure 3.44, three different applications (a bridge structure and structural beams for a roof) of a single linkage can be used for deployable structures on three different buildings. Various selections of the fixed bar reveal dramatically different output motions. Various applications of identical linkages thus serve several purposes.

Figure 3.43. Linkage design of the *Tree House* project in fully closed, semi open and fully open positions
(Source : Ten Fold Engineering, 2017)

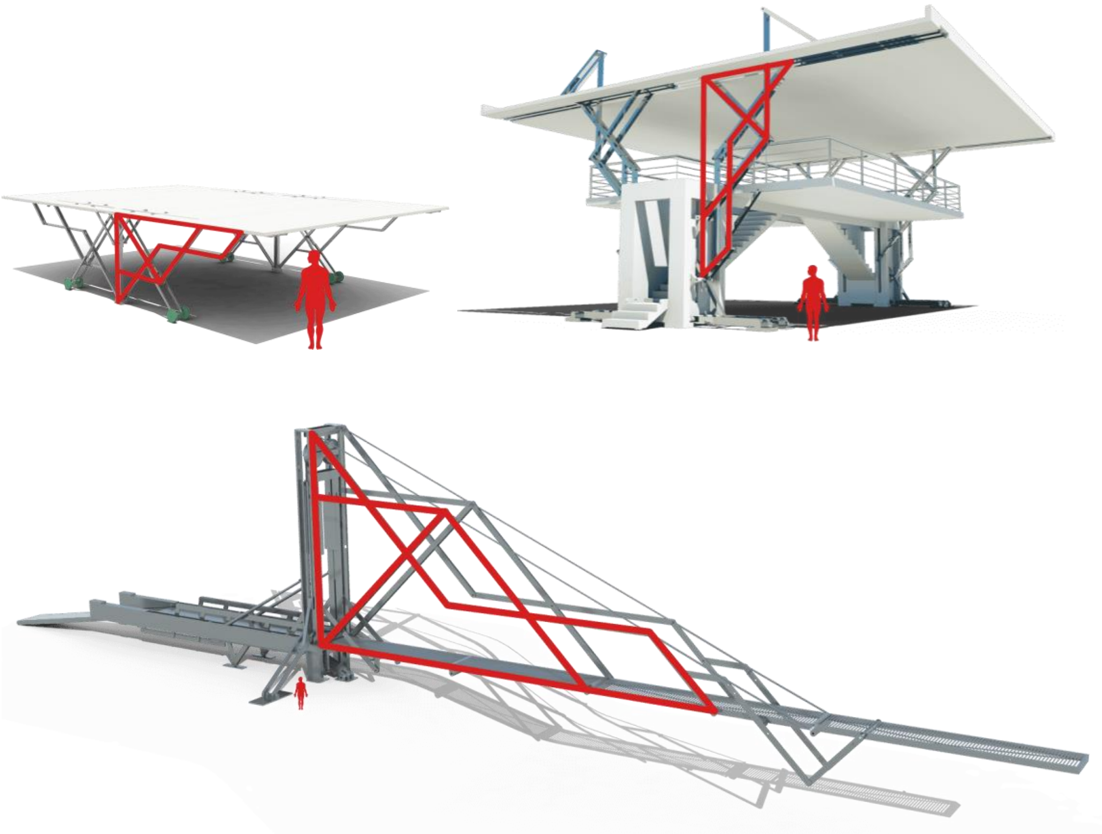


Figure 3.44. Various architectural applications of a single linkage
(Source: Ten Fold Engineering, 2018)

Several counterbalanced folding linkages designed for various architectural applications by Ten Fold Engineering are shown in Figure 3.45. Binary, ternary and quaternary links that are connected with revolute joints generate various mechanisms such as 4-bar 5-bar and 6-bar linkages. All of these mechanisms are capable of full closure and opening on a plane (Ten Fold Engineering, 2018).

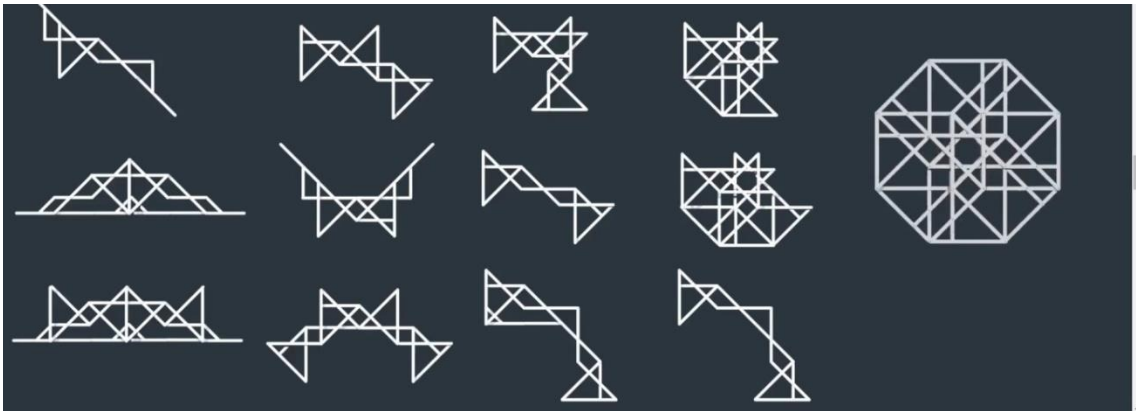


Figure 3.45. Several linkages designed for architectural applications
(Source: Ten Fold Engineering, 2018)

3.9.1.2. Cam Mechanisms

Mechanisms carrying at least one cam are stated as *cam mechanisms* (IFToMM, 2014, no.1.3.39). Cams are driver links that transmit motion generally by rotating at a constant speed to a connected follower that generates a predetermined periodic output motion. Type selection of the cam mechanisms is based on the purpose, timing, and nature of motion as well as economic reasons.

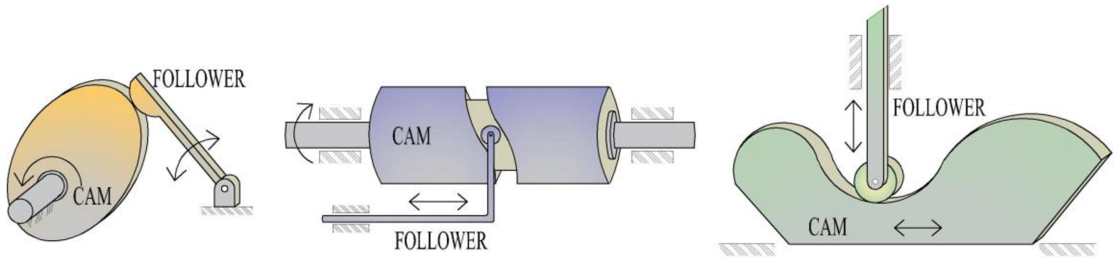
Cams can be designed in various shapes including circles. The follower is stationary in case a circular cam is pivoted right in the center; the cam is thus pivoted off-center to obtain motion. Such cams are called eccentric cams. Followers can be positioned along a direction passing through the cam rotation center of the cam or with an offset.

The classification of cam-follower mechanisms are based on several properties. They can be classified with respect to the *cam type* as disk cam, cylindrical cam, wedge cam, etc. They can be classified with respect to the type of the *following motion* either as translating or oscillating. They can be classified with respect to the *joint closure* type either as force-closed or form-closed. They can be classified with respect to the type of *surface contact of the follower* as a knife-edge follower, a roller follower, a flat-faced follower or a mushroom follower (Söylemez, 2000).

Examples of different cam types (disk cam, cylindrical cam and wedge cam) are shown in Figure 3.46. *A disk (plate) cam* is defined as a “disk that rotates about an axis perpendicular to its plane and drives a follower through contact with its profile” (IFToMM, 2014, no.1.1.16). An example of plate cam, is shown in Figure 3.46.(a). *A cylindrical (barrel) cam* is defined as a “rotating cylinder with a curved groove in its surface or a curved rib on its surface whereby contact is made with a follower” (IFToMM, 2014, no.1.1.18). An example of plate cam is shown in Figure 3.46.(b). *A wedge (translation) cam* is defined as a “cam with a translatory motion having a profile on one side whereby contact is made with a follower (Rao & Dukkipati, 2006, p.78). Translation cams are rarely used. Contrary to other cams that generate rotations, forward and backward movements of the wedge cam generate over and back translation. An example of translation cam is shown in Figure 3.46.(c).

Two types of motion are generated by followers during the movement of the cam: translation or rotation (oscillation). The follower in 3.46.(a) is oscillating whereas the follower in 3.46.(b, c) are translating.

Form or force-closed cam mechanisms are constructed depending on the closure of cam joint. The examples in Figure 3.46 consist of two force-closed cam-follower systems in which either gravity or springs are used as external forces to keep the system in contact with each other (Figure 3.46.(a, c)) The form-closed cam-follower system's follower tracks a predetermined path (generally contact in two points) on the cam, no external force or arrangement is thus required to keep the system together (Figure 3.46.(b)) .



(a) (b) (c)

Figure 3.46. Examples of various cam types
(a) Plate cam (b) Cylindrical cam (c) Wedge (translation) cam

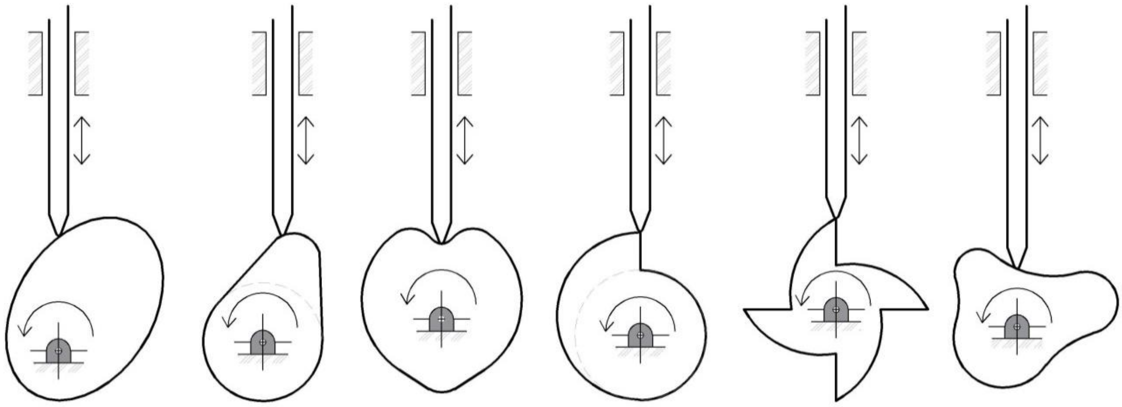
Plate cams are frequently used in automata. Wanda Sowry's automaton design *the Day of the Dead Skeleton Band* in which sound is obtained via moving skeleton parts, is shown in Figure 3.47. The manually operated mechanism is single DoF. Several force-closed plate cams are serially connected to the operator with different angles in order to obtain different follower motion with varying timing of several acts for the models (see Figure 3.47).

Cams are designed in varying shapes and sizes depending on the aimed motion and velocity. Different examples of plate cams are shown in Figure 3.48. During a complete revolution (cycle) of an *elliptical cam*, the follower is stationary for a while and followingly executes a translation movement (rise and fall) in Figure 3.48.(a). The follower in Figure 3.48.(b). is stationary during one half cycle of a *pear-shaped cam*, while it executes a translation movement (rise and fall) during the second half of the

Figure 3.47. Use of various plate cams in the automaton of the
Day of the Dead Skeleton Band
(Source: Sowry, 2017)

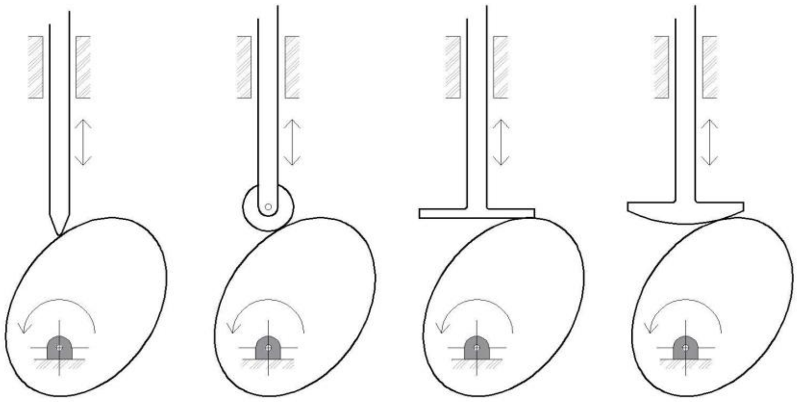
cycle. *Heart-shaped cams* (see Figure 3.48.(c)) provide uniform velocity for followers. A *snail (nautilius) cam* is shown in Figure 3.48.(d). The follower is stationary for a while. The stationary period is then followed by a gradual rising and a sudden drop. Such cams are only unidirectionally rotated. A *four-pinned nautilius cam's* (see Figure 3.48.(e)) one full cycle is corresponded with 4 translation movements and 4 sudden drop of the follower. That is 4 different movements of the follower for each cycle of the cam. An *irregularly-lobed cam* is shown in Figure 3.48.(f). Translation is executed in varying speed by the follower during one cycle of the cam.

Depending on the purpose, different types of followers are selected with respect to their surface contact. Various selections of the follower type for a *plate cam* are shown in Figure 3.49. *Roller followers* (b) are preferred over *knife-edge followers* (a) due to their corrosive characteristic. *Flat-faced followers* (c) are easily stored as they take a smaller place up than *roller followers*. *Mushroom followers* (d), on the other hand, are curved-face versions of *flat-face followers*.



(a) (b) (c) (d) (e) (f)

Figure 3.48. Cam plates in various shapes
(a) An elliptical cam (b) A pear-shaped cam (c) A heart-shaped cam (d) A snail (nautilius) cam (e) A four-pinned nautilius cam (f) An irregularly-lobed cam



(a) (b) (c) (d)

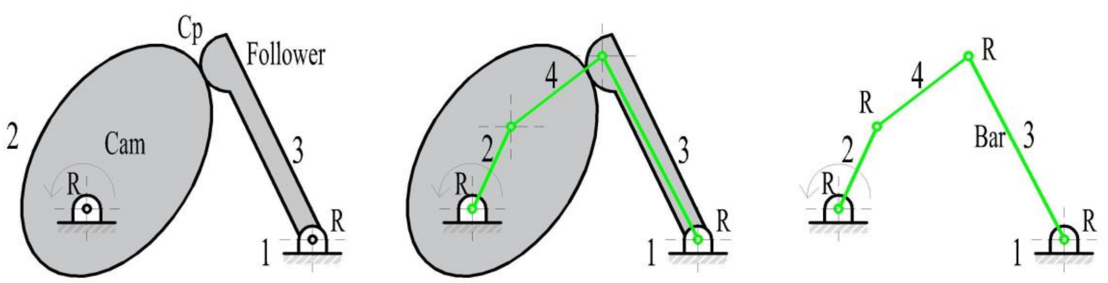
Figure 3.49. Different follower types with respect to surface contact for plate cam
(a) Knife-edge follower (b) Roller follower (c) Flat-faced follower (d) Mushroom follower

Figure 3.50. *Force-closed* plate cams with *roller followers* at the kinetic sculpture, *Bird* (Source: Margolin, 2005)

Cam mechanisms are frequently used in kinetic sculptures as well. For example, force-closed plate cams are connected to roller followers in order to move the wings through cables in Reuben Margolin's the *Bird* (2005) design which is an open loop 7-bar mechanism (see Figure 3.50). The rotation motions of seven cams are transmitted through the oscillating motion of followers.

Linkages, depending on their purposes, can be replaced by cam or gear mechanisms with smiliar motion properties. The linkage transformation of a cam mechanism to a four-bar equivalent schematically is shown in Figure 3.51. The same output (oscillitating motion) is obtained by generation of an equivalent four bar mechanism with respect to the designed cam mechanism. $M = 1$ in the cam mechanism. A four-bar mechanism revealing the same output motion with identical mobility $(M = 1)$ is generated by replacing 1 cam pair (2 DoF) with 2 revolute (1 DoF) joints and a bar put in between.

Cams and linkages, whether combined together or used individually, are frequently used in machines. Both have their advantages and disadvantages. Cams are advantageous in terms of size as they are both smaller and easier to pack whereas linkages are advantageous in terms of affordability and durability. Although linkages are cheaper to produce, they are more difficult to design. Environmental conditions affect cams far more than linkages. Linkages fit better in fast movement with high loads whereas cams are more accurate in terms of motion (Norton, 2004).



$n = 3 \;\; j_1 = 2 \;\; j_2 = 1 \;\; M = 1$

$M = 3(3-1) - 2x2 - 1 = 1$

$n = 4 \;\; j_1 = 4 \;\; M = 1$

$M = 3(4-1) - 2x4 = 1$

(a) (b) (c)

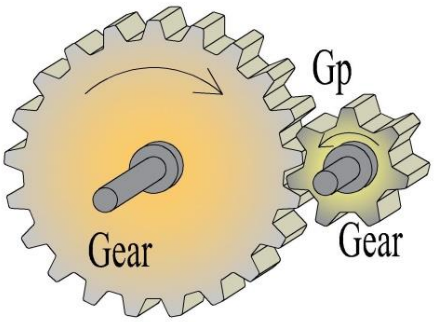
Figure 3.51. Linkage transformation of a cam mechanism to four-bar equivalent
(a) A cam mechanism
(b) Linkage transformation of the cam mechanism
(c) A linkage transformed from the cam mechanism

3.9.1.3. Gear Mechanisms

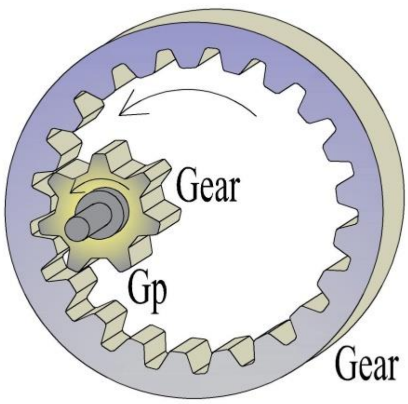
Gear mechanisms are mechanisms which contain at least one gear pair. Gears transmit motion through a process called meshing. Gear teeth that are carried by each gear generate meshing. A *gear tooth* is a “shape on a link or transmission of motion by means of interaction with a corresponding shape of another link” (IFToMM, 2014, no.12.1.29). Gears, which are components meshing through their teeth take part in several function such as affecting the speed, direction, location or angular orientation of a rotational motion, conversion of motion type (rotational to linear and vice versa) (Sclater & Chironis, 2007).

Gears are connected in various positions depending on a predetermined purpose. The internal gear’s teeth are positioned on the inner circle surface while the external gears’s teeth are positioned on the outer circle surface. Internal gears rotate in identical directions while external gears rotate in opposite directions. A gearset is a combination of two gears. Examples of internal and external gearsets are shown in Figure 3.52.

Gear mechanisms are commonly used in a wide range of settings starting from everyday use such as toys and tools to kinetic art and architecture. Kinetic sculptor Bob Potts uses such gear systems in many of his designs. As an example of internal gear use, *Pursuit II*, built in 2009, in which a moving external gear is positioned inside of a stationary outer internal gear is shown in Figure 3.53. Rotating motion is transmitted from gears to links to create the motion of flying birds.



(a)



(b)

Figure 3.52. Two types of gearsets with respect to the teeth position
(a) External gearset (b) Internal gearset

Figure 3.53. Use of Internal gear in the kinetic sculpture, *Pursuit II*
(Source: PottsSculpture, 2011)

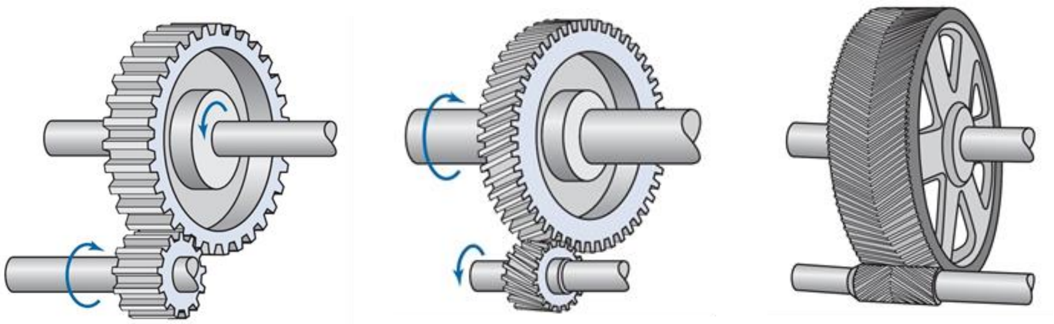
Spur gears, helical gears, herringbone gears, worm gears, rack and pinion, bevel gears are some examples of gear types used in art, architecture and product design. Gears can be circularly designed but they can also be in noncircular shape. The varying velocity ratio on different places of a single gear is provided by noncircular gears. Belt and chain drives which use similar principle of motion transmission with gears are preferred in order to transmit motion in longer distance. Spur, helical and herringbone gears are designed within the same axis with conjugate gears. Two gears come together and move following the same plane.

A *spur gear* is a “cylindrical gear with external teeth.” (IFToMM, 2014, no.1.1.26). The axes of the connecting gears need to be parallel (on the same plane) for a spur gear to work. Spur gears are the most commonly used gear type due to the their simplicity (Norton, 2004). Helical gears are preferred over spur gears due to the noise that is generated by simultaneous connection of all of the teeth. An illustration of a spur gear is shown in Figure 3.54.(a).

A *helical gear* is a "gear with teeth wrapped helically on a cylindrical surface.” (IFToMM, 2014, no.1.1.29). Helical gears that can be used for similar purpose with spur gears carry teeth inclined to the rotation axis. The relatively gentle movement provided by the inclination reveals better performance in high-speed, less noise, thrust forces and bending couples (Myszka, 2012). An illustration of a helical gear is shown in Figure 3.54.(b).

A *herringbone (double helical) gear* is a “gear comprising two integral helical gears, the helices of the gears being of opposite hand.” (IFToMM, 2014, no.1.1.30). Just as a spur gear, the axes of the connecting gears need to be parallel (on the same plane) for a herringbone gear to work. Similar to spur gears, herringbone gears work only on the same plane. Herringbone gears have similar applicational purposes with spur and helical gears. Herringbone gears are preferred in case thrust forces in helical gears are aimed to be eliminated. An illustration of a herringbone gear is shown in Figure 3.54.(c).

A *bevel (conical) gear* is a "gear with teeth formed on a conical surface." (IFToMM, 2014, no.1.1.31). Bevel gears that carry teeth positioned on conicle surfaces are used to transmit a rotational motion from a certain direction to another (nonparallel planes). Although bevel gears with meshing teeth in right angle are the most common, they can be designed in various angles. Bevel gears can be categorized with respect to teeth types as straight, spiral or hypoid (Norton, 2004). An illustration of a bevel gear is shown in Figure 3.55.



(a) (b) (c)

Figure 3.54. Various types of gears working on the same axis
(a) Spur gear (b) Hellical Gear (c) Herringbone gear
(Source: Myszka, 2012)

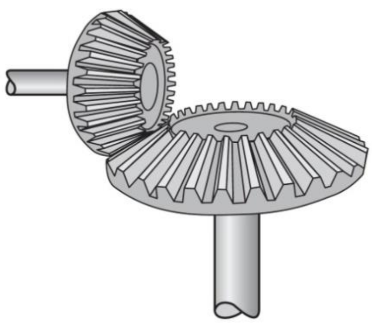


Figure 3.55. Bevel gear
(Source: Myszka, 2012)

A *worm gear* is a “gear with one or more teeth wrapped helically on a cylinder (or a globoid), the pitch of the helix being less than the diameter of the gear.” (IFToMM, 2014, no.1.1.33). Motion in nonparallel and non-coincident planes are transmitted through unidirectionally driven worm gears which require support of the axial force just as helical gears do (Myszka, 2012). Worm gears provide efficient performance in confined space (Norton, 2004). Both the motion direction and efficiency are affected by wheel and worm gear mechanism. Worm gear mechanisms are preferred in case of cross-axis motion transmission. An illustration of a worm gear is shown in Figure 3.56.

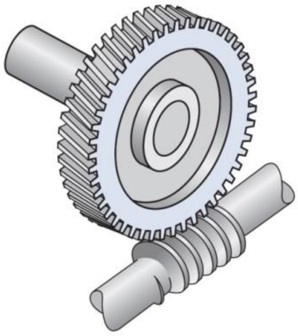


Figure 3.56. Worm gear with helical gear
(Source: Myszka, 2012)

A *rack and pinion gear* is a “Gear pair of which one link is a rack.” where a pinion is “the smaller of a pair of meshing cylindrical gears” or “cylindrical gear meshed with a rack.” and a rack is a “segment of a cylindrical gear of infinite radius.” (IFToMM, 2014, no.1.1.36, 1.1.37). A rack is sort of a flat spur gear, translation motion is generated by the combination of two. A rack and pinion gear is preferred in case translational motion is aimed to be transformed to rotational motion, or vice versa. Translation of the rack and rotation of the pinion is used in the transformation process. An illustration of a rack and pinion is shown in Figure 3.57.

A kinetic daylighting and shading system designed by Taylor Short as an architecture degree project at the University of Oregon, *Penumbra* is shown in Figure 3.58 (Frearson, 2014). The motion enabling the horizontal positioning of shading panels is generated by a mechanical system including the Rack and Pinion gear system. Rotation motions of 8 pinions are generated by the translation of a single rack.

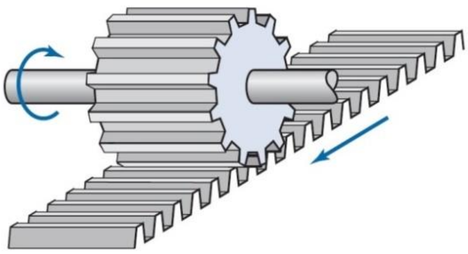


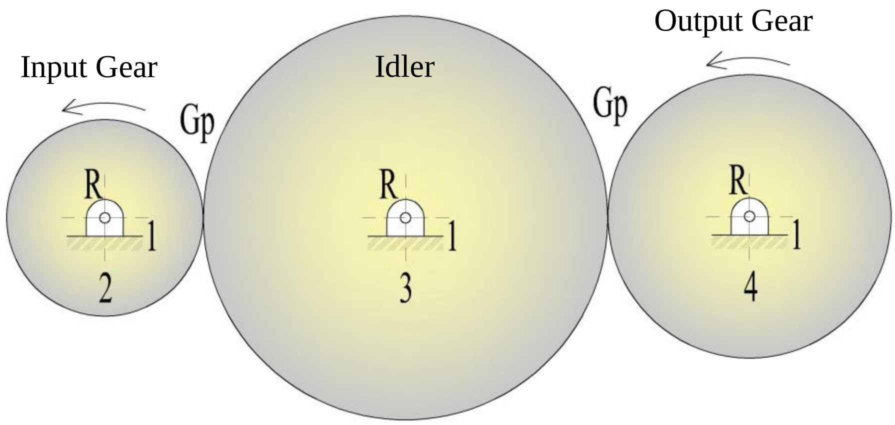
Figure 3.57. Rack and pinion gear
(Source: Myszka, 2012)


Figure 3.58. Use of Rack and Pinion Mechanism for a movable shading system
(Source: Short, 2014)

Many gears can be connected together. The most common use is as several types of *gear trains* that are defined as “assembly containing more than one pair of gears.” (IFToMM, 2014, no.1.3.42). Examples of gear trains are simple gear trains, compound gear trains or planetary gear trains (Norton, 2004).

Simple gear trains are preferred in situations where there is a long distance between input and output planes. Speeds of the input and output motion are taken into account in a gear train formation. The input gear needs to be smaller than the output gear in cases of transformation of a fast motion into a slower motion. A faster output motion is created by an input gear bigger than the output gear.

An *idler* is a “gear intermediate between a driving and a driven gear, which affects the sense of rotation of the latter but does not affect the velocity ratio.” (IFToMM, 2014, no.1.1.38). An idler is used to affect the speed direction as well as to keep the gear diameter of the output link in the lowest value in cases of combination of two gears with long distances between input and output motions.



$n = 4 \;\; j_1 = 3 \;\; j_2 = 2 \;\; M = 1$

$M = 3(4-1) - 2x3 - 2 = 1$

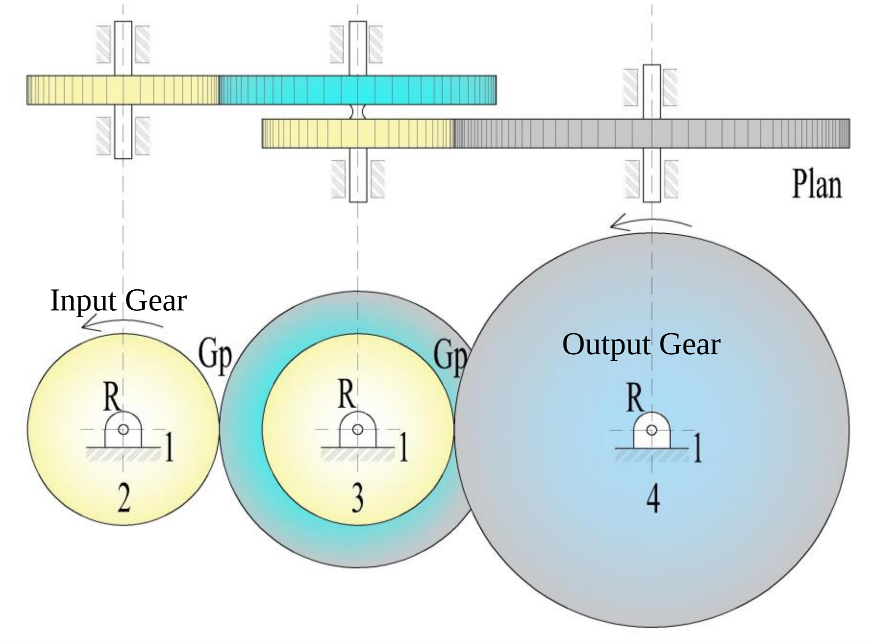
Figure 3.59. A simple gear train

A kinematic diagram of a simple 1 DoF gear train is shown in Figure 3.59. Three spur gears are meshing. The frame link is number 1. Gear number 2 is the input link. The idler gear that has no effect on velocity but transmit motion in a certain distance with the help of position change in the output motion is no. 3. Gear number 4 is the output link.

Compound gear trains include 1 or more shaft with multiple gears and are preferred in situations where the input velocity is ten times faster than the output velocity (Norton, 2004). Division of the input speed by the output speed reveals the transmission ratio. The *gear ratio* is the "transmission ratio for a gear train" (IFToMM, 2014, 2.2.56). Gear ratio depends on the number of teeth carried by a gear. The input gear (carries fewer gear teeth) motion speed is faster than the output gear (carries more gear teeth) motion speed.

A compound gear train may include various gear types such as spur, helical or bevel gears (Norton, 2004). The requirement of sudden changes in velocity among input and output planes that are close together is fulfilled by compound gear trains.

Unlike simple gear trains, intermediate gears affect velocity in compound gear trains. Output speed, direction and transmission are all affected by intermediate gears (Norton, 2004). A kinematic diagram of a 1 DoF compound gear train that consists of 4 spur gears is shown in Figure 3.60. The frame link is number 1. Two gears with identical motion speed and direction are positioned on a single shaft in link number 3.



$$n = 4 \;\; j_1 = 3 \;\; j_2 = 2 \;\; M = 1,$$

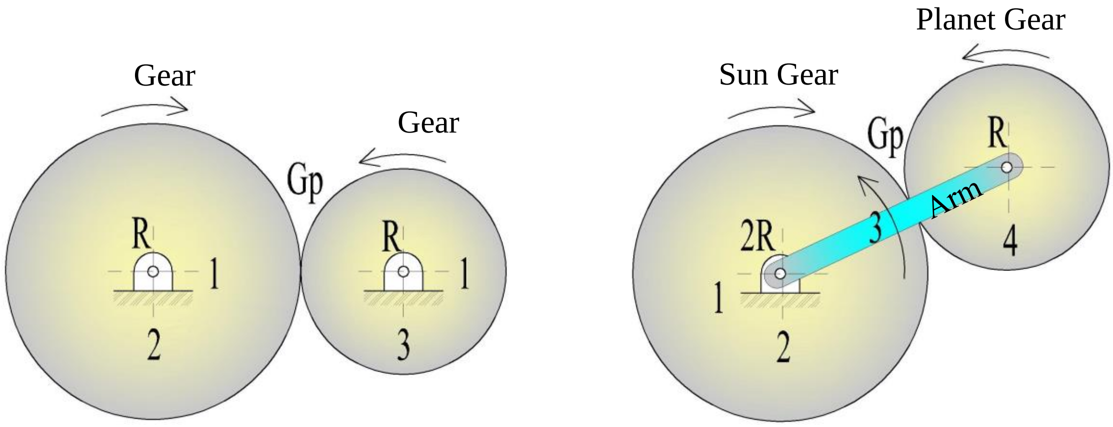
$$M = 3(4-1) - 2x3 - 2 = 1$$

Figure 3.60. A compound gear train

The input gear (link number 2) and output gear (link number 4) rotate in the same direction at different speeds. The input gear (carries fewer gear teeth) motion is faster than the output gear (carries more gear teeth) motion.

A *planetary (epicyclic) gear train* is a "gear train in which a planetary gear meshes with two gears that are both centered on the axis about which the center of the planet rotates." (IFToMM, 2014, no.1.3.44). Planetary trains are preferred for "higher power density, lower radial support loads, lower noise levels, greater kinematic flexibility" (Talbot, 2012, p.ii). A planetary gearset consists of 4 components: base link, sun gear, planet gear and arm. An additional ring gear is generally added for gear trains.

A *sun gear* is an "external gear with immovable axis of rotation, as applied in a planetary gear train." (IFToMM, 2014, p.2.6.8). A *planet gear* is a "gear that rotates on an axle whose own axis is constrained to rotate about another axis." (IFFToMM, 2014, no.1.1.35). A planet gear turns around the sun with the help of arms. An arm that provides a connection between two gears is also called a *planet carrier* or simply an *arm*. Both meshing gears are connected to a fixed link in simple gearsets. A planet gear is connected to a fixed link with the help of a movable arm and meshes with the sun gear in planetary gearsets.



$$n = 3 \quad j_1 = 2 \quad j_2 = 1 \quad M = 1$$
$$M = 3(3-1) - 2x2 - 1 = 1$$

(a)

$$n = 4 \quad j_1 = 3 \quad j_2 = 1 \quad M = 2$$
$$M = 3(4-1) - 2x3 - 1 = 2$$

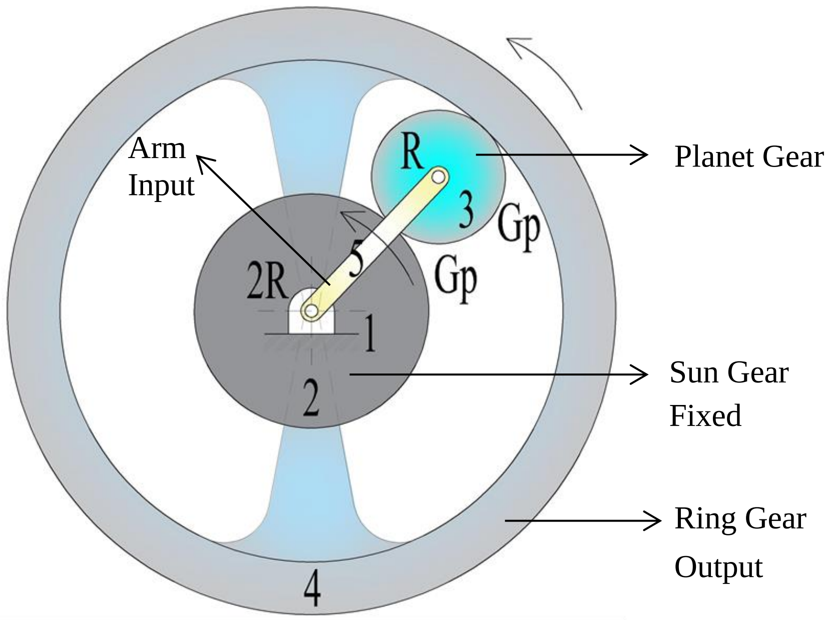
(b)

Figure 3.61. Simple and planetary gearsets (a) Simple gearset (b) Planetary gearset

Examples of a simple gearset and a planetary gearset are shown in Figure 3.61. Rotation on a constant axis is generated by each gear in a simple gearset. Link number 1 is the fixed link (see Figure 3.61.(a)). The arm between two links (link number 3) is not constant in planetary gearsets, it is capable of rotating as well. The planet gear thus can rotate around its own axis as well as around the sun gear (see Figure 3.61.(b)). The DoF value of a simple gearset is 1 where the DoF of a planetary gearset is 2. Two input motions are required in the planetary gearset. For example, in case the input motion is transmitted to both the sun gear and the arm, the planet gear is the output link (see Figure 3.61).

Planetary gear trains can be designed as either simple or compound gearsets. Numereous links and various gear types such as spur gears, helical gears, etc. can be used in planetary gear train design. The output motion is mostly provided by an additional ring gear or another combination in planetary gear trains. A *ring gear* is an "internal gear with immovable rotation axis, as applied in a planetary gear train" (IFToMM, 2014, no.12.6.7). A spur (external) sun ring is positioned in the center. A spur link is in connection with the arm link while rotating around the sun ring and meshing with the internal ring.

A single DoF planet gear can be designed in several ways by fixation of various links. A planetary gear train is shown in Figure 3.62. The sun gear (link number 2) is



$$n = 5 \;\; e = 2 \;\; j_1 = 3 \;\; j_2 = 2 \;\; M = 1$$
$$M = 3(5-2) - 2x3 - 2 = 1$$

Figure 3.62. A planetary gear train with fixed sun gear and input arm link

fixed while the input motion is transmitted to the arm link (link number 5). The planet gear therefore both turns and spins where the output ring gear (number 4) is faster than and in the identical direction with the input gear.

Various fixed links and input motions can be used for different applications of the same gear train. Another variation is obtained by keeping the sun gear fixed while transmitting the input motion to the ring gear. This results in obtains a spin and a turn of the planet gear where the arm, as the output, rotates slower than and in the same direction with the input gear. Several variations such as fixed ring gear and an input sun gear or a fixed arm and an input sun gear, etc. are possible.

Planetary gear trains are used in various products such as in cars and clocks, as well as for architectural purposes. For example, the *Falkirk Wheel*, a project by the RMJM Architecture and Masterplanning in is completed in 2002 (see Figure 3.63). Connecting two canals between East and West Scotland is the purpose of the *Falkirk Wheel*. Four boats (2 up and 2 down the 35 meters drop) are capable of transporting between two canals. The purpose of taking the boats up and down the lift requires tanks to be kept parallel to the ground (RMJM, 2020).

The rotation of the *Falkirk Wheel* is provided by planetary gear train (see Figure

3.64). An input arm link is used for wheels to work on. The big wheel 'A' in the center is a sun gear fixed to the structure. The planet gear's rotation around the sun gear is started by the rotation of the arm link. Motion is transmitted to the outer 'B' gear by affecting motion direction; gondolas are thus kept upright (horizontal). All wheels are spur gears. Two output gears generate identical rotation toward the opposite direction of the input link.

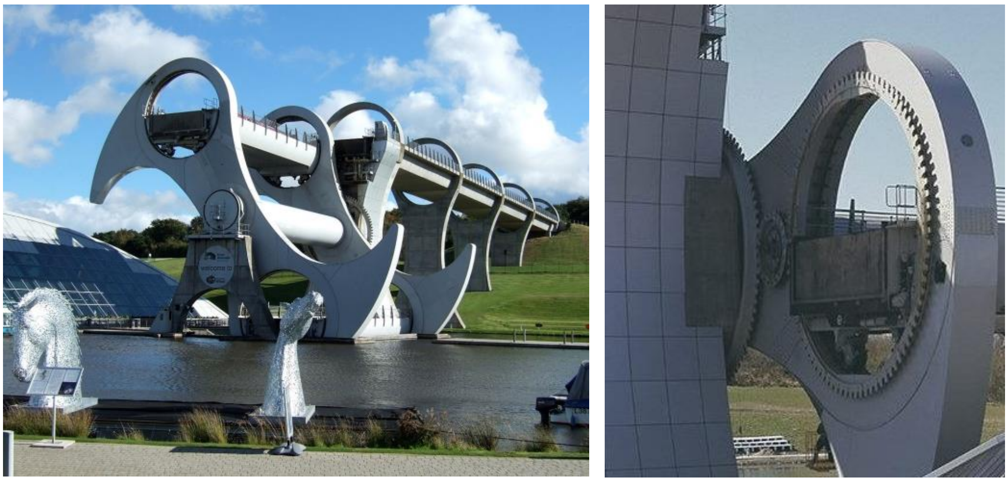
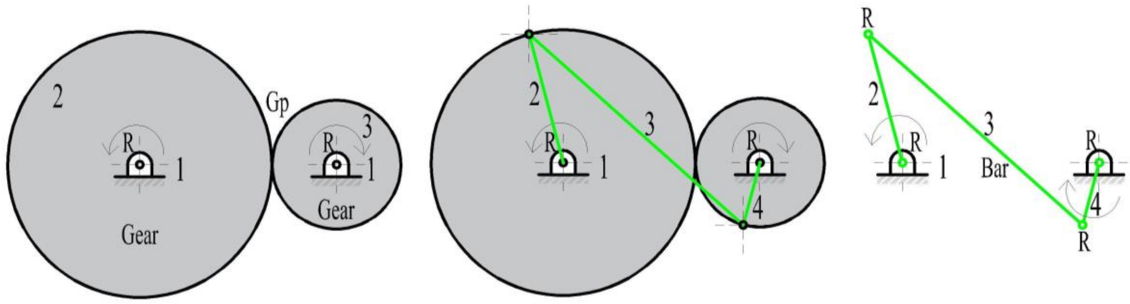


Figure 3.63. Use of the gear train in the Project of *Falkrik (Millenium) Wheel* (Source: RMJM, 2020)

Figure 3.64. Planetary gear train mechanism of the *Falkrik (Millenium) Wheel* (Source: Laverick, 2020)

Just as gear mechanisms can be used in place of linkages, linkages can also be used in place of gear mechanisms. A transformation of a gear and a linkage is schematically shown in Figure 3.65. For example, a gear pair in a gear mechanism with 1 DoF can be replaced by 2 revolute joints and one link, revealing a linkage with 1 DoF or vice versa. The input output relationship of the linkage is only instantaneously equivalent to that one of the gear mechanism.



$n = 3 \;\; j_1 = 2 \;\; j_2 = 1 \;\; M = 1$

$M = 3(3-1) - 2x2 - 1 = 1$

$n = 4 \;\; j_1 = 4 \;\; M = 1$

$M = 3(4-1) - 2x4 = 1$

(a) (b) (c)

Figure 3.65. Linkage transformation of a gear mechanism to four-bar equivalent
(a) A gear mechanism (b) Linkage transformation of the gear mechanism (c) Linkage transformed from the gear mechanism

3.9.2. Mechanism Types with Respect to the Motion Space

Planar, spherical and spatial mechanisms are categorized with respect to the motion space. Motion type of the links carried by those mechanisms is the essence of this type of categorization (Uicker et al., 2003). Planar mechanisms are the most commonly used mechanisms in art and architecture, thus most frequently mentioned in the current study.

3.9.2.1. Planar Mechanisms

A planar mechanism is “a mechanism in which all points of its links describe paths located in parallel planes.” (IFToMM, 2014, no.1.3.17), where the plane addresses is the motion plane. Translations in two independent directions and one rotational motion can be generated in a ($\lambda = 3$) single plane of a planar mechanism. Planar mechanisms can consist of various link types such as bar, cam or gear links or a combination of those. Revolute and prismatic joints (1 DoF) as lower pairs and cam or gear pairs (2 DoF) as higher pairs can be used in planar mechanisms.

A planar mechanism consisting of links and gears connected with revolute, prismatic joints and a gear pair is shown in Figure 3.66. The input rotational motion is transmitted from the gears through bars carrying parallelogram loops that obtain the reversing linear translational output motion.

Most of the common mechanism types used today such as the planar four-bar linkage, the plate cam and follower, gears working with parallel axes and the slider-crank linkage are planar mechanisms. The simplicity of mathematical calculations and ease of assembly of links with joints are the underlying reasons for the greater use of planar mechanisms over spatial and spherical mechanisms.

Planar mechanisms thus move in 2 dimensional planar spaces. Combination or repetition of 2D planar mechanisms are also used to construct commonly used 3D

You & Chen (2012) used rigid planar plates in the retractable roof design that provides the capability of complete coverage in the closed position. Planar double chain linkages constructed with plates in varying positions are shown in Figure 3.67. All top and bottom plates are ternary links connected to each other by revolute joints in varying design.

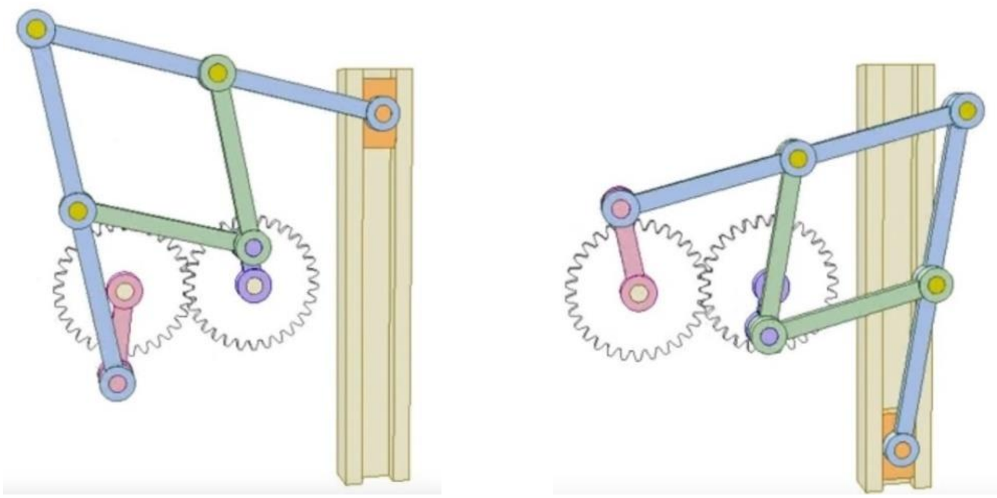


Figure 3.66. A planar mechanism with gears and bars
(Source: Thang, 2015)

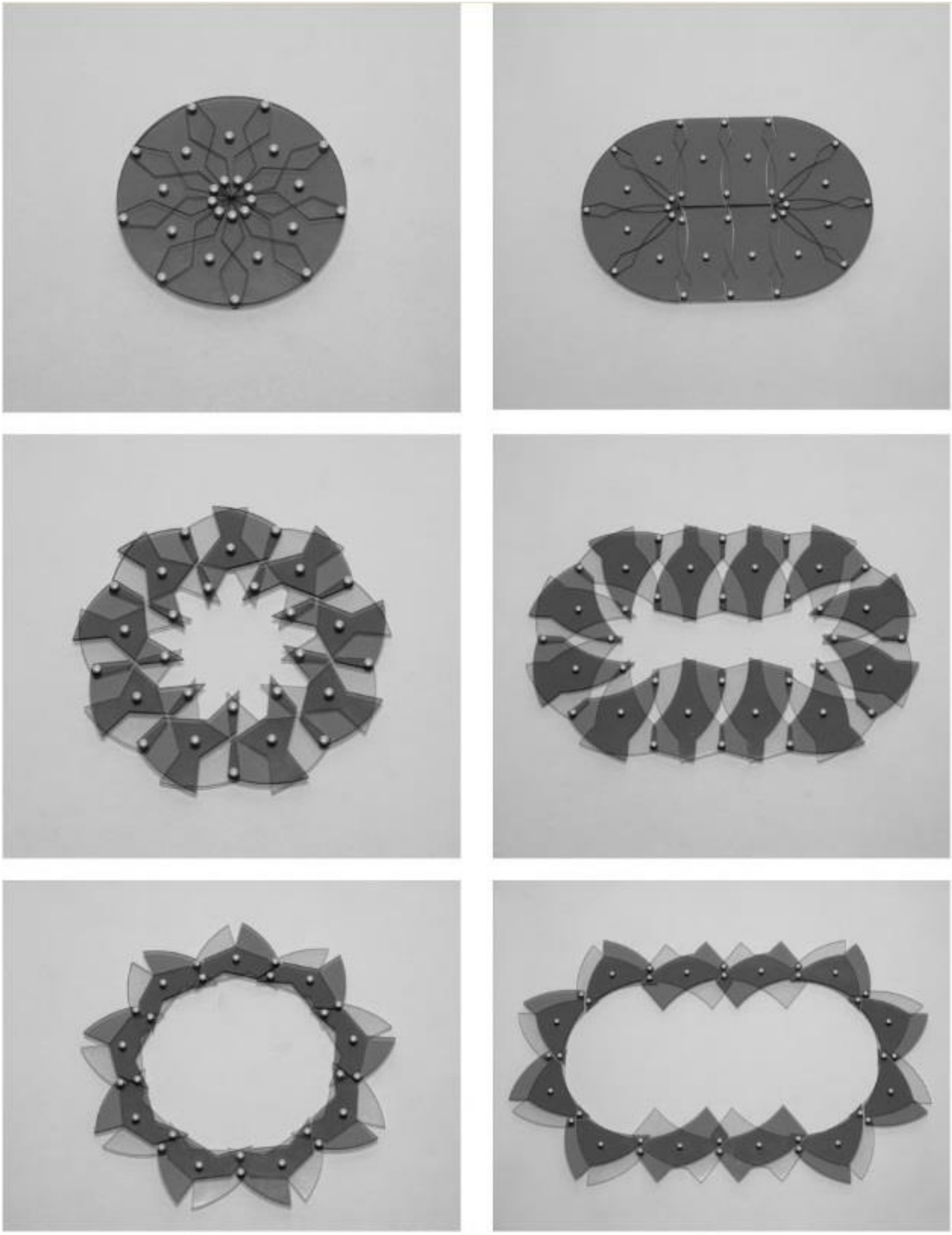
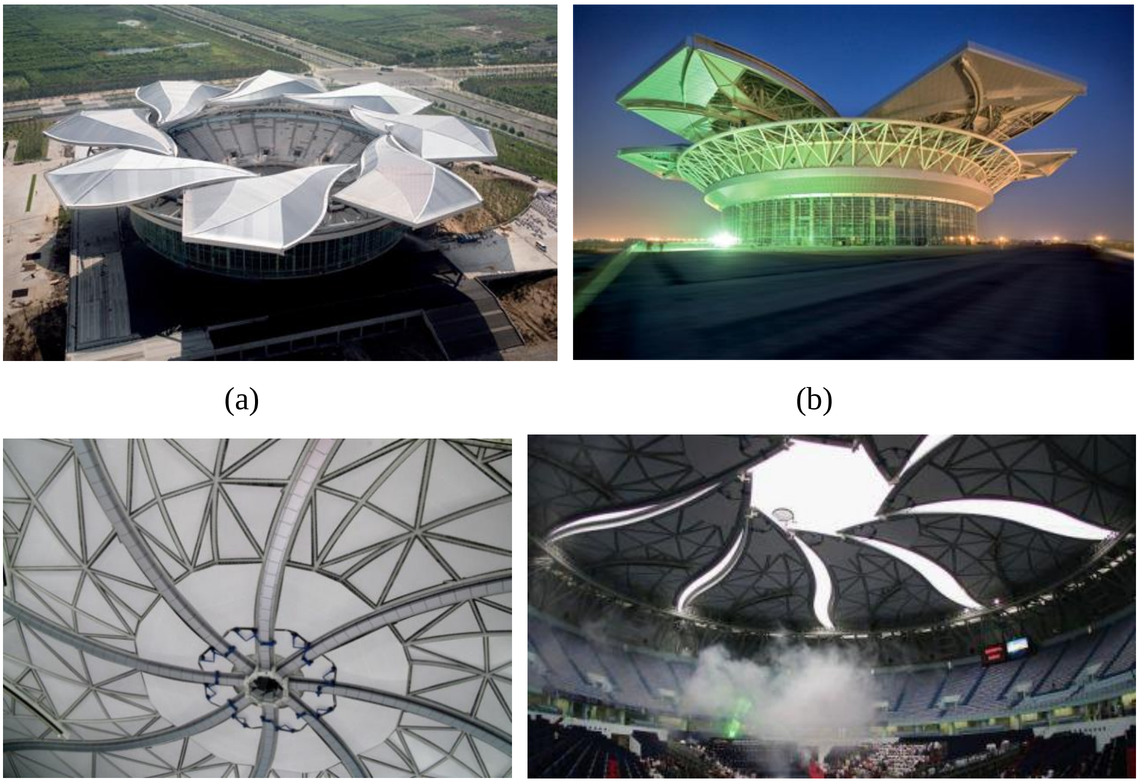


Figure 3.67. Varying positions of two planar double chain linkages constructed with plates for retractable roofs
(Source: You & Chen, 2012)

The movable roof of *Magnolia Stadium* designed by architect Mitsuru Senda has similar design principles with planar mechanisms. The floral shape roof consisting of 8 opening panels is shown in Figure 3.68.



(a) (b)

(c) (d)

Figure 3.68. Interior and exterior views of the movable roof of *Magnolia Stadium* in different positions
(a) Top view in open position
(Source: Berrones, 2007)
(b) Elevation view in open position
(Source: Berrones, 2007)
(c) View from interior in the closed position
(Source: Smith, 2008)
(d) View from interior in motion
(Source: Mun Fitness Blog, 2008)

3.9.2.2. Spherical Mechanisms

A *spherical mechanism* is a mechanism "in which all points of its links describe paths located on concentric spheres." (IFToMM, 2014, no.1.3.18). Spherical mechanisms may contain several parts, such as linkages with revolute and arc prismatic joints as well as spherical cam mechanisms, bevel gears and tapered roller bearing (You & Chen, 2012). A spherical 4-bar mechanism consisting of 4 binary links and 4 revolute joints is shown in Figure 3.69.

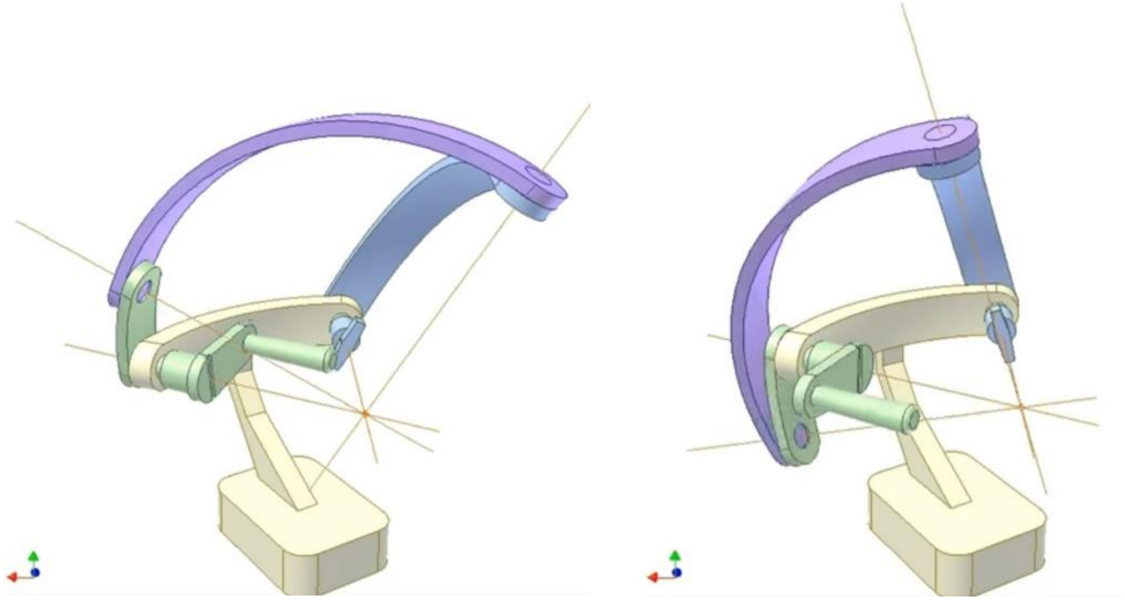


Figure 3.69. Two positions of a four-bar spherical mechanism model
(Source: Thang, 2011)

Spherical mechanisms ($\lambda = 3$), allow 3 independent rotational motions and constrain 3 translations in all directions. Revolute joint axes are parallel to each other in planar mechanisms whereas joint axes of spherical mechanisms intersect at a certain point.

Action origami structures with rigid plates comprise several spherical loops. Translation and application of such principles to architecture that is inspired by origami reveals great opportunities in terms of movable structure design.

A Miura-ori unit with 4 surfaces that are able to fold through the vertex (intersecting point) is shown in Figure 3.70. Each surface of the unit rotates through the vertex. The spherical characteristic of the origami unit consists of four bars and four revolute joints.

Various deployable plate structures consist of several spherical origami units that are coupled together to cover surfaces. Several action origami units used as sun shading devices on the facades of the Al-Bahr towers is shown in Figure 3.71. Six triangular panels folding around a vertex are combined together to generate an origami unit which is a six bar spherical mechanism. Repetition of this triangular unit is used to cover the facade of the building for sunlight control.

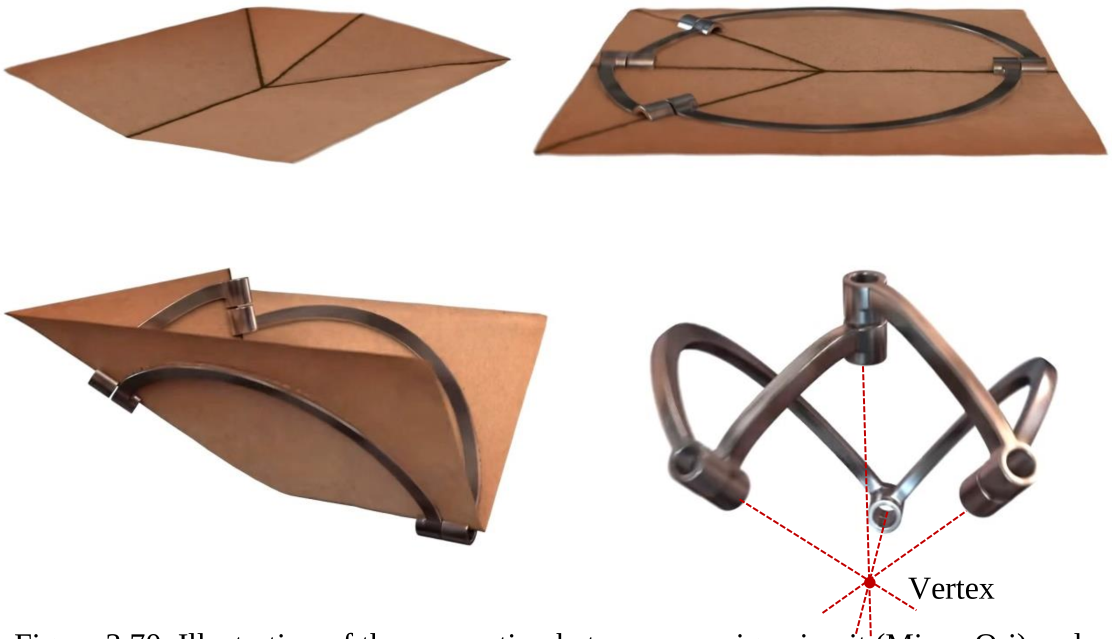


Figure 3.70. Illustration of the connection between an origami unit (Miura-Ori) and a four-bar spherical mechanism
(Source: Mooth, 2014)

Figure 3.71. Spherical mechanism usage as sun shading panels in the *Al-Bahr Towers*
(Source: Aedas, 2012)

3.9.2.3. Spatial Mechanisms

A spatial mechanism is a "mechanism in which some points of some of its links describe non-planar paths, or paths located in non-parallel planes." All or some of 6 types of movements ($\lambda = 6$) can be generated by spatial mechanisms depending on their design. Both lower pair and higher pairs can be used in 3D mechanisms.

A four-bar linkage carrying 4 different lower pair types connected with 4 binary links is shown in Figure 3.72. A sliding motion is provided in the output link (green link) by transmission of rotation motion through the input link (orange link). Revolute, spherical, cylindrical and prismatic joints are used resprectively starting from the input link.

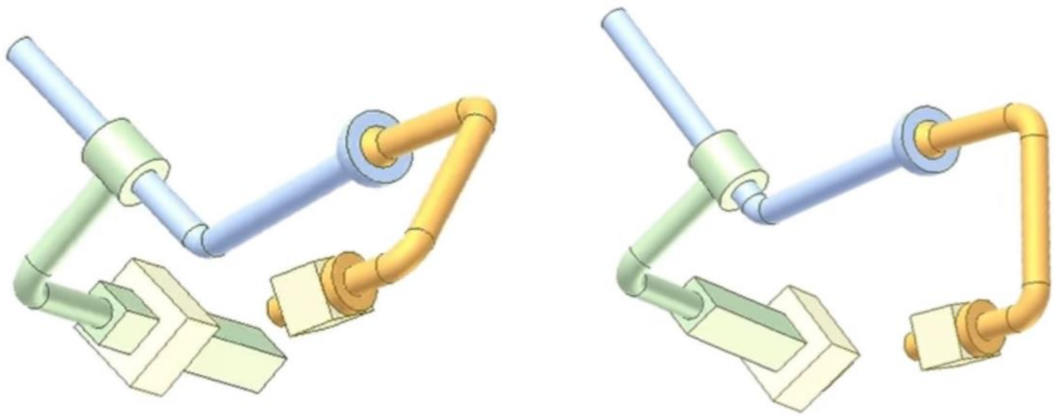


Figure 3.72. Spatial RSCP linkage in two positions
(Source: Thang, 2012)

Usually planar mechanisms are preferred over spatial mechanisms due to easier calculation methods whereas spatial mechanisms have the advantages of requiring a fewer number of elements during motion transmission and revealing a wider variety of movement type. Planar and spatial mechanisms can also be used together.

A spatial mechanism ($\lambda = 6$) used in deployable structure design is shown in Figure 3.73. Seven revolute joints are connected with 7 binary links in a closed loop. This mechanism carries the advantage of using revolute joints for 3D mechanisms in 1 DoF configuration.

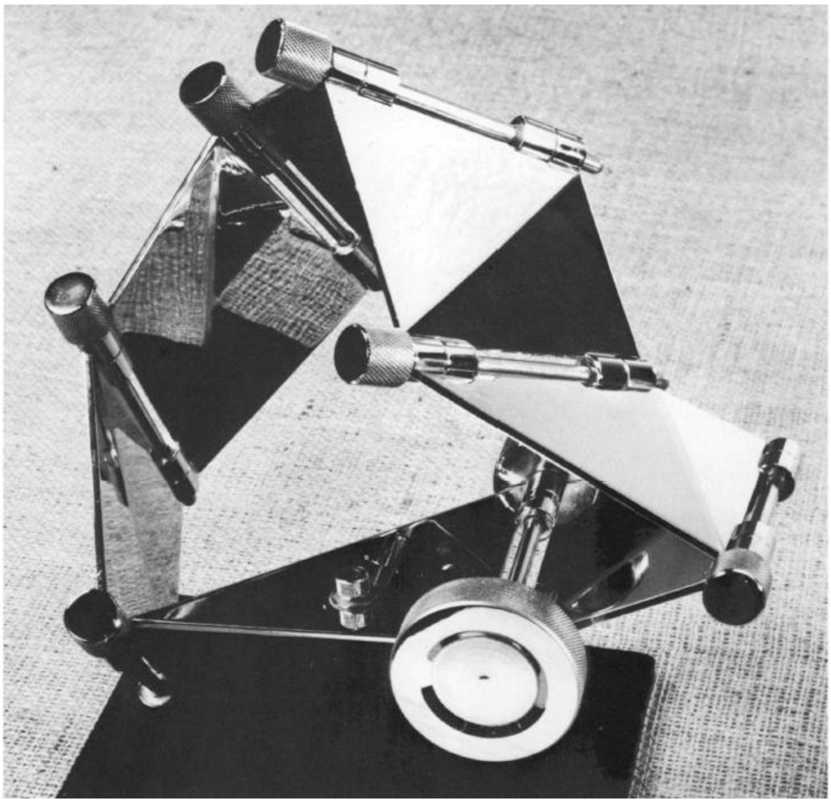


Figure 3.73. A spatial mechanism with 7 binary links and 7 revolute joints
(Source: Phillips, 2007)

Advantages and frequency of use of mechanisms carrying bars and revolute joints are mentioned above. At least 7 links and 7 revolute joints are required for a spatial linkage consisting of bars and revolute joints to have mobility if the link lengths are to be kept arbitrary. An example of this kind of mechanism is shown in Figure 3.73.

$$M = 6(7 - 1) - 5x7 = 1$$

Movement can be enabled in mechanisms that are categorized as stationary for the Gruebler – Kutzbach mobility formula by their special geometrical conditions. These are called overconstrained mechanisms. Various overconstrained linkages that are proposed by Sarrus (1853), Bennet (1903), Delassus (1992), Bricard (1927), Myard (1931), Goldberg (1943), Waldorn (1967), Wohlhart (1987), and Dietmaier (1995) are prefered in deployable structures because of their stiffness (Chen, 2003).

Sarrus is the first one that published research on overconstrained mechanisms (Chen, 2003). Rectilinear motion of a Sarrus mechanism in varying positions is shown in Figure 3.74. The Sarrus mechanism ($\lambda = 5$) with 1 DoF consists of 6 links and 6 revolute joints.

$$M = 5(6 - 1) - 4x6 = 1$$

The geometrical principles of various trusses in folding structures and the Sarrus mechanism are revealed in the examinations of Calatrava (1981). The side view of his basic element model of generating square projection is shown in three positions (see Figure 3.75).

It is possible to use various combinations of Sarrus linkages in deployable structure design. Figure 3.76.(a) shows an 18 times repetition of a module that consists of three Sarrus linkages and Figure 3.76.(b) shows a 12 times repetition of a module that consists of four Sarrus linkages (Wohlhart, 2000).

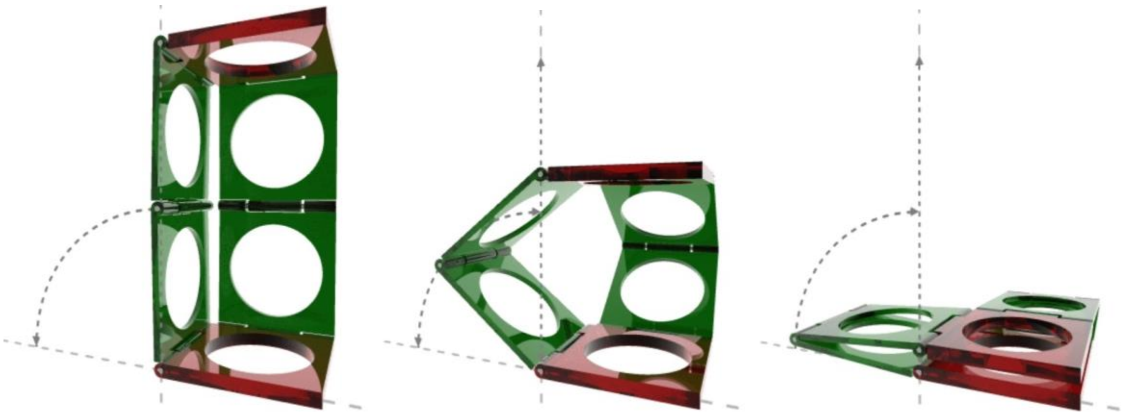


Figure 3.74. Three positions of a Sarrus mechanism
with 6 binary links and 6 revolute joints
(Source: Helsing, 2007)

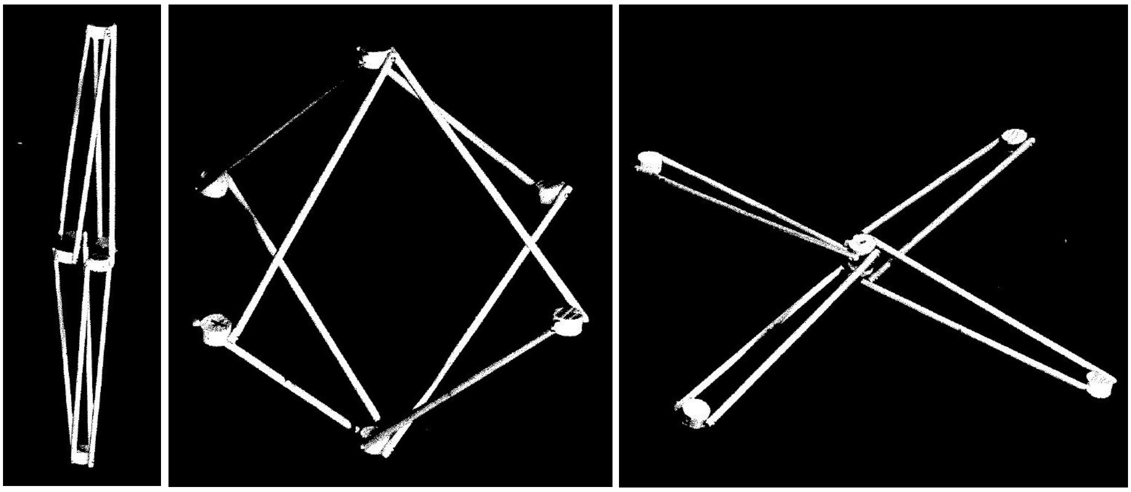
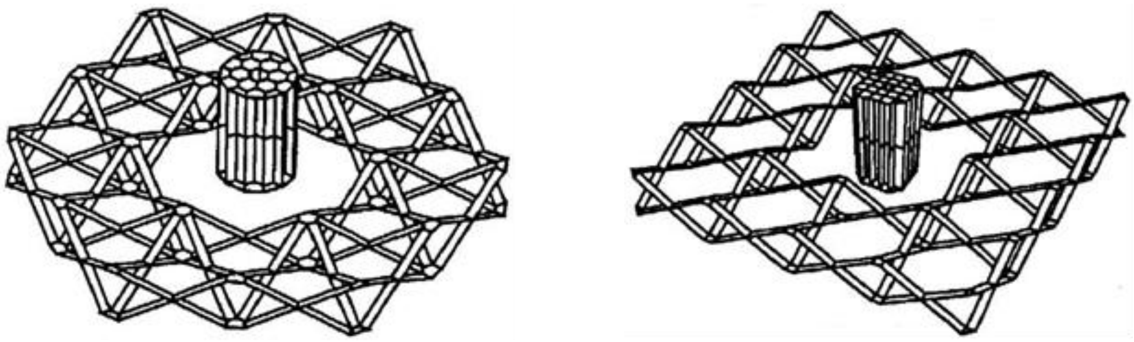


Figure 3.75. A foldable module model from Sarrus mechanism
(Source: Calatrava, 1981)



(a) (b)

Figure 3.76. Varying combinations of the Sarrus linkage for deployable structures in closed and open position (a) Repetition of a unit with three Sarrus linkages (b) Repetition of a unit with four Sarrus linkages
(Source: Wohlhart, 2000)

3.10. The Process of Mechanism Design

The design process consists of a series of products and systems -including feedback- that assure the final product to be working properly (Yan, 1998). The generation of a machine involves processes of planning related components in line with an aimed purpose, clearly defining the geometry of every component and properly assembling the components with respect to the design details. Experimentation and judgment based on detailed analyses are required in the design process which is strengthened with experience (Rao & Dukkipati, 2006). Mechanism design can be used to generate a product or device as well as a building or building component. Despite contradictory information in the literature of design, similar underlying processes are carried by every system that involves mechanisms. The process of designing mechanisms and machines is shown Figure 3.77 (Yan, 1998).

Branches of kinematics are categorized as *analysis* and *synthesis* (Rao & Dukkipati, 2006). Both start with drawings of the kinematic diagrams and determining the mobility. Kinematic analysis is the process of examining a particular mechanism's geometry and characteristics (Sandor & Erdman, 1984). Kinematic synthesis, on the other hand, is the process of generating a mechanism to produce an aimed sequence of motion (Uicker et al., 2003). Kinematic synthesis involves a systematic generating process to determine basic characteristics of the mechanism including the link and joint

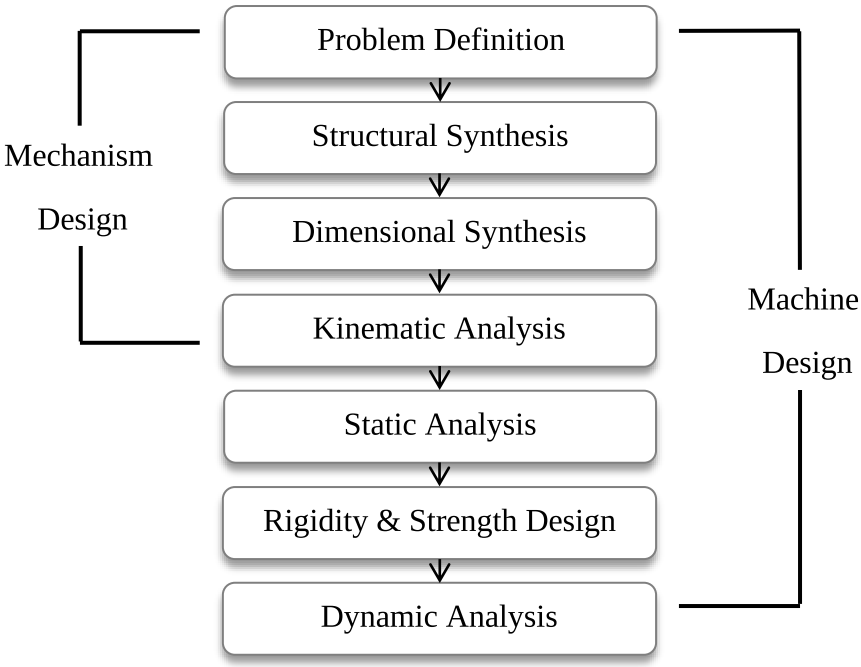


Figure 3.77. Design process of mechanisms and machines
(Redrawn by author from: Yan, 1998)

types, angular positions of links and DoF of the mechanism and dimensions of the links.

Several subjects are concerns of kinematic synthesis. Each consisting of three subcategories, phases (*types*) and *tasks* of kinematic synthesis are briefly examined in the current study. *Type*, *number* and *dimension synthesis* generate phases of kinematic synthesis while *function*, *path* and *motion generation* are tasks of kinetic synthesis (Figure 3.78).

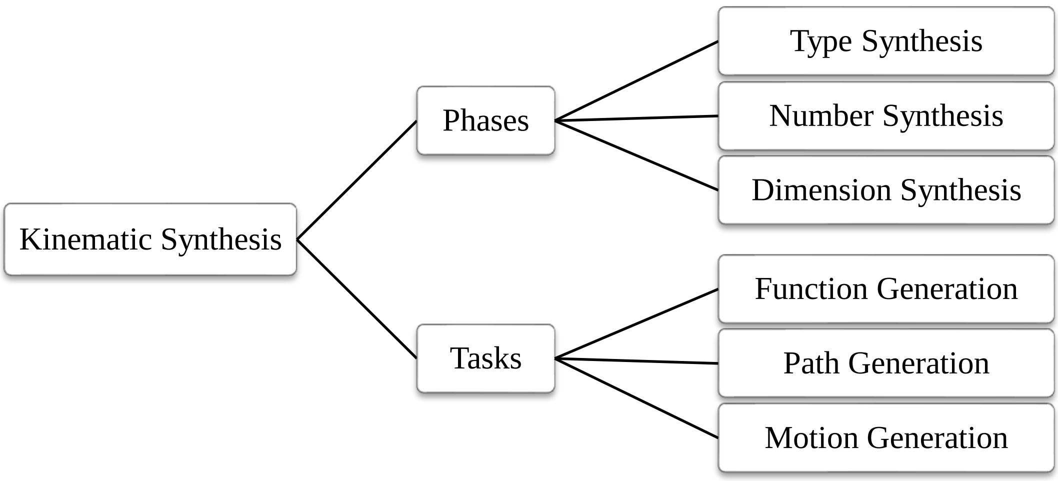


Figure 3.78. Phases and tasks of kinematic synthesis

Type synthesis, the first phase of kinematic synthesis, is an essential decision-making process about the mechanism type. A linkage, gear or cam system can be selected as the mechanism type depending on an aimed purpose. This process is used to determine the basic structural figure of the mechanism (Söylemez, 2000). Usage, manufacturing processes, available materials, safety, economics and space are some factors that affect mechanism type selection (Uicker et al., 2003).

The second phase of kinematic synthesis, *number synthesis*, is a determination process for the number of links and joints necessary to generate a particular sequence of motion (Uicker et al., 2003). The required number of joints in the connection to the binary, ternary, quaternary, etc. links can be examined with respect to a certain DoF value (Phakatkar, 2009). After examining numerous potential combinations, the optimum combination and order of links are chosen through number synthesis. Type sysnthesis, together with number synthesis is also called structural synthesis (Merlet, 2006).

The third phase of kinematic synthesis is to determine the required dimensions of components to be used in a mechanism to obtain an aimed motion through *dimensional synthesis* (Phakatkar, 2009). Length and angles of the links and ratios of gears are some dimensional variables that affect the obtained motion. Two types of methodology are used in dimensional synthesis to determine the optimum dimension of related mechanism parts, geometric construction, and analytical (mathematical) calculation.

Kinematic synthesis is mainly concerned with function, path and motion generation. These concerns are called tasks of kinematic synthesis (Sandor & Erdman, 1984). Motion is considered without respect to forces and moments in kinematic synthesis.

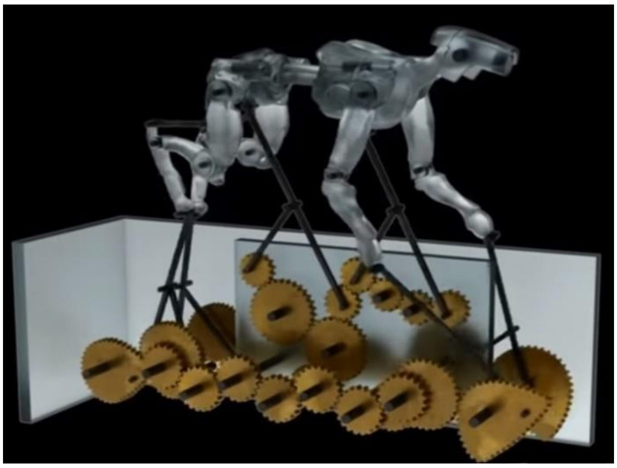
Function generation is a process in which possible mechanisms in line with a particular purpose involving the correlated motion of input and output links with respect to an aimed function are provided. A predetermined motion is generated by the output member's rotation, oscillation or reciprocation depending on the function of the mechanism (Phakatkar, 2009). Determination of mechanisms with respect to the intended function that fulfills related requirements is aimed at the process. Each output position depends on the input position.

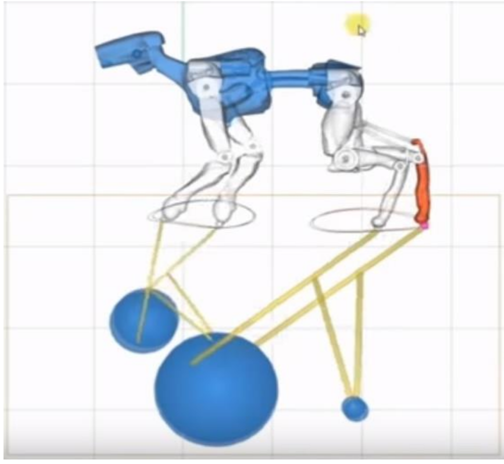
Path generation is the phase in which a coupler link point is responsible for generating a predetermined path that may include circle, arc, elliptical or straight line portions (Uicker et al., 2003).

An interactive design that is developed to be used in mechanical animation characters is shown in Figure 3.79. Mechanisms that are created by the design team for the movement of mechanical characters are 1 DoF and mostly planar (Coros et al., 2013). A mechanical character of Ema Galop that consists of gears and bars is shown in Figure 3.79.(a). Circular gears are used as well as non-circular gears to provide the aimed timing of the motion. The path that is drawn by a character's feet to enable the character's walking motion and the enabling mechanism is shown in Figure 3.79.(b). Mechanisms with gears and bars connected through gear pairs, revolute joints and prismatic joints that generate desired paths are shown in Figure 3.79.(c).

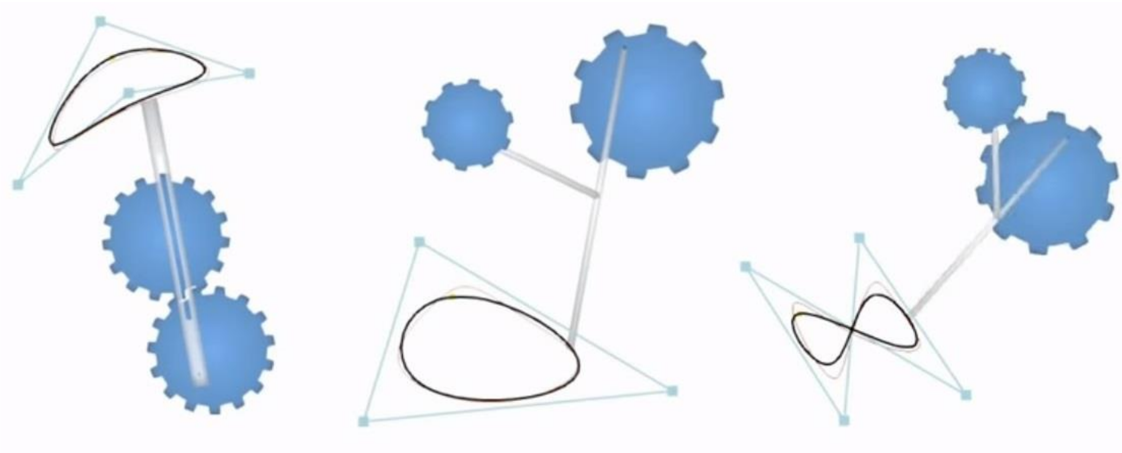
Motion generation, a more general task than path generation, requires a body to generate a predetermined motion (Phakatkar, 2009). Motion of an object from a starting pose to a final pose is the main problem in motion generation. A study of a building's folding roof covering in open and closed states is an example of motion generation.

Kinematic analysis, as stated above, is a process of detecting the characteristics of motion in an existing mechanism (Söylemez, 2000). Displacements, velocities, acceleration, specification of the input motion or method of actuation are revealed by kinematic analysis (Sandor & Erdman, 1984).





(a) (b)



(c)

Figure 3.79. An interactive design based on the path generation system
(a) The mechanical character of *Ema Galop*
(b) The mechanism generated by the walking motion path of the character
(c) Generation of various mechanisms from specified paths
(Source: Disney Research Hub, 2013)

CHAPTER 4

KINEMATIC STRUCTURAL ANALYSES OF KINETIC ART & ARCHITECTURE PRODUCTS

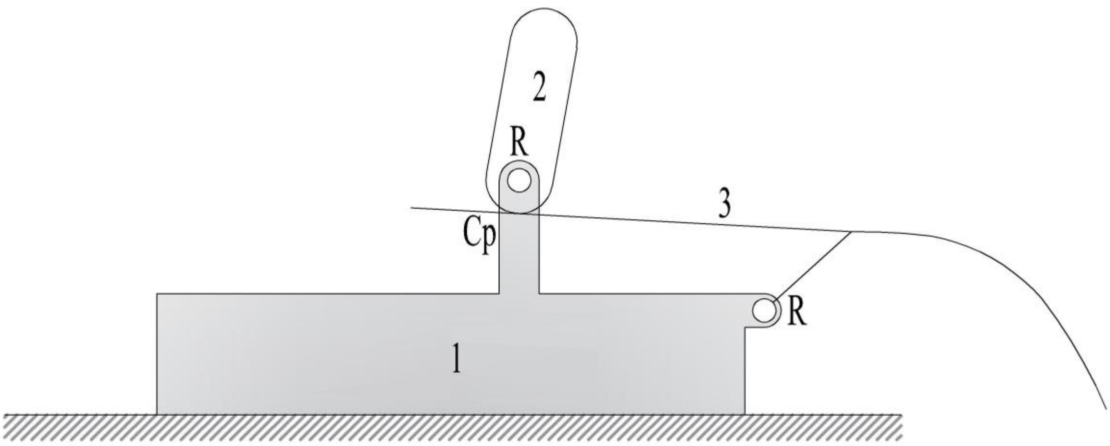
Kinematic structural analysis is based on the type and number analyses of the mechanism. This analysis involves types and numbers of joints and links, as well as mobility calculations of the mechanism with kinematic diagrams that show the geometry of the mechanism and connection relations between the links and joints that affect motion.

Numerous kinetic art and architectural designs are constructed by the repetition of a primary movable unit. Final products are developed using various techniques such as symmetrical repetitions of these units. The mobility analysis of a primary unit, therefore also reveals the mechanism properties of the whole product (Zhao, Chu, & Feng, 2009). The primary units of selected movable products are revealed and analyzed to examine their connection methods that affect mobility in this Chapter.

4.1. The Fingers Mk III by Nik Ramage

The kinetic sculpture, *Fingers Mk III,* is designed by Nik Ramage, is shown in motion in Figure 4.1.(a). The motion of a finger is provided by 1 DoF, a planar cam mechanism (see Figure 4.1.(b)). The given input rotation motion in the mechanism is transformed to the oscillating motion of the coupler link (finger). A force-closed plate cam (link no. 2) is connected with a cam pair to the flat-face follower (link no. 3) and all are connected to the base (link no. 1) with revolute joints. The repetition of the unit as 4 serially connected cam mechanisms provides the motion of the fingers. The 1 DoF mechanism is controlled by a single actuator.

(a)



$$n = 3 \quad j_1 = 2 \quad j_2 = 1 \quad M = 1$$

$$M = 3(n - 1) - 2j_1 - j_2$$

$$M = 3(3 - 1) - 2x2 - 1 = 1$$

(b)

Figure 4.1. Nik Ramage's *Fingers Mk III*
(a) *Fingers Mk III* in motion
(Source: Ramage, 2013)
(b) Kinematic diagram and mobility calculation of the primary unit of *Fingers Mk III*

4.2. The Redwood and the Helix by Reuben Margolin

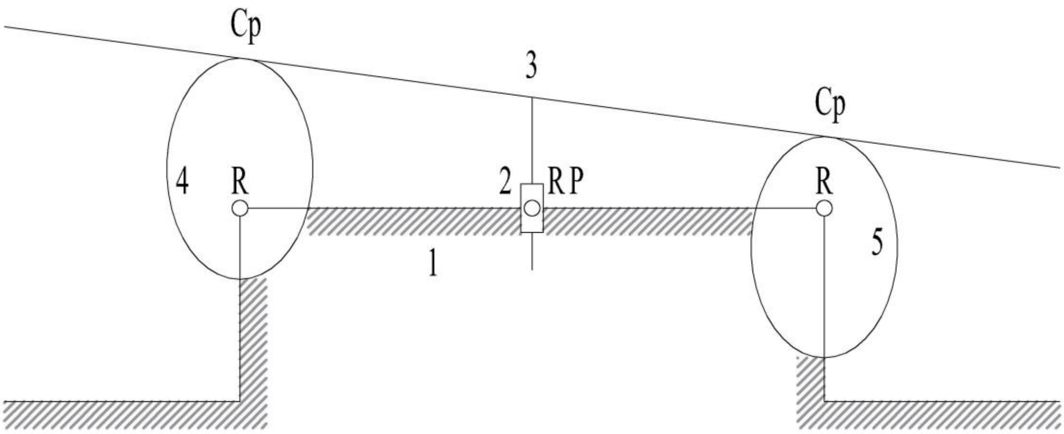
The kinetic sculpture, *Redwood* (28” x 38” x 12” high), designed by Reuben Margolin in 2007 is shown in Figure 4.2.(a). The 2 DoF sculpture that is operated by two hands is designed so that primary unit which is a 2 DoF planar mechanism repeats 30 times (see Figure 4.2.(b)). The rotation input motion is transferred to two plate cams (links no. 4 and 5) that are connected to the base (link no. 1) by revolute joints. Two cams that are connected by cam pairs through a mutual follower (link no. 3) generate the oscillating motion of the coupler link. The follower is connected to the base link through link no. 2 with prismatic and revolute joints. Cams are connected to the input link in various angles in the mechanism that is developed by the repetition of these units. The waving motion of the *Redwood* sculpture is provided by the sequential oscillating motion of the followers that is generated via varying connection angles of the cams.

Reuben Margolin's kinetic sculpture, *Helix* (2011), that is constructed with 40 oscillating wooden slats is shown in Figure 4.3. *Helix* is developed with a mechanism principle similar to *Redwood*'s. A mechanism that is controlled by 2 actuators is generated by the interconnection of bars that provides varying connection angles rather than by plate cams that are connected in various angles. The input rotation motion is not transmitted to the followers through direct contact as in the cam pair but instead the rotation motion is transmitted through cables to generate the oscillating motion (see Figure 4.3).

4.3. Movable Lights by West 8

The urban square of *Schouwburgplein* at Rotterdam that is designed by the urban design and landscape architectural studio West 8 is shown in Figure 4.4.(a). The crane-like lights are operated by park users (West 8, 1996). Kinematic diagram and mobility calculations of a light’s planar mechanism is shown in Figure 4.4.(b). The 2 DoF mechanism is controlled in two sides by the actuators’ sliding input motion (between links no. 2, 3 and 5, 6). Binary links (links no. 1, 2, 3, 5, 6, 7) and the quaternary link (link no. 4) are connected by revolute and prismatic joints.

(a)



$n = 5$ $j_1 = 4$ $j_2 = 2$ $M = 2$,

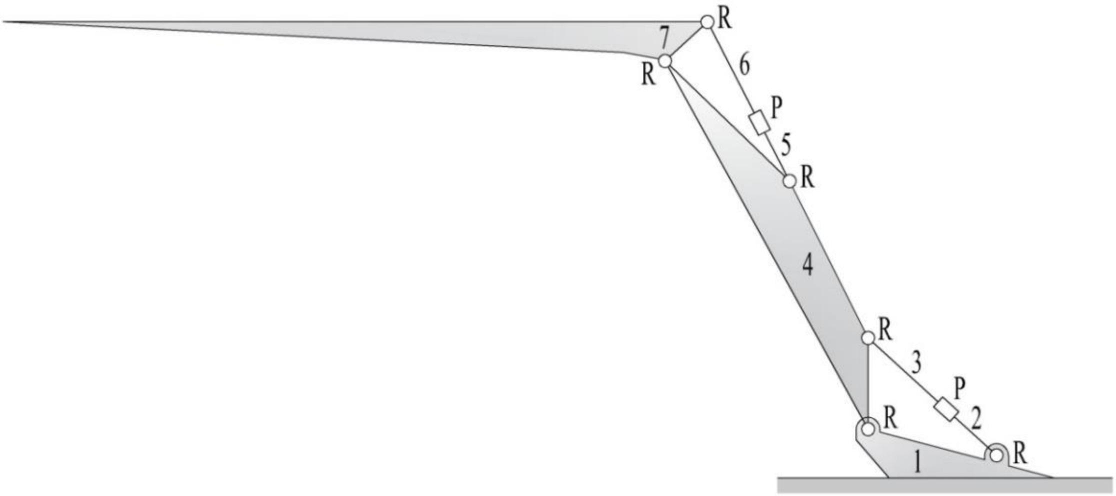
$$M = 3(5-1) - 2x4 - 2 = 2$$

(b)

Figure 4.2. Reuben Margolin's kinetic sculpture *Redwood*
(a) *Redwood* in motion
(Source: Margolin, 2020d)
(b) Kinematic diagram and mobility calculation of *Redwood*

Figure 4.3. Reuben Margolin's kinetic sculpture *Helix*
(Source: Margolin, 2020c)

(a)



$$n = 7 \quad j_1 = 8 \quad M = 2$$

$$M = 3(n-1) - 2j_1$$

$$M = 3(7-1) - 2x8 = 2$$

(b)

Figure 4.4. West 8's the crane-like *Lights* in theatre square *Schouwburgplein* at Rotterdam
(a) The *Lights* in motion
(Source: Urbanidentity, 2020)
(b) Kinematic diagram and mobility calculation of a light

4.4. The Acrobat by Volkert van der Wijk

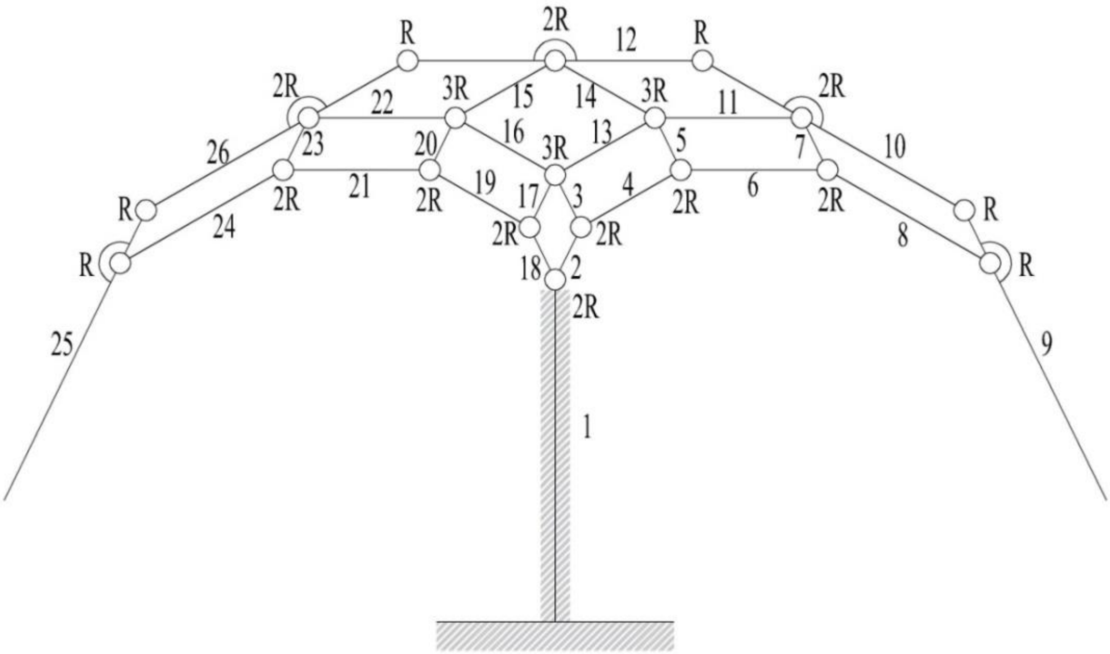
The Acrobat that is designed by mechanical engineer and kinetic art designer Volkert van der Wijk is shown in Figure 4.5.(a). The kinematic diagram and mobility equations of *The Acrobat*'s planar mechanism are shown in Figure 4.5.(b). The 5 DoF *Acrobat* is gravity balanced in each position due to the linkage which is designed to keep in balance at a stationary center of mass. The monary link (base link no. 1), binary links (links no. 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25) and ternary links (links no. 10, 12, 26) are connected by only revolute joints.

4.5. The Strandbeest by Theo Jansen

The Strandbeest, a kinetic design of a new creature which is similar to an animal in terms of being able to walk via wind force is shown in Figure 4.6.(a). A model of the walking legs in three positions is shown in Figure 4.6.(b). Two sides of the legs are connected to each other via common joints and links (links no. 1 and 2), thus are able to move together (see Figure 4.6.(c)). The walking movement, which consists of the sequential motion of symmetrical right and left legs (links no. 8 and 14), is enabled by the rotation motion of link no. 2. The 1 DoF planar mechanism involves binary links (links no. 2, 3, 5, 6, 7, 8, 9, 11, 12, 13, 14) and ternary links (links no. 1, 4, 10) that are connected by only revolute joints.

Considering these parameters $n = 8,\ j_1 = 10$ the mobility calculation is $M = 3(8 - 1) - 2x10 = 1$ in a single leg of *The Strandbeest* mechanism. Mutual joints and links are used in linkage design to generate an eight-bar mechanism with single mobility. Assembly of three different four-bar loops of *The Strandbeest* mechanism is shown in Figure 4.7. The first four-bar loop (links no. 4, 5, 6, 8) is assembled to the second four-bar loop (links no. 3, 4, 6, 7) with two mutual links (links no 4 and 6). The resulting 1 DoF planar linkage is assembled to the third four-bar loop (links no 1, 2, 3, 4) with two mutual links (no. 3 and 4). Thus the numbers of required actuators remain the same (1 DoF).

(a)

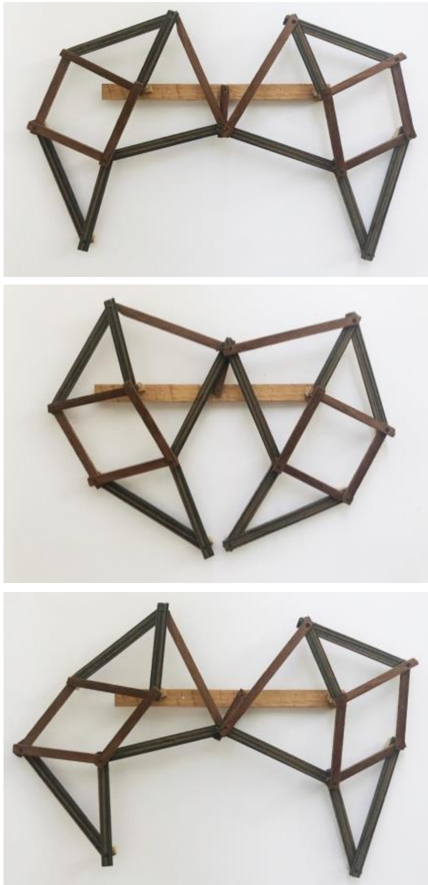


$n = 26 \quad j_1 = 35 \quad M = 5$

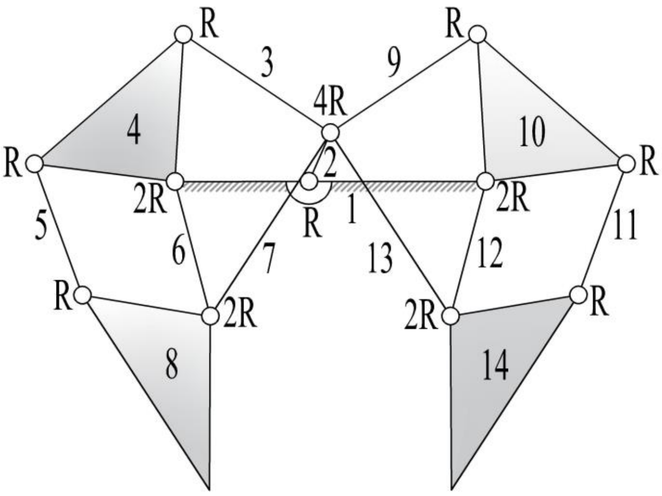
$M = 3(26 - 1) - 2x35 = 5$

(b)

Figure 4.5. Volkert van der Wijk's kinetic sculpture *The Acrobat (2009)*
(a) *The Acrobat* in motion
(Source: Wijk, 2009)
(b) Kinematic diagram and mobility calculation of *The Acrobat*



(a) (b)



$n = 14 \quad j_1 = 19 \quad M = 1$

$M = 3(14 - 1) - 2x19 = 1$

(c)

Figure 4.6. Theo Jansen's kinetic sculpture *The Strandbeest*
(a) *The Strandbeest* in motion
(Source:Strandbeest, 2012)
(b) A unit model of *The Strandbeest* in three positions
(c) Kinematic diagram and mobility calculation of *The Strandbeest* unit

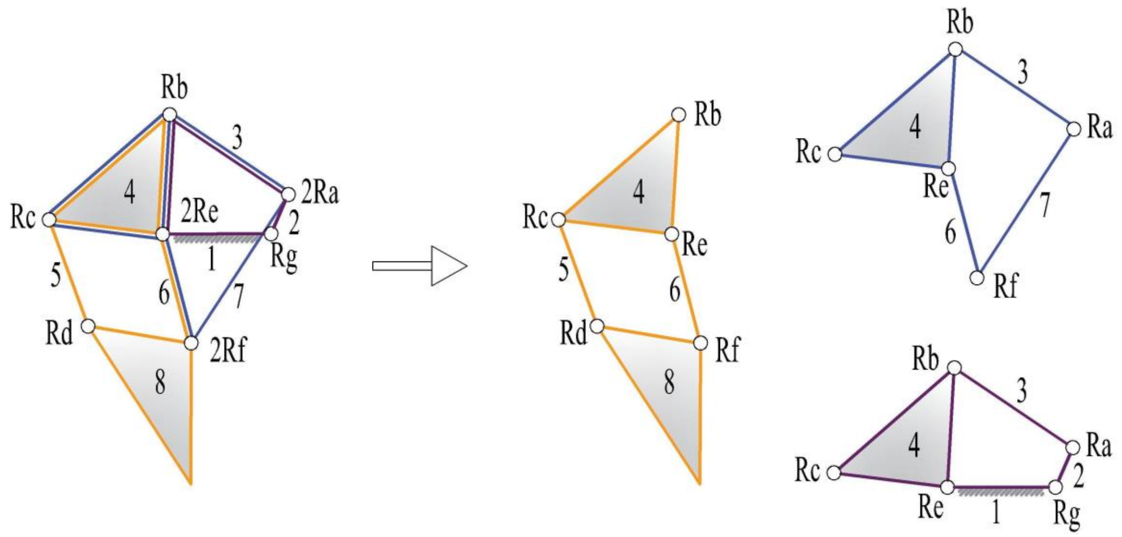


Figure 4.7. Dismantling the three four-bar linkage of the *Strandbeest* mechanism

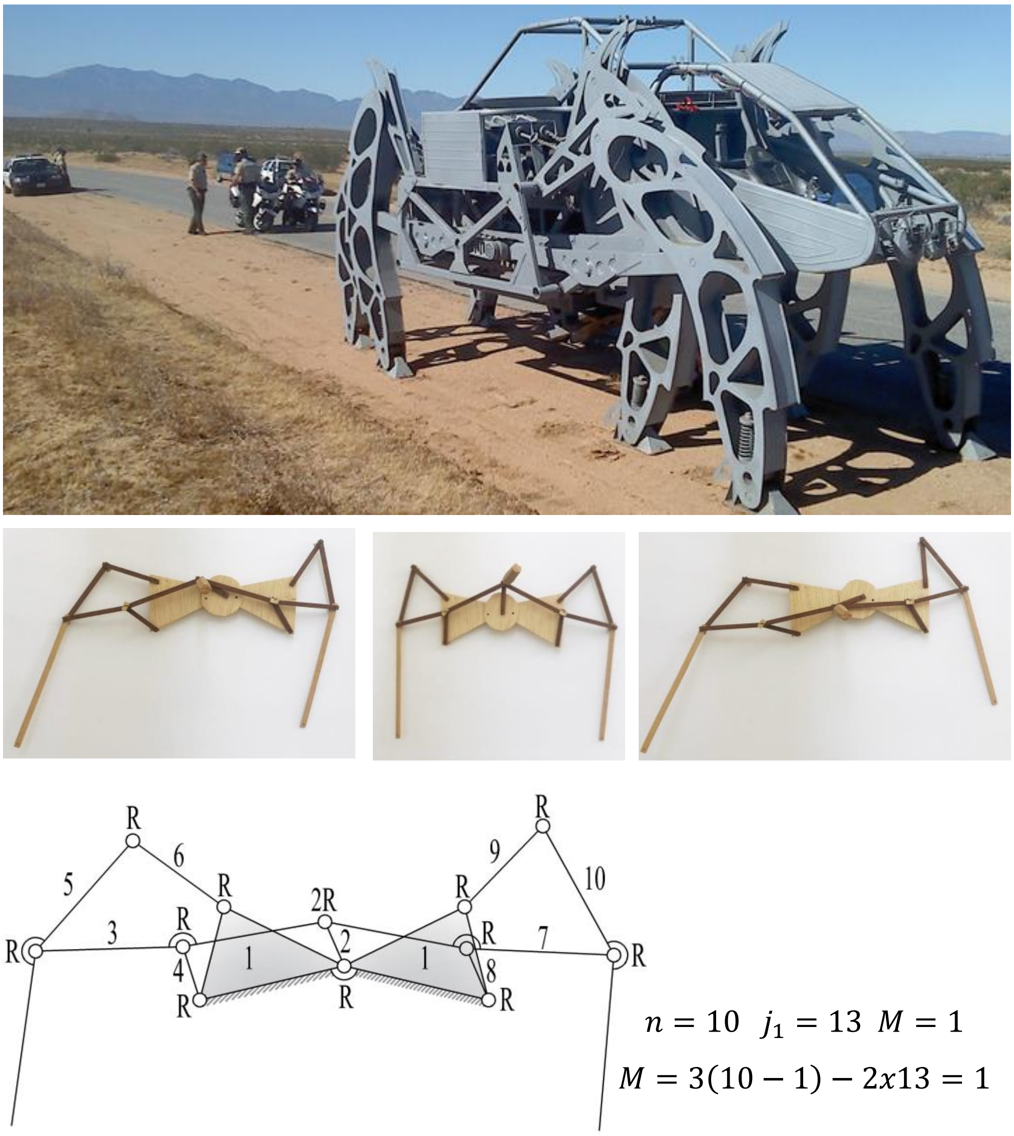
4.6. The Walking Beast by Moltensteelman

The Walking Beast that is built by Martin Montesano is shown in Figure 4.8.(a). Its leg mechanism is based on Klann's patented 6-bar linkage system (Montesano, 2011). A model of the walking legs in three positions is shown in Figure 4.8.(b). Two sides of the legs move together. Two symmetrical legs are assembled with mutual links (links no. 1 and 2) (see Figure 4.8.(c)). The sequential movement (walking) on the legs (links no. 5 and 10) is transformed through the rotation motion of link no. 2. The 1 DoF planar mechanism design consists of binary links (no. 2, 4, 5, 6, 8, 9, 10), ternary links (no. 3 and 7) and a quinary base link with 5 nodes (link no. 1) that are connected by revolute joints.

The *Klann* (2001) *Mechanism* (6-bar and 1 DoF) comprises a *Steffenson chain* (6-bar and 1 DoF) are shown in Figure 4.9.

4.7. The Rolling Bridge by Heatherwick Studio

The *Rolling Bridge* that is designed by the Heatherwick Studio in London, United Kingdom (2002) is shown in Figure 4.10.(a). The underlying idea is to generate a sculptural bridge that provides both a path for pedestrians when deployed and a passage for boats in a compact position. The bridge has 7 actuators on each side, is



(a)

(b)

(c)

Figure 4.8. The *Klann Mechanism*
(a) Moltensteelman's *The Walking Beast*
(Source: Montesano, n.d.)
(b) A unit model of the *Klann Mechanism* in three positions
(c) Kinematic diagram and mobility calculation of the *Klann Mechanism* unit

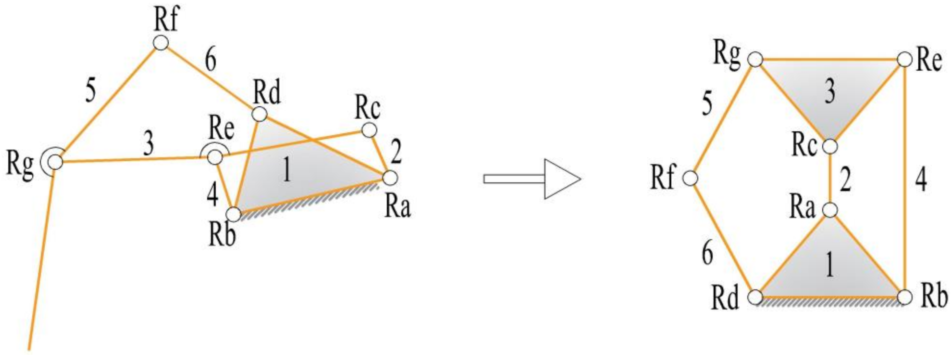


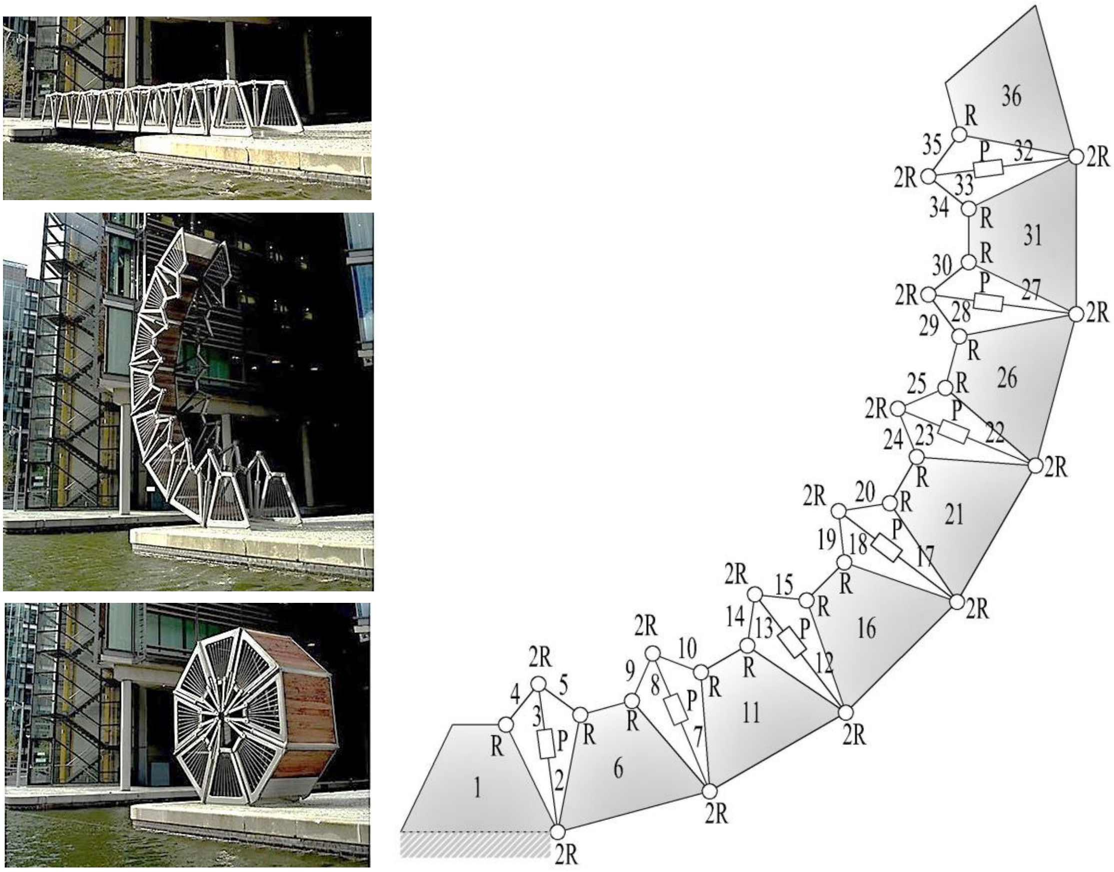
Figure 4.9. The Klann Mechanism and a Steffenson chain

totally activated by 14 actuators. The mechanism in each side of the bridge consists of binary links (no. 1, 2, 3, 4, 5, 7, 8, 9, 10, 12, 13, 14, 15, 17, 18, 19, 20, 22, 23, 24, 25, 27, 28, 29, 30, 32, 33, 34, 35, 36) and quaternary links (no. 6, 11, 16, 21, 26, 31) that are connected with revolute and prismatic joints is shown in Figure 4.10.(b). All actuators operate simultaneously and reveal the same movement. Although the planar mechanism is 7 DoF, performance of the same movement causes the mechanism to operate as a 1 DoF. The bidirectionally repeated planar mechanism also provides the curling movement of a movable floor that consists of 8 pieces of plates that are connected to each other by revolute joints.

The assembly of the first three four-bar loops of the *Rolling Bridge*'s mechanism is shown in Figure 4.11. The first four-bar loop (links no. 1, 2, 3, 4) is assembled to the second four-bar loop (links no 2, 3, 5, 6) with two mutual links (no. 2 and 3). Considering these parameters $n = 6,\ j_1 = 7,$ the mobility calculation is $M = 3(6-1) - 2x7 = 1$. The linkage remains 1 DoF. The second four-bar loop (links no. 2, 3, 5, 6) is assembled to the third four-bar loop (links no. 6, 7, 8, 9) with one mutual link (no. 6). Mobility increases in the absence of two mutual links in the assembly of two four-bar linkages. Considering these parameters $n = 9,\ j_1 = 11$ the mobility calculation is $M = 3(9-1) - 2x11 = 2.$ The mobility value increases to 7 DoF with such additions of several loops.

4.8. The Open View by Ten Fold

The foldable building, *Open View* that is designed by Ten Fold Engineering is shown in Figure 4.12. The kinetic building can be deployed via its mechanisms. Some of the links in the mechanism go up while some of them go down in balance to easily move and carry the loads (Ten Fold Engineering, 2018). Two different planar mechanisms of the *Open View* are shown in Figure 4.12. Models of their deployed and closed configurations are shown in Figure 4.13. These mechanisms are used in both sides of the structure. The opening movement of the *Expand* mechanism provides straight linear transmission of the wall and opening of the floor simultaneously. Binary links (no. 1, 3, 4, 5, 6, 7) and ternary links (no. 2 and 8) that are connected with revolute joints in a 1 DoF mechanism are shown in Figure 4.14.(a). When the mechanism of the



(a) (b)

$$n = 36 \quad j_1 = 49 \quad M = 7$$

$$M = 3(n-1) - 2j_1$$

$$M = 3(36-1) - 2x49 = 7$$

Figure 4.10. Heatherwick Studio's the *Rolling Bridge*
(a) The *Rolling Bridge* in motion
(Source: Heatherwick Studio, 2002)
(b) Kinematic diagram and mobility calculation of the *Rolling Bridge*

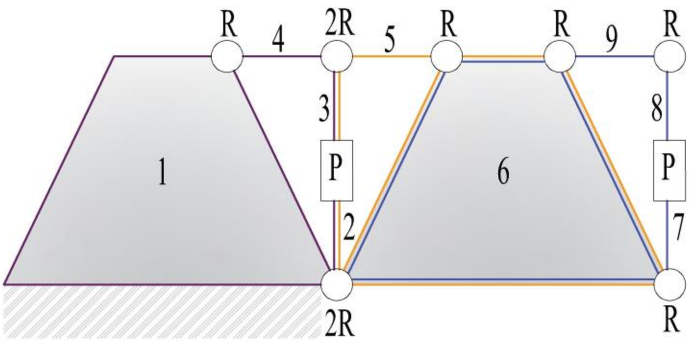


Figure 4.11. The *Rolling Bridge*'s repetitive unit with four-bar configurations

Raise opens the floor, the complex motion of the roof simultaneously results in going up. Binary links (no. 1, 2, 4, 5, 6, 9, 10) and ternary links (no. 3, 7, 8) that are connected with revolute joints in a 1 DoF mechanism are shown in Figure 4.14.(b).

The assembly of three different four-bar loops of the *Expand* is shown in Figure 4.15. The first four-bar loop (links no. 1, 2, 3, 4) is assembled to the second four-bar loop (links no. 2, 4, 6, 8) with two mutual links (no. 2 and 4). The second four-bar loop (links no. 2, 4, 6, 8) is assembled to the third four-bar loop (links no. 5, 6, 7, 8) with two mutual links (no. 6 and 8).

The assembly of four different four-bar loop of the *Raise* is shown in Figure 4.16. The first four-bar loop (links no. 1, 2, 3, 4) is assembled_to the second four-bar loop (links no. 3, 4, 5, 6) with two mutual links (no. 3 and 4). Second four-bar loop (links no. 3, 4, 5, 6) is assembled to the third four-bar loop (links no. 5, 6, 7, 8) with two mutual links (no. 5 and 6). The third four-bar loop (links no. 5, 6, 7, 8) is assembled to the fourth four-bar loop (links no. 7, 8, 9, 10) with two mutual links (no. 7 and 8).

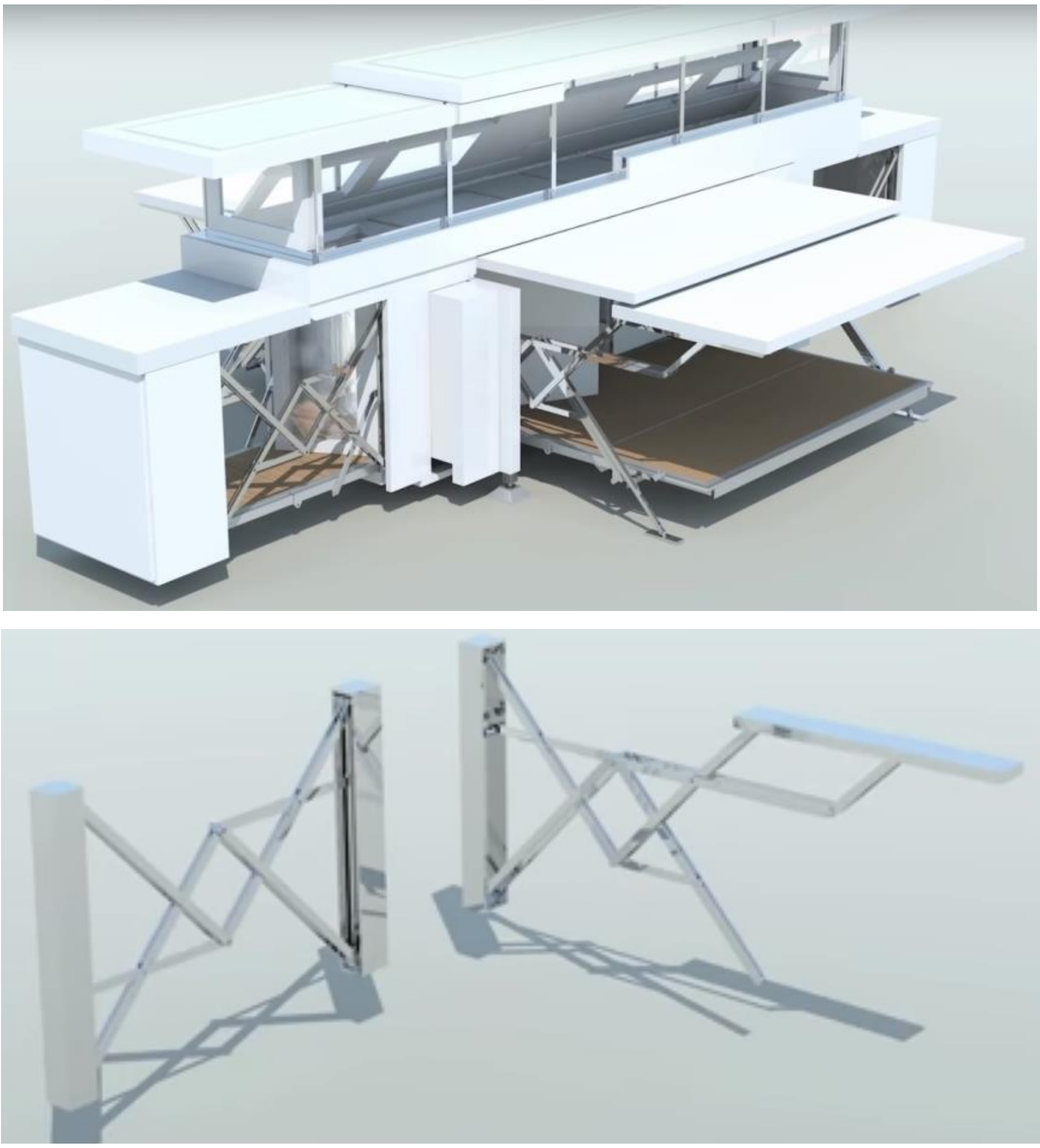
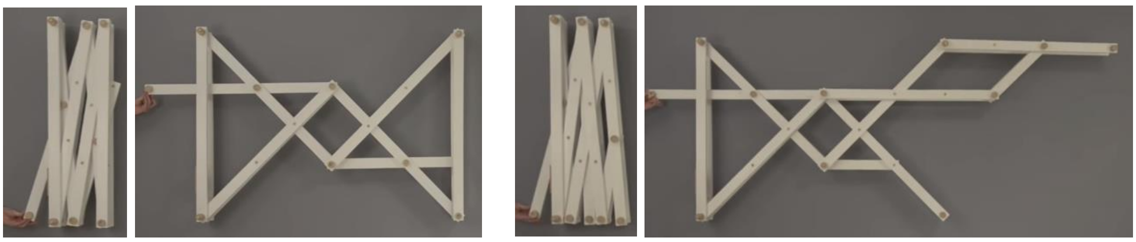
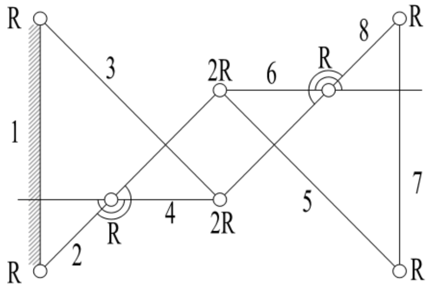


Figure 4.12. Ten Fold Engineering’s foldable builiding *Open View*
(Source: Ten Fold Engineering, 2014)



(a) (b)

Figure 4.13. Two mechanism models of *The Open View*
(a) The *Expand*
(Source: Ten Fold Engineering, 2016)
(b) The *Raise*
(Source: Ten Fold Engineering, 2016b)

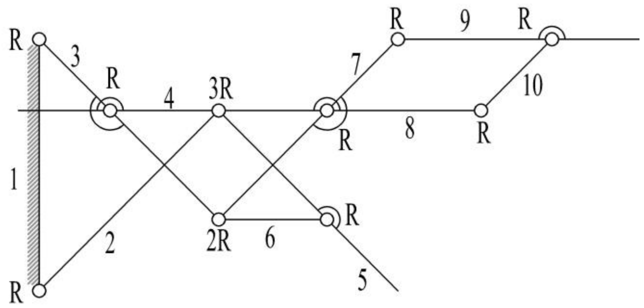


$n = 8 \quad j_1 = 10 \quad M = 1$

$$M = 3(n-1) - 2j_1$$

$$M = 3(8-1) - 2x10 = 1$$

(a)



$n = 10 \quad j_1 = 13 \quad M = 1$

$$M = 3(n-1) - 2j_1$$

$$M = 3(10-1) - 2x13 = 1$$

(b)

Figure 4.14. Kinematic diagrams and mobility equations of two primary units of the *Open View* (a) The *Expand* (b) The *Raise*

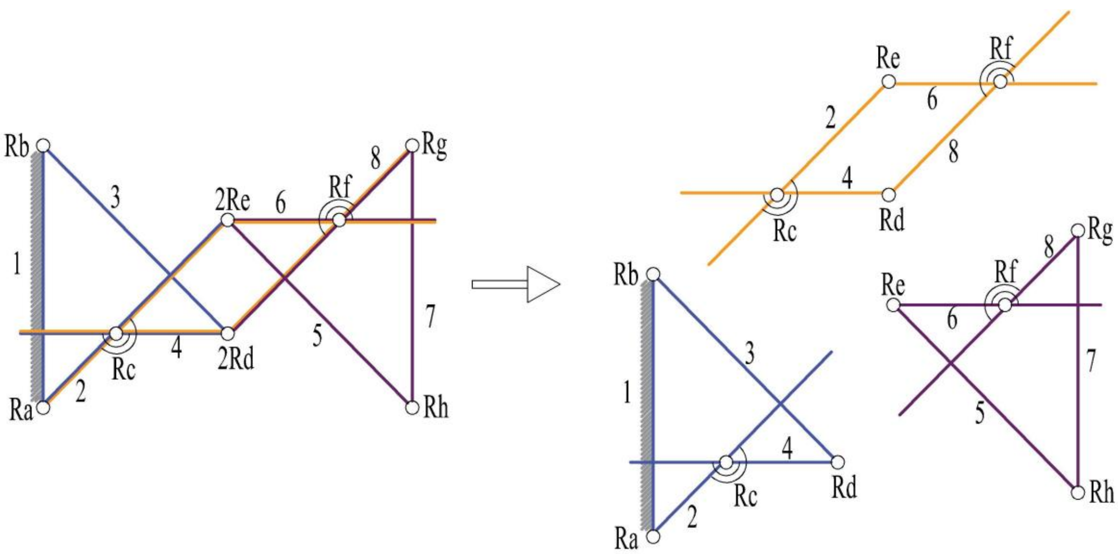


Figure 4.15. Dismantling the three four-bar loop of the *Expand*

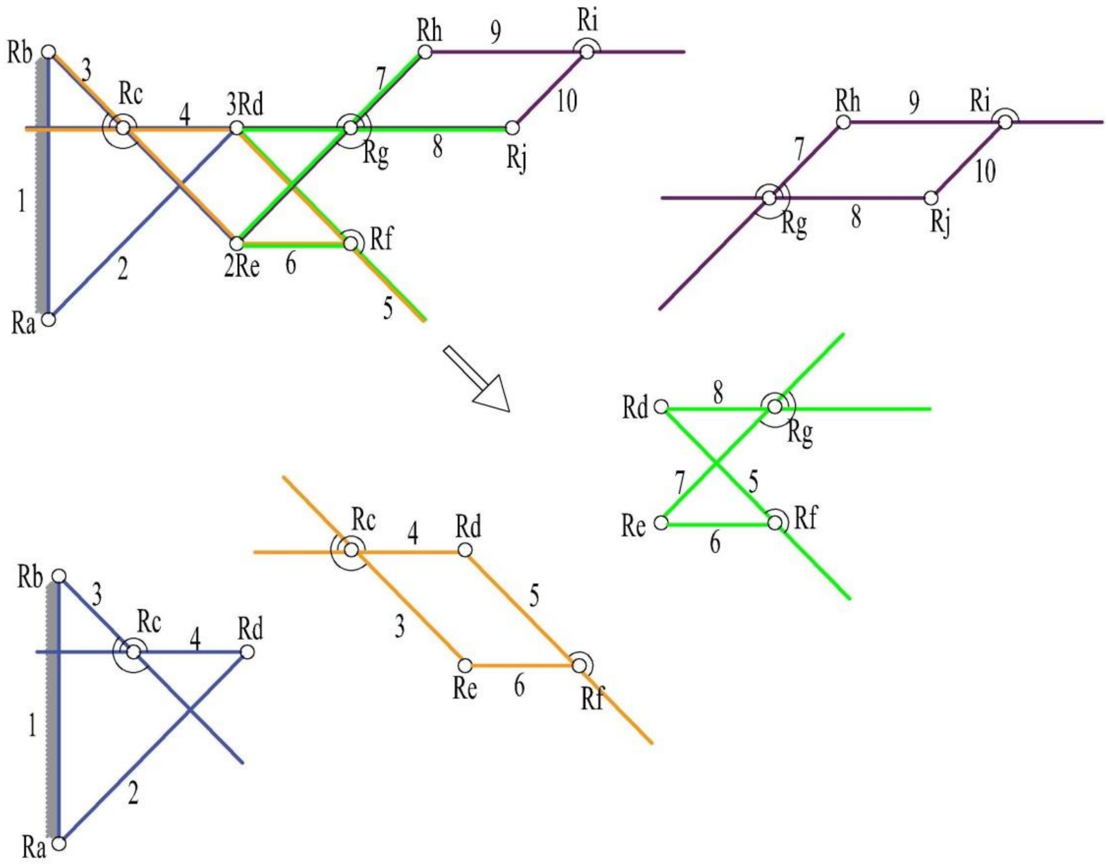


Figure 4.16. Dismantling the four four-bar loop of the *Raise*

CHAPTER 5

CASE STUDY

5.1. Definition of the Deployable Surface Design Problem and Method

Building parts that are adaptable to changing environmental conditions are sought out in today's architecture. Proper solutions can be offered by deployable planar surfaces. A deployable surface can be described as a part of a building that allows movement to respond to the changing environmental conditions and user needs. The objective of the present section is to develop a deployable system that can be used as a part of a building.

This section describes the process of a novel deployable system that is capable of creating 1 DoF adaptable planar surfaces through mechanisms. Numerous architectural forms, including facades, walls, separators, roofs and canopies, consist of planar surfaces. The purpose of the current chapter is to develop a deployable system to be used in presence of movable surfaces with 1 DoF mechanisms. This system can serve as an architectural element such as sun shading panels do. This system can also be produced as statues or statue elements since a 3D dynamic form is revealed in motion.

Regular convex polygons are selected to obtain a deployable system. Development of a unit adaptable to all regular convex polygons is aimed. A movable primary unit design that is relevant to the current design problem is generated. The primary unit is the assembly of a planar 4-bar loop and a spherical 4-bar loop. The planar surface is generated in the deployed configuration and reveals 3D forms through the spherical loop during movement. This unit is topologically Bennett’s (1995) variation of Sarrus’s overconstrained 6-bar, 1 DoF plano-spherical mechanism.

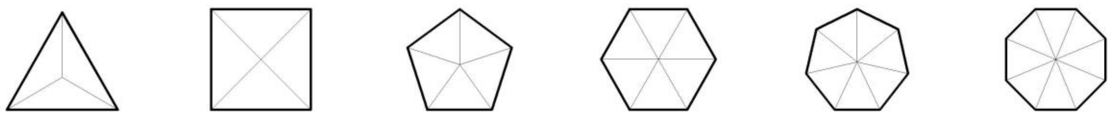
After the primary unit is generated, it is adapted to be repeated in regular convex polygons by changing the link dimensions and angles of the connections. Models and analyses are mostly examined on the planar configurations that are the focal point to serve the purpose of revealing mobility. Various 3D deployable polygonal modules are subsequently selected for modeling and analyzing.

The following procedure is the repetition of deployable modules to cover the planar surfaces leaving no gaps or overlaps in the deployed position. Deployable regular and semi-regular tessellations that are designed with the assembly of these deployable polygons.Mutual links and connections are selected with respect to the assembly of two or more polygons that can move without collision or overlapping.

Kinematic designs are generated with the synthesis and analysis methods. Types and numbers of links with joints, as well as mobility analyses, are revealed with kinematic diagrams, calculations, and CAD models for the design. The drawings and CAD models are generated using Autocad© and Solidworks© programs.

5.2. Kinematic Design of a Primary Unit

The first decision is made about the primary linkage unit design which is aimed to be used in a movable planar surface. Regular convex polygons are examined in order to develop an adaptable unit. These are triangle, tetragon, pentagon, hexagon, etc. Firstly, the regular convex polygons are broken up into as many triangles as the number of polygon sides. The triangles formed with lines that are drawn from the geometric center to the vertices of each polygon are shown in Figure 5.1. Thus, the triangle is selected as the primary unit.



Triangle Tetragon Pentagon Hexagon Heptagon Octagon

Figure 5.1. The break up of regular convex polygons into triangles

As aforementioned, the simplest planar linkage is 4-bar. Thus, a 4-bar linkage that has a triangular shape in the fully deployed configuration is generated. A 6-bar linkage is subsequently developed with 2 additional plates to cover a surface. The design steps from a triangle to a plano-spherical 3D linkage in its fully deployed form are shown in Figure 5.2.

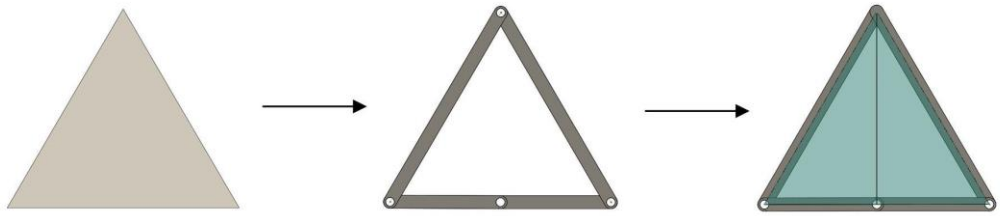


Figure 5.2. The design steps of a primary unit from a triangle to a plano-spherical linkage

This 3D linkage is topologically Bennett's (1905) variation of Sarrus's 6-bar, 1 DoF, overconstrained mechanism if the top revolute joint of the four-bar loop in Figure 5.2 is removed. Bennett describes the Sarrus linkage and two other variations as double-spherical (spherical and spherical), plano-spherical (planar and spherical) and double-planar (the Sarrus linkage) (Alizade, Kiper, Dede, & Uzunoğlu, 2014). As mentioned, joint axes of spherical mechanisms intersect on a finite point whereas joint axes of planar mechanisms are parallel. Bennett defines the variations as two imaginary four-bars (spherical and/or planar) that are assembled with two common links. One of the four-bar loop is planar and the other is spherical in the plano-spherical linkage.

The Sarrus linkage and the primary unit linkage are step by step shown with their similarities and differences in Figure 5.3. The plano-spherical linkage defined by Bennett with the model and the plan for the disconnected state of links R and S are shown in Figure 5.3.(a). The first four-bar loop in which A, T, U, B links are connected with revolute joints is planar while the second four-bar loop in which A, R, S, B links are connected with revolute joints is spherical. The ATUB loop is assembled with the ARSB loop with two common links: A and B. The intersection of revolute joints in the ATUB loop occurs on an infinite point, thus their axes (Y) are parallel to each other while the axes of revolute joints at the ARSB loop intersect on a finite point (X). The point X acts as a virtual hinge that is categorized as a redundant joint during motion (Bennett, 1905).

A 6-bar primary linkage unit that has identical topological properties with the Bennett plano-spherical mechanism is generated. A and B are used as common links in the assembly of the ATUB planar four-bar loop with the ARSB spherical four-bar loop. The DoF in the mechanism thus remains the same with the use of two common links in the assemly of two four-bar loops as explained in section 4.5. The axes of revolute joints of the ATUB planar loop are parallel to each other (Y). The revolute joint axes of the ARSB four-bar spherical loop intersect on a finite point (X). The triangular shape in the deployed position of the unit is generated by the decision of the shapes, junction procedures and dimensional ratios of the links. R and S are right triangular shaped binary links. The joint axes between A-R and S-B links have right angles to the ATUB loop joint axes (Y). The dimensions of the links R = S, A = B, and T = U (see Figure 5.3).

The top view of CAD models and the kinematic diagrams of 4-bar planar and 6-bar plano-spherical mechanisms are shown in Figure 5.4. Links no. 1 are taken to be fixed. Considering these parameters $n = 4,\ j_1 = 4,$ the mobility calculation of the 4-bar planar ($\lambda = 3$) mechanism (see Figure 5.4.(a)) is:

$$M = 3(n-1) - 2j_1$$
$$M = 3(4-1) - 2\text{x}4 = 1$$

Despite the 4-bar primary unit being in a triangular shape in the deployed position, it is categorized as a quadrilateral geometric shape since it is generated by a 4-bar linkage. The quadrilateral unit is in the special *kite* shape. The kite geometry reveals equal lengths of adjacent links. The length of link no.1 is equal with link no. 2, and the length of link no. 3 is equal with link no. 4.

Considering these parameters $n = 6,\ j_1 = 6,$ the mobility calculation of the 6-bar plano-spherical overconstrained ($\lambda = 5$, 3 rotations and 2 translations) mechanism (see Figure 5.4.(b)) is:

$$M = 5(n-1) - 4j_1$$
$$M = 5(6-1) - 4\text{x}6 = 1$$

Both 4-bar and 6-bar (with two plates) units are 1 DoF mechanisms. In a plano-spherical mechanism, the spherical four-bar ARSB linkage's revolute joint axes intersect at point X. This point X, which corresponds to the Rc joint in the 4-bar linkage, is shown in Figure 5.4. Rc is the actual joint of the 4-bar unit in the current study that examines motion. Addition of plates makes the Rc joint redundant, thus it is removed from the cad models. Removals of redundant joints have no effect on kinematic motion.

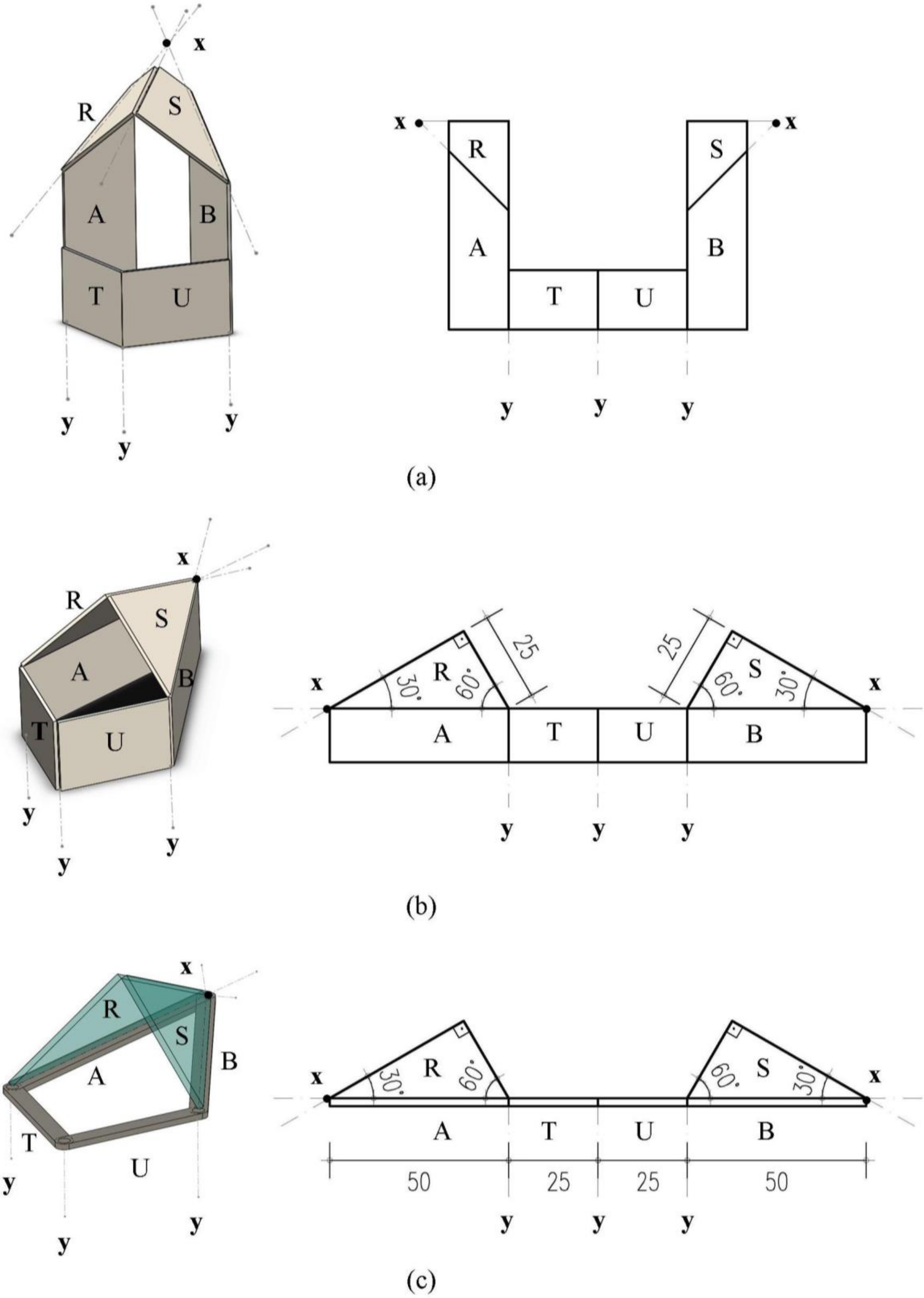
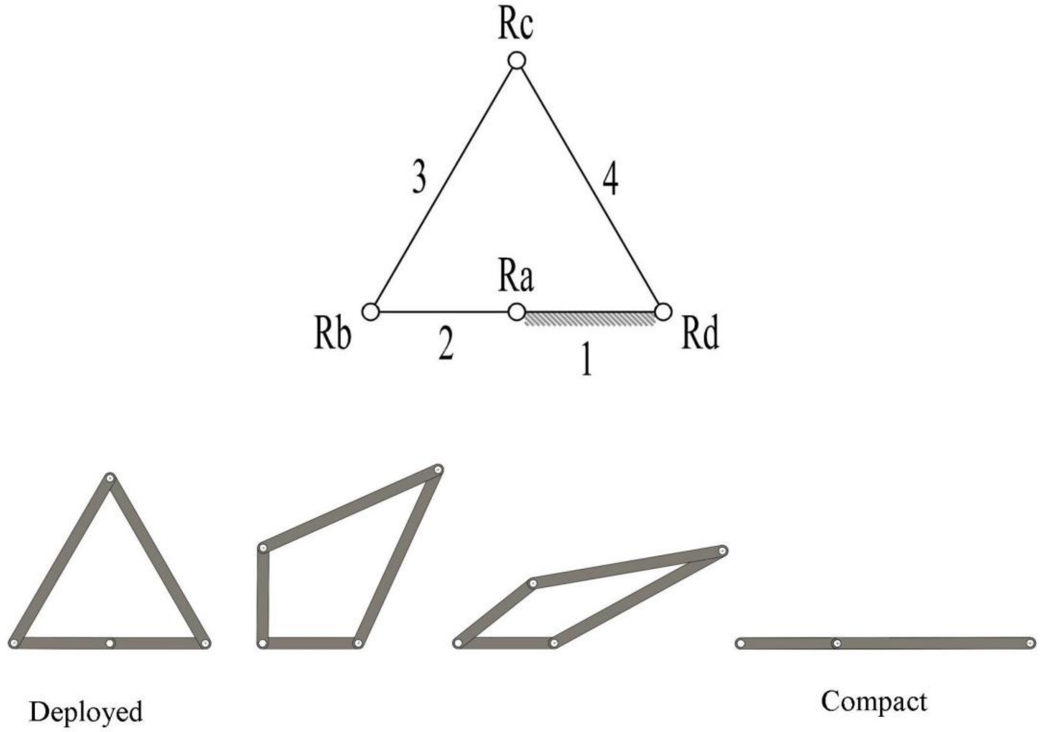
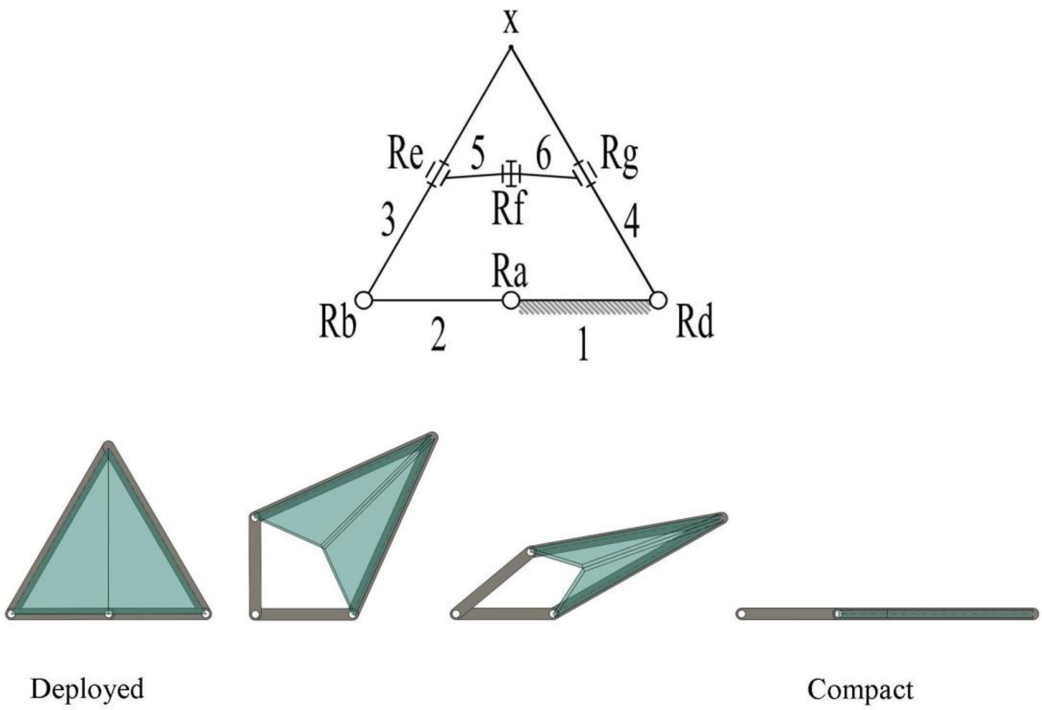


Figure 5.3. Plano-spherical mechanism models and plans when the R and S links are disconnected from each other and the mechanisms are flattened
(a) A Bennett's plano-spherical mechanism
(Source: Redrawn by the author from Bennett, 1905)
(b) The developed unit with only plates
(c) The generated deployable unit with two plates R, S and four bars A, T, U, B



(a)



(b)

Figure 5.4. Kinematic diagrams and motion sequence of the primary mechanism units
(a) 4-bar planar mechanism (b) 6-bar plano-spherical mechanism

5.3. Repetition of the Primary Unit in the Deployable Polygons

A figure with at least three line segments that are closed in a plane is called a *polygon*. The straight line segments are referred as the *sides* and the intersections of the sides are referred as *vertices*. Polygons are named by their number of sides. Polygons with equal interior angles and equal side lengths are called *regular polygons* which are either convex or star shaped. Regular convex polygons from the triangle up to the dodecagon are shown in Figure 5.5.

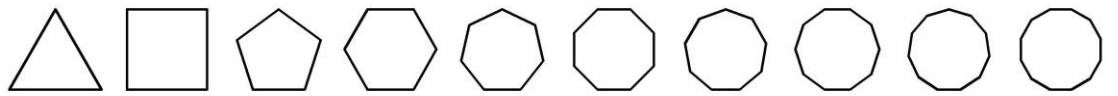


Figure 5.5. Regular convex polygons from the triangle to the dodecagon

Each regular convex polygon can be broken up into triangles by a line drawn from the geometric center to the vertices. Triangles are congruent (identical in shape and size) in each polygon. Primary linkage unit dimensions and angles are adapted to the triangles that are used. Units have rotational symmetry around the centers of the polygons and they are repeated as many times as the number of the sides of the polygon. The units are assembled from the center of the polygon with two mutual links. This method provides each deployable polygon 1 DoF. Mobility is primarily analyzed in terms of planar modules that assemble 4-bar units.

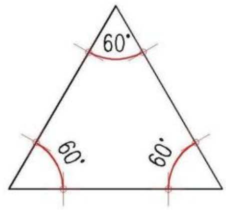
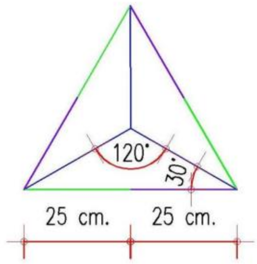
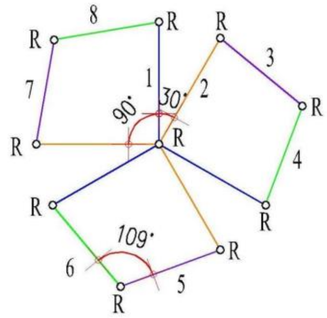
The assembly of three congruent four-bar loops in the planar deployable *triangle* is shown in Table 5.1. The first four-bar loop (links no. 1, 2, 3, 4) is assembled to the second four-bar loop (links no. 1, 2, 4, 5) and the third four-bar loop (links no. 1, 2, 7, 8) with two mutual links (no. 1 and 2). In this mechanism, links no. 1and 2 are congruent quaternary links (4 nodes) and congruent links no. 3, 4, 5, 6, 7, 8 are binary links (2 nodes). Link no. 1 is the fixed link and the input rotation motion is actuated by link no. 2. A rotation of 120° ($\frac{2\pi}{3}\ rad$) is generated by link no. 2 between the compact and deployed positions of the mechanism. Considering these parameters $n = 8,\ j_1 = 10,$ the mobility calculation is $M = 3(8-1) - 2x10 = 1$.

The assembly of four congruent four-bar loops in the planar d*eployable square* is also shown in Table 5.2. The first four-bar loop (links no. 1, 2, 3, 4) is assembled to the second four-bar loop (links no. 1, 2, 4, 5), the third four-bar loop (links no. 1, 2, 7, 8) and the fourth four-bar loop (links no. 1, 2, 9, 10) with two mutual links (links no. 1 and 2). In this mechanism, links no. 1 and 2 are congruent-quinary links (5 nodes) and links no. 3, 4, 5, 6, 7, 8, 9 and 10 are congruent binary links (2 nodes). Link no. 1 is the fixed link and the input rotation motion is actuated by link no. 2. A rotation of 90° ($\frac{2\pi}{4}$ rad) is generated by link no. 2 between the compact and deployed positions of the mechanism. Considering these parameters $n = 10,\ j_1 = 13,$ the mobility calculation is $M = 3(10-1) - 2x13 = 1$.

The single Dof planar deployable polygons' mobility parameters with link and joint numbers of the deployable polygons, from the pentagon to the dodecagon, are shown in Table 5.3. The same method of the deployable triangle and square is used for repetition and assembly in the design process of the other deployable polygons. Links no. 1 and 2 are congruent and have 6 nodes (senary) links in the deployable pentagon (5 sides), 7 nodes (septenary) links in the deployable hexagon (6 sides), 8 nodes (octonary) links in the deployable heptagon (7 sides), 9 nodes (nonary) links in the deployable octagon (8 sides), 10 nodes (denary) links in the deployable nonagon (9 sides), 11 nodes (undenary) links in the deployable decagon (10 sides), 12 nodes (duodenary) links in the deployable undecagon (11 sides), and 13 nodes (tredenary) links in the deployable dodecagon (12 sides). Remaining links are equal-length binary links (2 nodes).

The base link (no. 1) and the rotation degree of the input link (no. 2) in the planar designs, from the deployable pentagon to the deployable dodecagon, are shown in Table 5.3 as well. 2π radians correspond to $360°$. Rotation of $\frac{2\pi}{5}$ rad is generated by link no. 2 between the compact and deployed positions of the deployable pentagon. A rotation of $\frac{2\pi}{6}$ rad is generated in the deployable hexagon, $\frac{2\pi}{7}$ rad in the deployable heptagon, $\frac{2\pi}{8}$ rad in the deployable octagon, $\frac{2\pi}{9}$ rad in the deployable nonagon, $\frac{2\pi}{10}$ rad in the deployable decagon, $\frac{2\pi}{11}$ rad in the deployable undecagon and $\frac{2\pi}{12}$ rad in the deployable dodecagon. 1 DoF mechanisms can be controlled by a single actuator.

Table 5.1. Kinematic properties of the *planar deployable triangle module*

Deployable Triangle — Planar		
Triangle	Deployed Triangle	Kinematic Diagram
		
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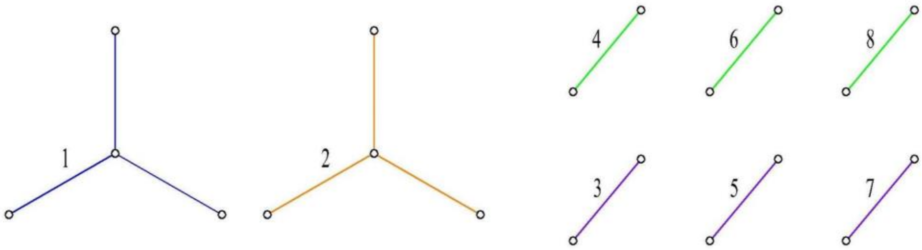		
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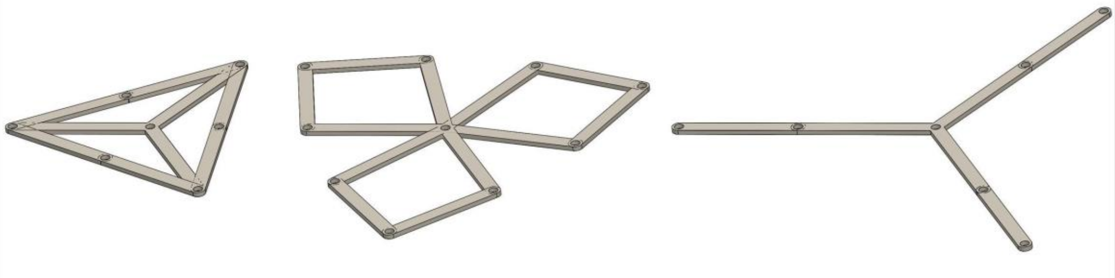
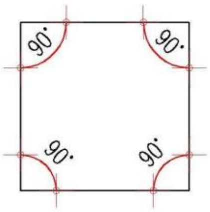
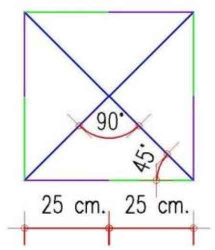
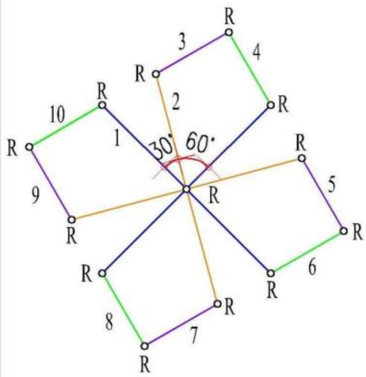
		

Table 5.2. Kinematic properties of the *planar deployable square module*

<table>
<tr><td colspan="3">Deployable Square — Planar</td></tr>
<tr><td>Square</td><td>Deployed Square</td><td>Kinematic Diagram</td></tr>
<tr><td></td><td></td><td></td></tr>
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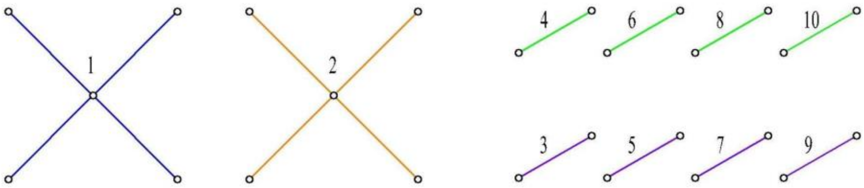
<tr><td colspan="3"></td></tr>
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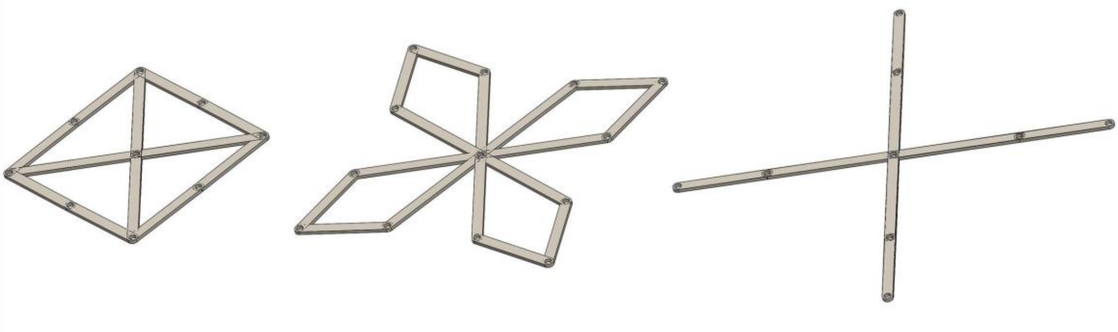
<tr><td colspan="3"></td></tr>
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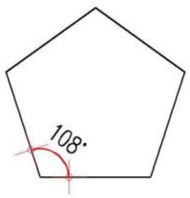
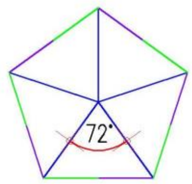
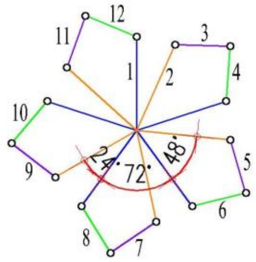
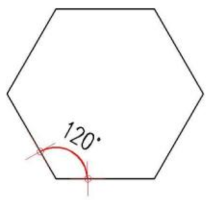
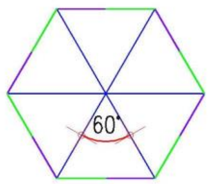
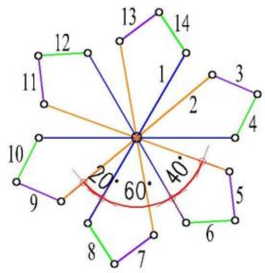
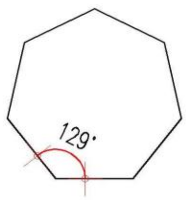
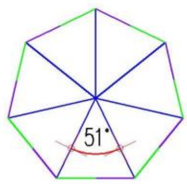
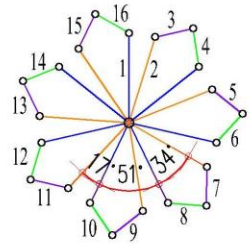
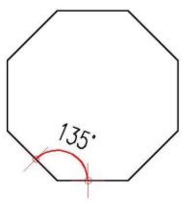
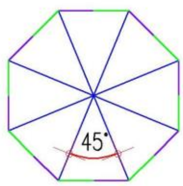
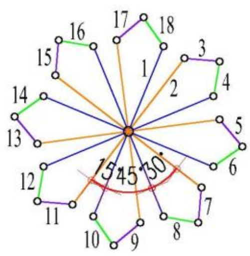
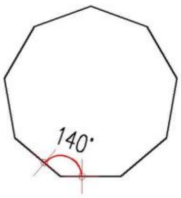
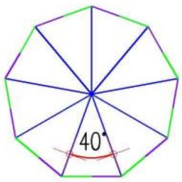
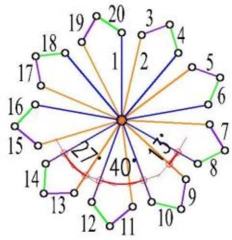
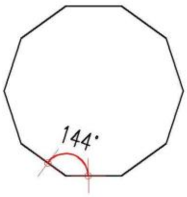
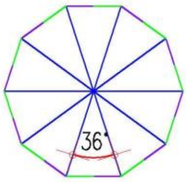
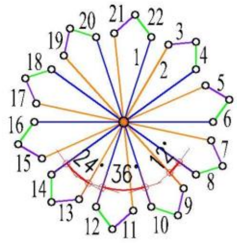
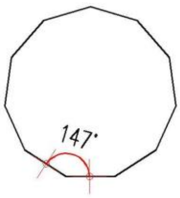
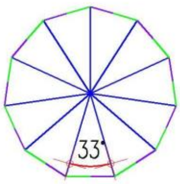
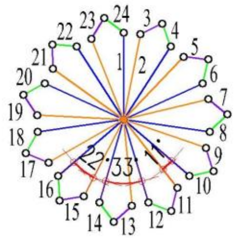
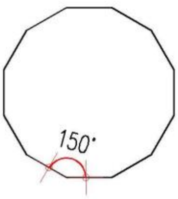
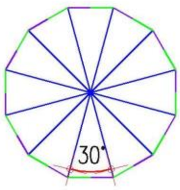
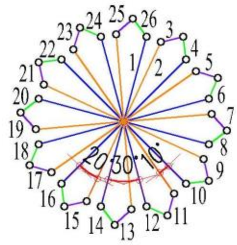
Table 5.3. Kinematic properties of the *planar deployable polygon modules*

	Regular Convex Polygons	Deployable Polygons	Kinematic Diagrams
Deployable Pentagon (5 side) $n = 12,$ $j_1 = 16,$ $M = 1$			
Deployable Hexagon (6 side) $n = 14,$ $j_1 = 19,$ $M = 1$			
Deployable Heptagon (7 side) $n = 16,$ $j_1 = 22,$ $M = 1$			
Deployable Octagon (8 side) $n = 18,$ $j_1 = 25,$ $M = 1$			

(cont. on next page)

Table 5.3. (cont.)

	Regular Convex Polygons	Polygon Mechanisms	Kinematic Diagrams
Deployable Nonagon (9 side) $n = 20,$ $j_1 = 28,$ $M = 1$			
Deployable Decagon (10 side) $n = 22,$ $j_1 = 31,$ $M = 1$			
Deployable Undecagon (11 side) $n = 24,$ $j_1 = 34,$ $M = 1$			
Deployable Dodecagon (12 side) $n = 26,$ $j_1 = 37,$ $M = 1$			

The addition of plates to the planar 4-bar unit, results in the generation of a 6-bar plano-spherical unit. The new 6-bar unit that is adapted to triangle and square polygons is examined in the current section. This method is adaptable to every polygon.

As mentioned before, redundant joints are not used in case of modules consisting of plano-spherical units. The axes in the spherical linkage of the 6-bar unit of these revolute joints intersect at the point X. The special geometrical condition provides the module with single DoF even though the links no. 1 and 2 are not directly connected to each other as shown in Table 5.4.

The mobility equation can be used for calculating mobility including the number of loops in the mechanism. Freudenstein and Alizade's formula (1975) is a modified version of the Grübler-Kutzbach formula (Gogu, 2005). This formula is used to determine the plano-spherical linkage assembly in the current study. The mobility formula of Freudenstein and Alizade's is:

$$M = \sum_{i=1}^{j} j_i - \sum_{k=1}^{L} \lambda_k$$

Where M is the mobility, L is the number of independent loops in the mechanism, λ_k is the active motion space dimension ($\lambda = 2,3,4,5,6$), n is the total number of links in a mechanism, j_i is the number of i DoF joints (Alizade, Bayram, & Gezgin, 2007).

The numbers of independent loops are determined via Euler's formula for polyhedral (Alizade et al., 2007). The Euler equation is:

$$L = j - n + 1$$

Where L is the number of independent loops, j is the number of joints and n is the number of the links.

The assembly of two congruent 6-bar plano-spherical linkage units is shown in Table 5.4. The first six-bar loop (links no. 1, 2, 3, 4, 7, 8) is assembled to the second six-bar loop (links no. 1, 2, 5, 6, 9, 10). In this mechanism, links no. 1 and 2 are congruent binary links (2 nodes). Bars no. 3, 4, 5, 6 and congruent plates no. 7, 8, 9, 10 are binary links (2 nodes). Link no. 1 is the fixed link and link no. 2 is the input link. Considering these parameters $n = 10,\ j_1 = 12,$ the independent loop calculation of the two plano-spherical unit assembly is $L = 12 - 10 + 1 = 3.$ There are 3 independent loops: the first one is plano-spherical ($\lambda = 5$), the second one is planar ($\lambda = 3$) and the third one is spherical ($\lambda = 3$). The three independent possible loops are shown in Table 5.4. Considering these parameters $j_1 = 12,\ L = 3,$ the mobility calculation is $M =$

$12 - (5x1) - (3x1) - (3x1) = 1$. This results in the assembly of two plano-spherical units with 2 mutual links to remain as a 1 DoF mechanism.

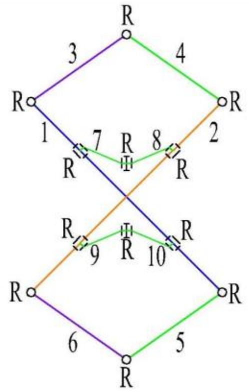
The assembly of three congruent 6-bar plano-spherical loop of the *Deployable Triangle* is shown in Table 5.5. The first six-bar linkage (links no. 1, 2, 3, 4, 9, 10) is assembled to the second six-bar loop (links no. 1, 2, 5, 6, 11, 12) and the third six-bar loop (links no. 1, 2, 7, 8, 13, 14) with two mutual links (no. 1 and 2). In this mechanism, links no. 1 and 2 are congruent ternary links (3 nodes). Bars no. 3, 4, 5, 6, 7, 8 and congruent plates no. 9, 10, 11, 12, 13, 14 are binary links (2 nodes). Link no. 1 is the fixed link and link no. 2 is the input link. Considering these parameters $n = 14,\ j_1 = 18,$ the independent loop calculation is $L = 18 - 14 + 1 = 5.$ There are 5 independent loops, one of them is plano-spherical ($\lambda = 5$), two of them are planar ($\lambda = 3$) and two of them are spherical ($\lambda = 3$). As an example, the loop that is formed by links no. 1, 14, 13, 2, 7, 8 is plano-spherical ($\lambda = 5$), the loop that is formed by links no. 2, 3, 4, 1, 6, 5 is planar and the loop that is formed by links no. 2, 9, 10, 1, 12, 11 is spherical ($\lambda = 3$). Considering these parameters $j_1 = 18,\ L = 5,$ the mobility calculation is $M = 18 - (5x1) - (3x2) - (3x2) = 1.$

The assembly of four congruent 6-bar plano-spherical linkages of the *Deployable Square* is shown in Table 5.6. The first 6-bar loop (links no. 1, 2, 3, 4, 11, 12) is assembled to the second 6-bar loop (links no. 1, 2, 5, 6, 13, 14), the third six-bar loop (links no. 1, 2, 7, 8, 15, 16), and the fourth six-bar linkage (links no. 1, 2, 9, 10, 17, 18) with two mutual links (no. 1 and 2). In this mechanism, links no. 1 and 2 are congruent quaternary links (4 nodes) and congruent bars no. 3, 4, 5, 6, 7, 8, 9, 10 and congruent plates no. 11, 12, 13, 14, 15, 16, 17, 18 are binary links (2 nodes). Link no. 1 is the fixed link and link no. 2 is the input link. Considering these parameters $n = 18,$ $j_1 = 24,$ the independent loop calculation is $L = 24 - 18 + 1 = 7.$ There are 7 independent loops, one of them is plano-spherical ($\lambda = 5$), three of them are planar ($\lambda = 3$) and three of them are spherical ($\lambda = 3$). As an example, the loop that is formed by links no. 2, 11, 12, 1, 4, 3 is plano-spherical ($\lambda = 5$), the loop that is formed by links no. 2, 3, 4, 1, 8, 7 is planar and the loop that is formed by links no. 2, 11, 12, 1, 18,17 is spherical ($\lambda = 3$). Considering these parameters $j_1 = 24,\ L = 7,$ the mobility calculation is $M = 24 - (5x1) - (3x3) - (3x3) = 1.$

Table 5.4. Kinematic properties of the assembly of two *plano-spherical units*

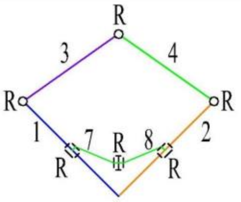
Assembly of Two Units — Plano-Spherical

Kinematic Diagram

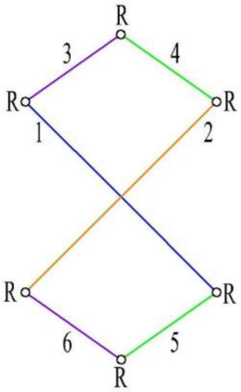


Loops

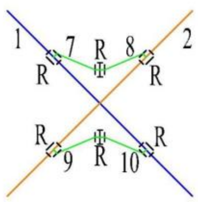
A Plano-Spherical Loop



A Planar Loop



A Spherical Loop



Motion Sequence

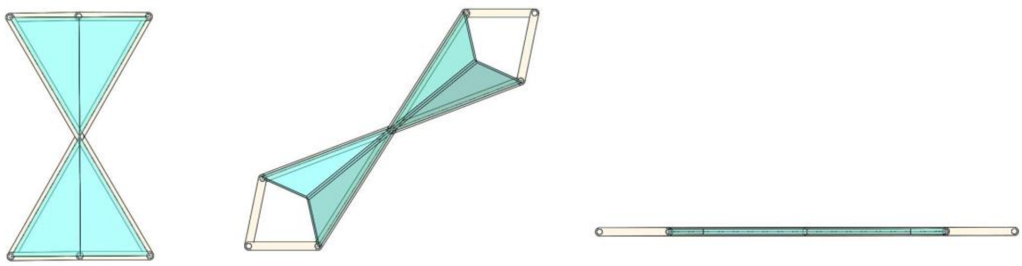


Table 5.5. Kinematic properties of the *plano-spherical deployable triangle module*

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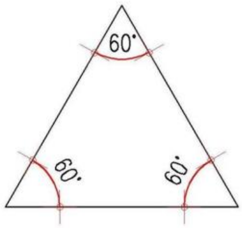
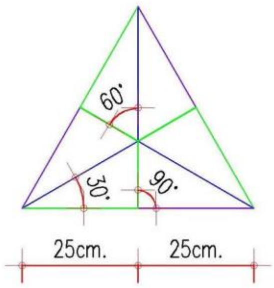
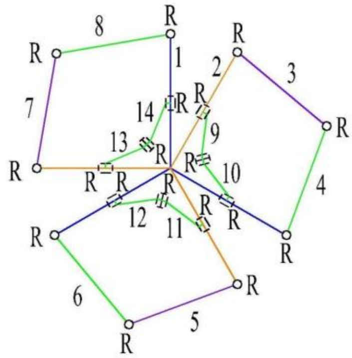
<tr><td colspan="3">Deployable Triangle — Plano-Spherical</td></tr>
<tr><td>Triangle</td><td>Deployed Triangle</td><td>Kinematic Diagram</td></tr>
<tr><td>
</td><td>
</td><td>
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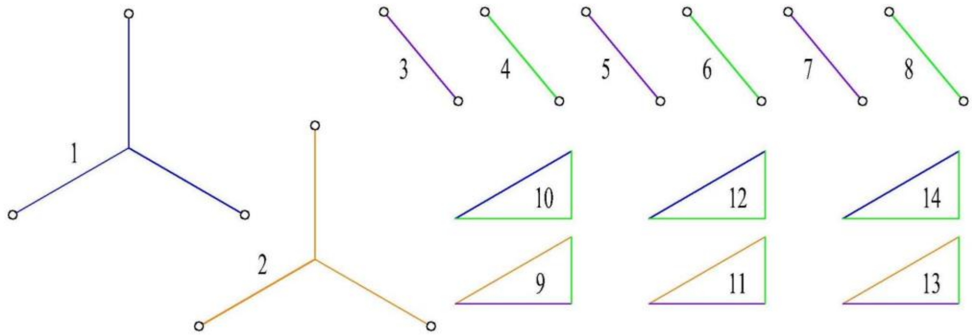
<tr><td colspan="3">
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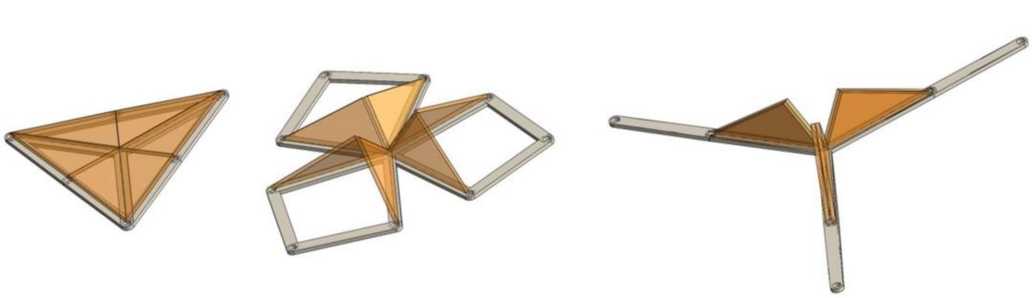
<tr><td colspan="3"></td></tr>
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Table 5.6. Kinematic properties of the *plano-spherical deployable square module*

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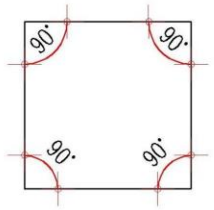
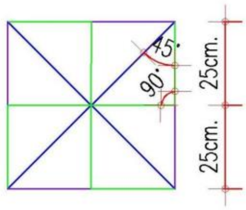
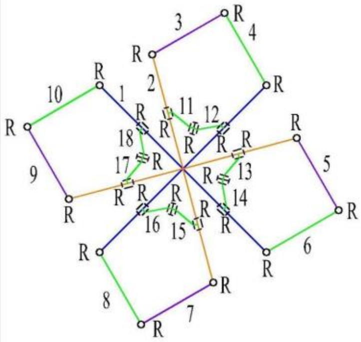
<tr><td>Square</td><td>Deployed Square</td><td>Kinematic Diagram</td></tr>
<tr><td>
</td><td>
</td><td>
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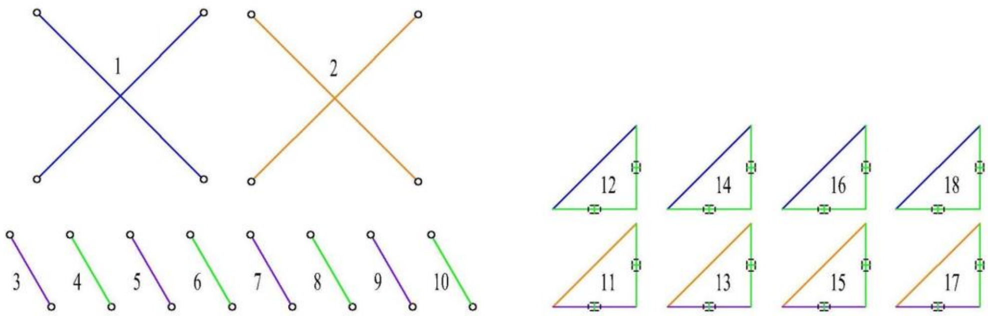
<tr><td colspan="3">Links</td></tr>
<tr><td colspan="3">
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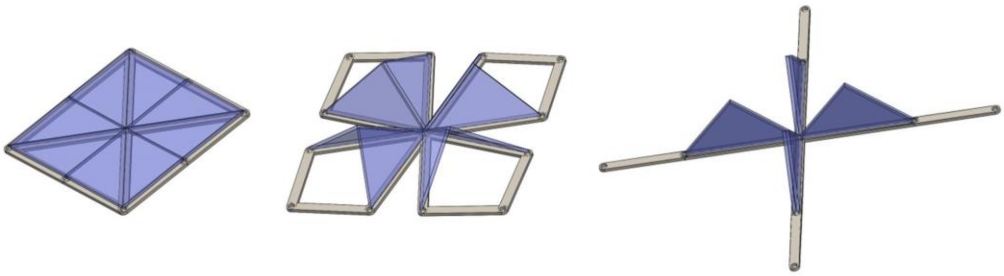
<tr><td colspan="3"></td></tr>
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5.4. Repetition of Deployable Polygon Modules in Archimedean Tilings

Either the deployable polygon modules or the repetition of these modules are used for surface covering. Archimedean tilings (regular and semi-regular tessellations) that consist of systematic repetitions of deployable polygons are selected in the present study. These provide coverage of a surface with no gaps and overlaps in the deployed position.

A tessellation, which is basically a composition of shapes to be used to cover a plane, consist mostly of repetitions of polygons (Clapman & Nicholson, 2014). Tessellations that are applied to planar surfaces are known as either tilings or mosaics. Tessellations are used in architecture for a wide range of purposes from covering materials to movable structural designs. The walls and floors covered with stones of selected color and shape are the first examples of tilings (Grünbaum & Shephard, 1987). Today, some movable tiling strategies are improved for architectural purposes. For example, architects Aylin Gazi and Koray Korkmaz generated a method that provides motion for certain types of one-uniform tessellations with retractable plates (Gazi & Korkmaz, 2017).

Archimedean tilings consist of regular convex polygons. Some of the polygons (triangle, square, hexagon, octagon and dodecagon) are repeated in line with the symmetry (examples: rotations, translations and reflections) in the Archimedean tilings. All vertices (intersection point of the polygons) in each tessellation are equivalent under these symmetries, thus they are called *1-uniform* tilings. The tiling elements are the *vertex*, the *edge* and the *tile* (Grünbaum & Shephard, 1987). All sides of the polygons in the Archimedean tilings are edges and all vertices coincide, thus they are called *edge-to-edge* tiling. The edges have identical lengths in each tessellation. The vertices are the endpoints of the edges and all the vertices are the same type in a uniform tessellation. A uniform tiling is denoted by the surrounded polygons in a vertex (n_1. n_2 .n_3…. n_r) in which *n* is the number of corners in a regular polygon (n_1-gon, n_2-gon…) and *r* is the number of intersecting polygons in a vertex (Wei & Wang, 2019). The square tiling that is called 4^4 (4.4.4.4) is shown in Figure 5.6. The tiles are *adjacent* in case two tiles have a common edge. For example, T1's adjacents are T2 and T3 that have a common edge. T1 and T4 have no common edge (but non-empty of their intersection), thus they are called *neighbor* tilings (Grünbaum & Shephard, 1987).

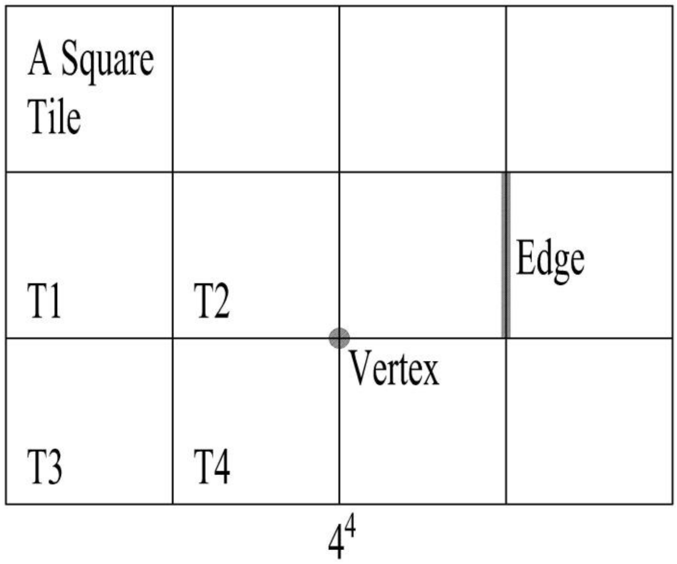


Figure 5.6. Tiling elements of the the regular tiling 4^4

In Archimedean tilings, all vertices are of the same type and are also called *regular* and *semi-regular* tessellations. There are three types of regular tessellations (3^6), (4^4) and (6^3) in which the vertices have the same type of congruent polygons. There are eight types of semi-regular tessellations (3.6.3.6), (3.4.6.4), (4.8^2), ($3^2.4.3.4$), (3.12^2), ($3^3.4^2$), (4.6.12), ($3^4.6$) which have the same vertex type but a vertex is not surrounded with all identical polygons. The eleven types of Archimedean tilings are shown in Figure 5.7.

The modules are adapted to the polygons in the tessellations in the current condition. The division into triangles and selected tessellation plans are shown in Figure 5.8. These polygons have equal-length sides which are modeled to have 50 cm length.

The deployable polygons are assembled one by one to the selected adjacent polygon. When two adjacent polygons are assembled, two links are used as mutual links. For example, the assembly of two squares is shown in Table 5.7. Links no. 5 and 6 are mutual ternary (3 nodes) links. Considering these parameters $n = 18,\ j_1 = 25,$ the mobility calculation is $M = 3(18 - 1) - 2x25 = 1$. Two mutual links assure that the mobility remains at 1 DoF. Link no. 1 is the fixed link and link no. 2 is the input link that rotates 90° starting from the deployed to the compact position of the mechanism. The same method is used for the assembly of deployable polygons.

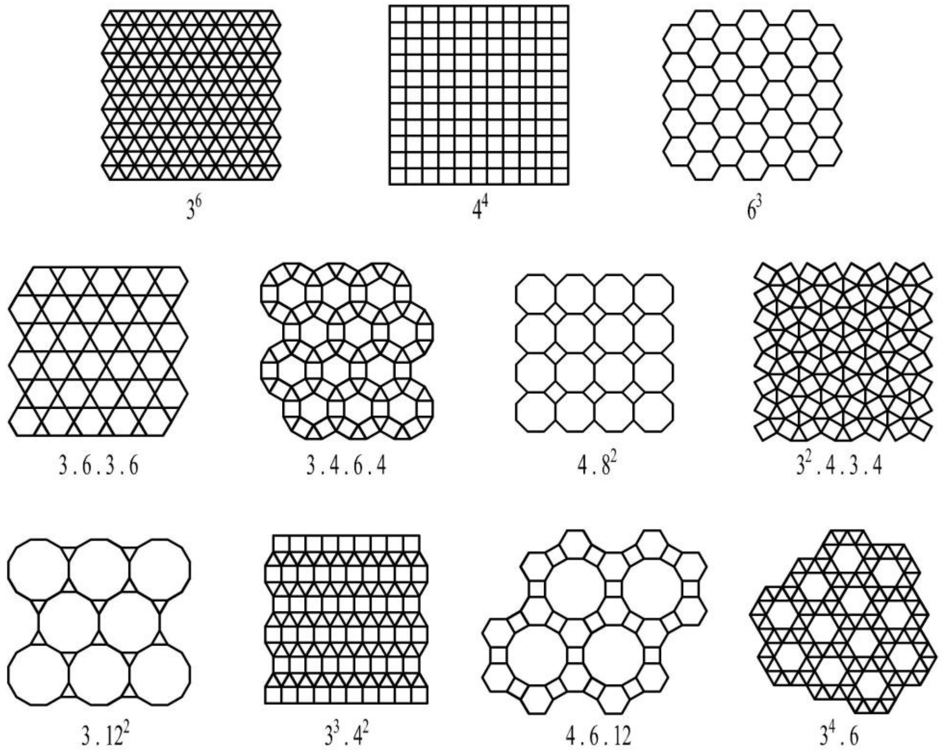


Figure 5.7. Archimedean tilings (regular and semi-regular tessellations)

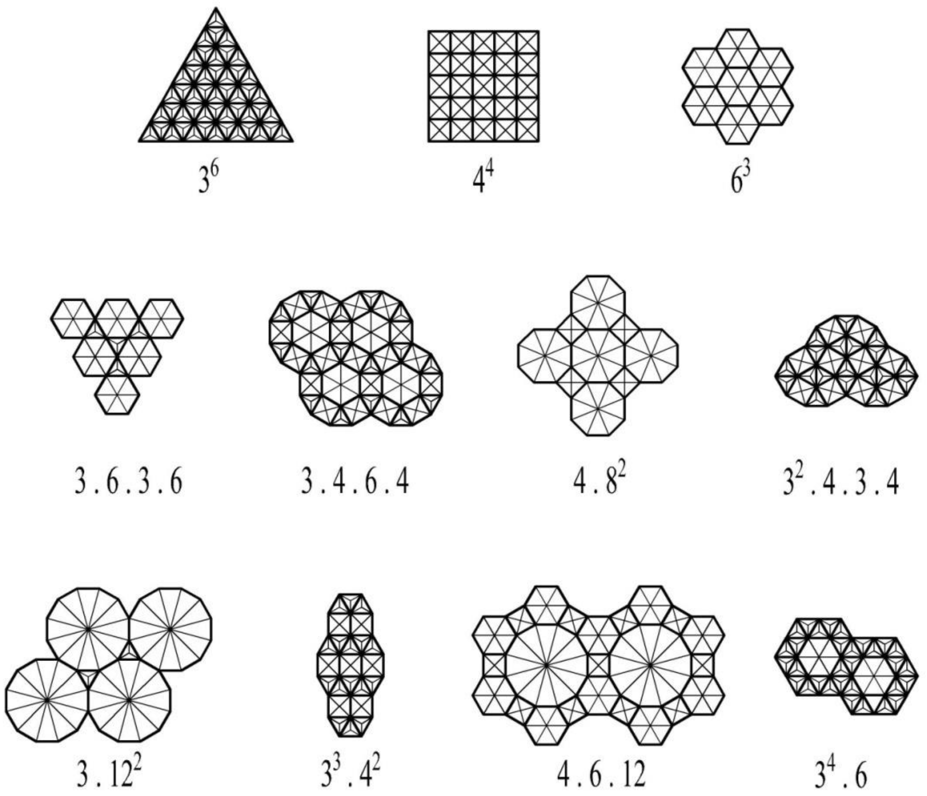


Figure 5.8. Selected parts of the Archimedean tilings for assembling the deployable polygon modules that are broken into triangles

Planar configurations are modeled to examine the mobility in the Archimedean tilings. The mutual links and connections are in the middle of the edges of tiles but not all the edges are connected in a deployable polygon assembly. The assembled edges are designed to move without collision or overlapping with each other.

The assembly of four squares in a closed-loop is shown in table 5.8. The parameters of a deployable square are $n = 10,\ j_1 = 13, M = 1.$ The parameters of the assembly of two squares are $n = 18,\ j_1 = 25, M = 1.$ The parameters of the assembly of three squares are $n = 26,\ j_1 = 37, M = 1.$ Considering these parameters $n = 32,$ $j_1 = 48$, the mobility calculation of the assembly of four squares is $M = 3(32 - 1) - 2x48 = -3$. In case deployable polygons that are assembled to each other reveal a closed-loop in between them, some of the joints can not be used. Three of the probabilities for redundant joints are modeled are shown in Table 5.8. There are 2 redundant joints that have no effect motion in each mechanism. Considering these parameters $n = 32,\ j_1 = 46,$ the mobility calculation is $M = 3(32 - 1) - 2x46 = 1$ in the absence of these two redundant joints. These redundant joints are used as actual joints in the repetition of the mechanisms of the current study. Fourty-eight revolute joints are thus used in the 1 DoF mechanism design where 2 of them are redundant and not included to the mobility calculation.

The connection of polygons and their motions are modeled. Modelings of the deployable tessellations in deployment of the (3^6) is shown in Figure 5.9, the (4^4) is shown in Figure 5.10, the (6^3) is shown in Figure 5.11, the (3.6.3.6) is shown in Figure 5.12, the (3.4.6.4) is shown in Figure 5.13, the (4.8^2) is shown in Figure 5.14, the (3^2.4.3.4) is shown in Figure 5.15, the (3.12^2) is shown in Figure 5.16, the ($3^3.4^2$) is shown in Figure 5.17, the (4.6.12) is shown in Figure 5.18, the (3^4.6) is shown in Figure 5.19.

Table 5.7. Kinematic properties of the assembly of two planar *deployable squares*

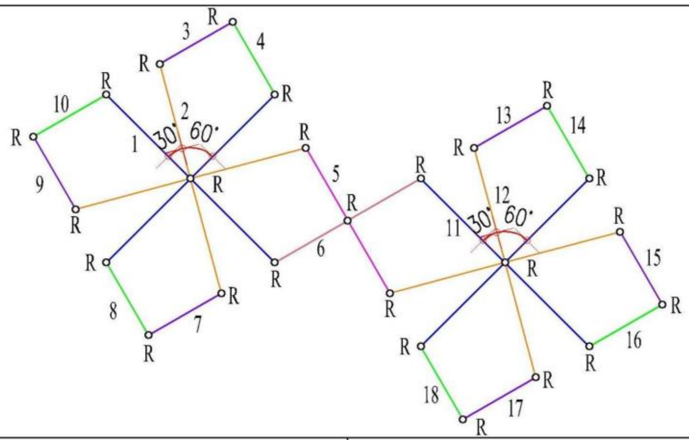
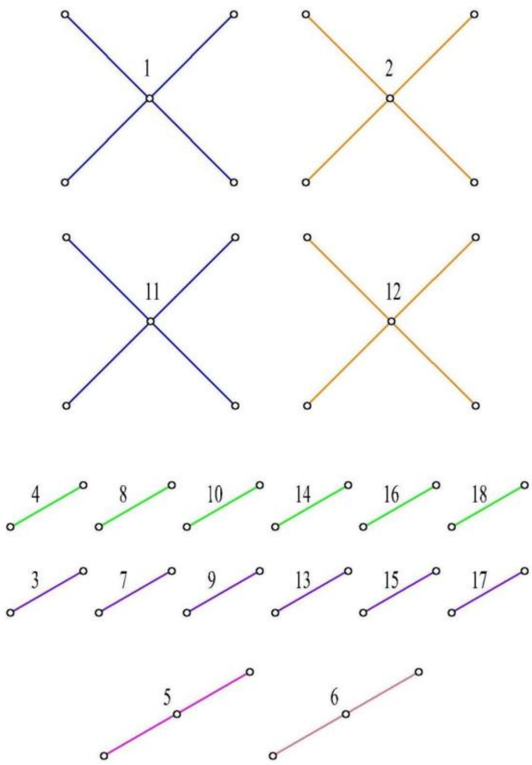
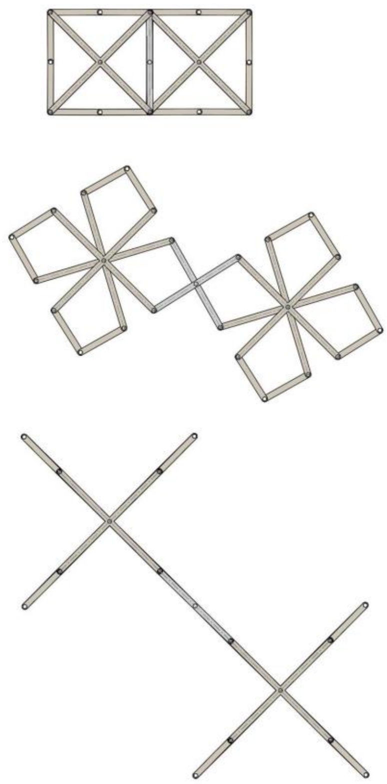
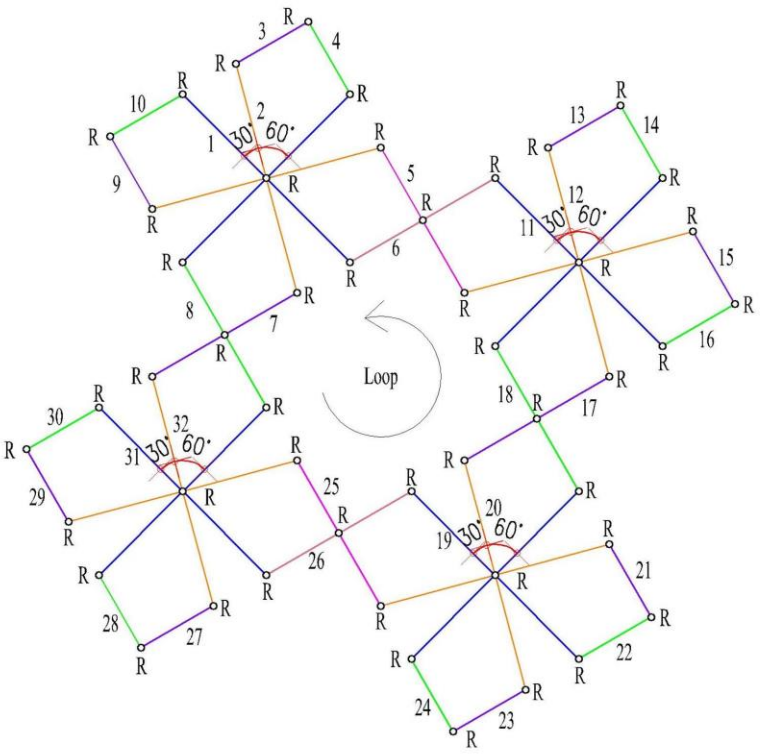
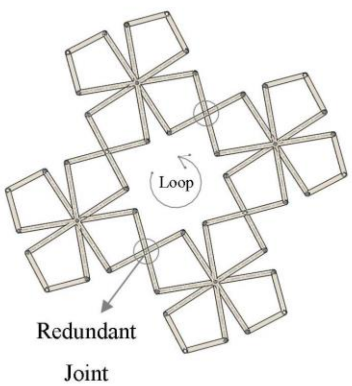
<table>
<tr><td colspan="2">Assembly of Two Square Modules— Planar</td></tr>
<tr><td colspan="2">Kinematic Diagram</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Links</td><td>Motion Sequence</td></tr>
<tr><td></td><td></td></tr>
</table>

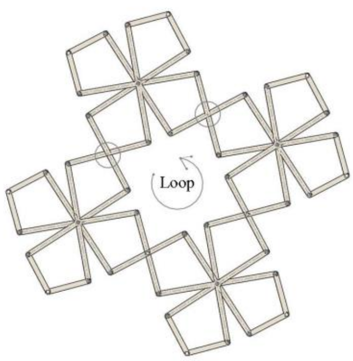
Table 5.8. Kinematic properties of the assembly of four planar *deployable squares*

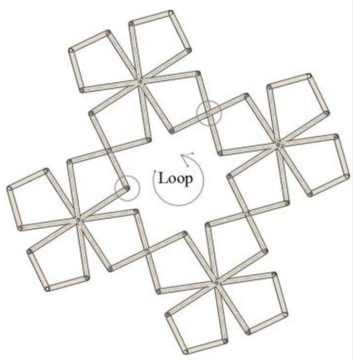
Assembly of Four Square Modules — Planar
Kinematic Diagram



Redundant Joints







The Deployable 3^6 Tessellation

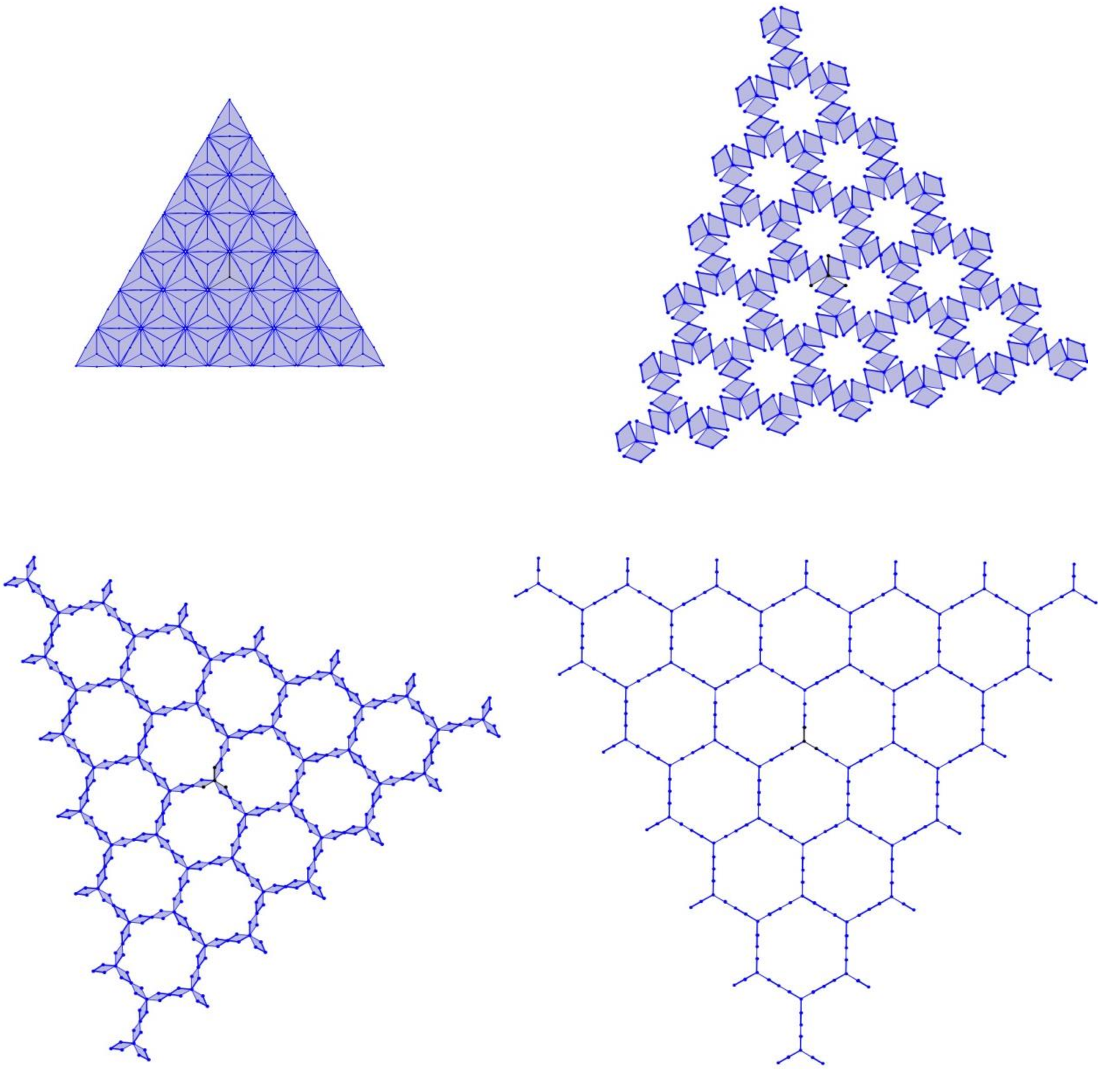


Figure 5.9. The deployable 3^6 regular tessellation with planar modules in 4 positions

The Deployable 4^4 Tessellation

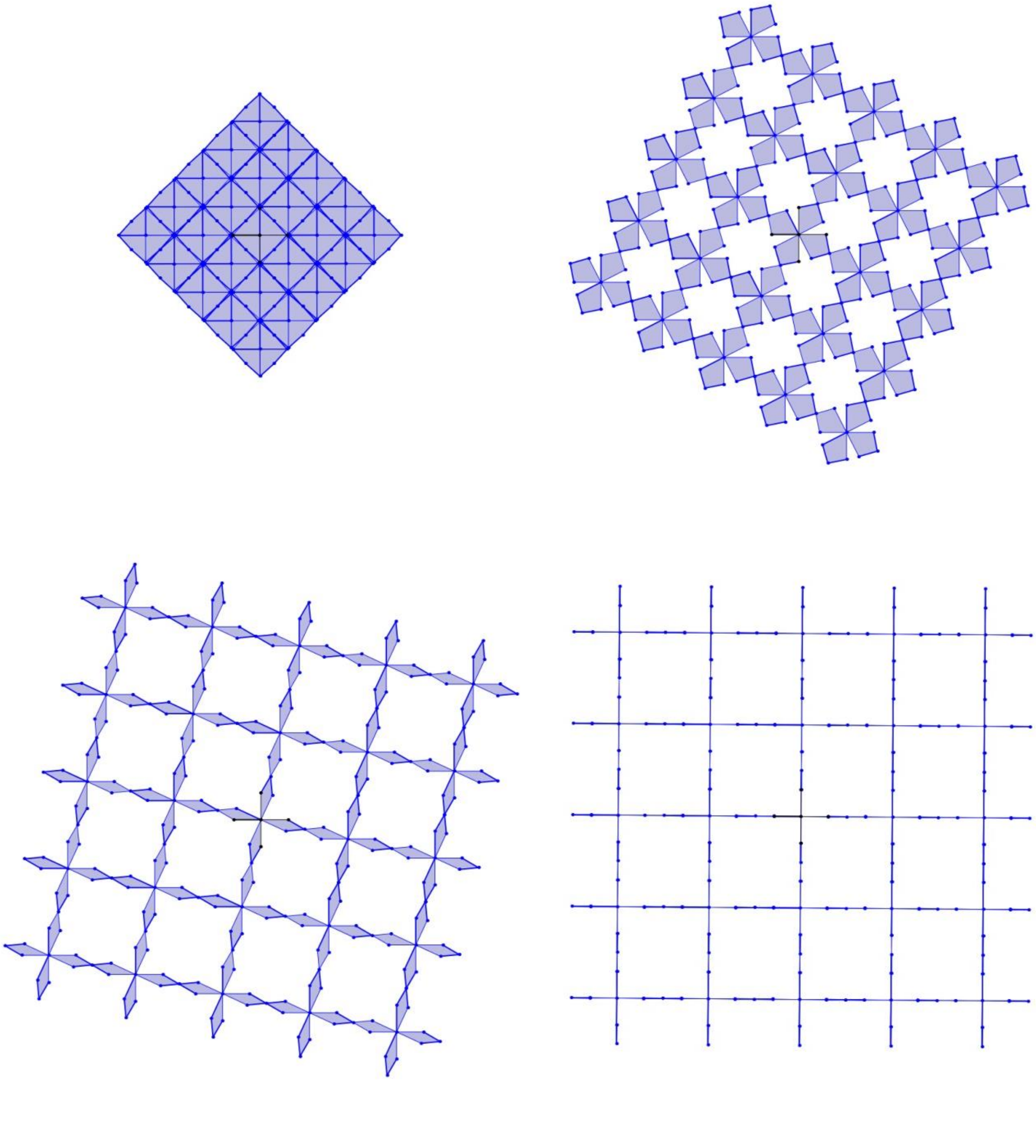


Figure 5.10. The deployable 4^4 regular tessellation with planar modules in 4 positions

The Deployable 6^3 Tessellation

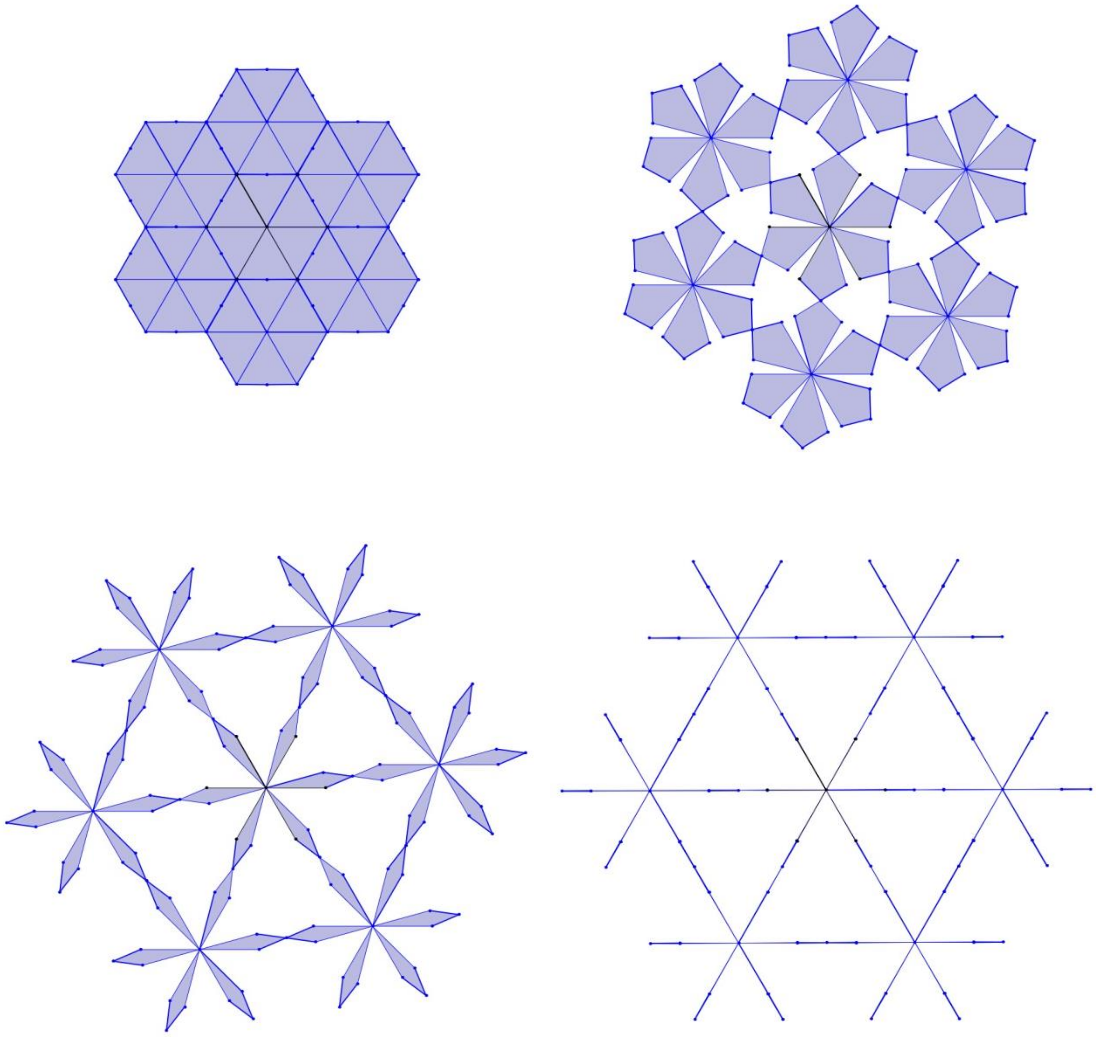


Figure 5.11. The deployable 6^3 semi-regular tessellation with planar modules in 4 positions

The Deployable 3.6.3.6 Tesellation

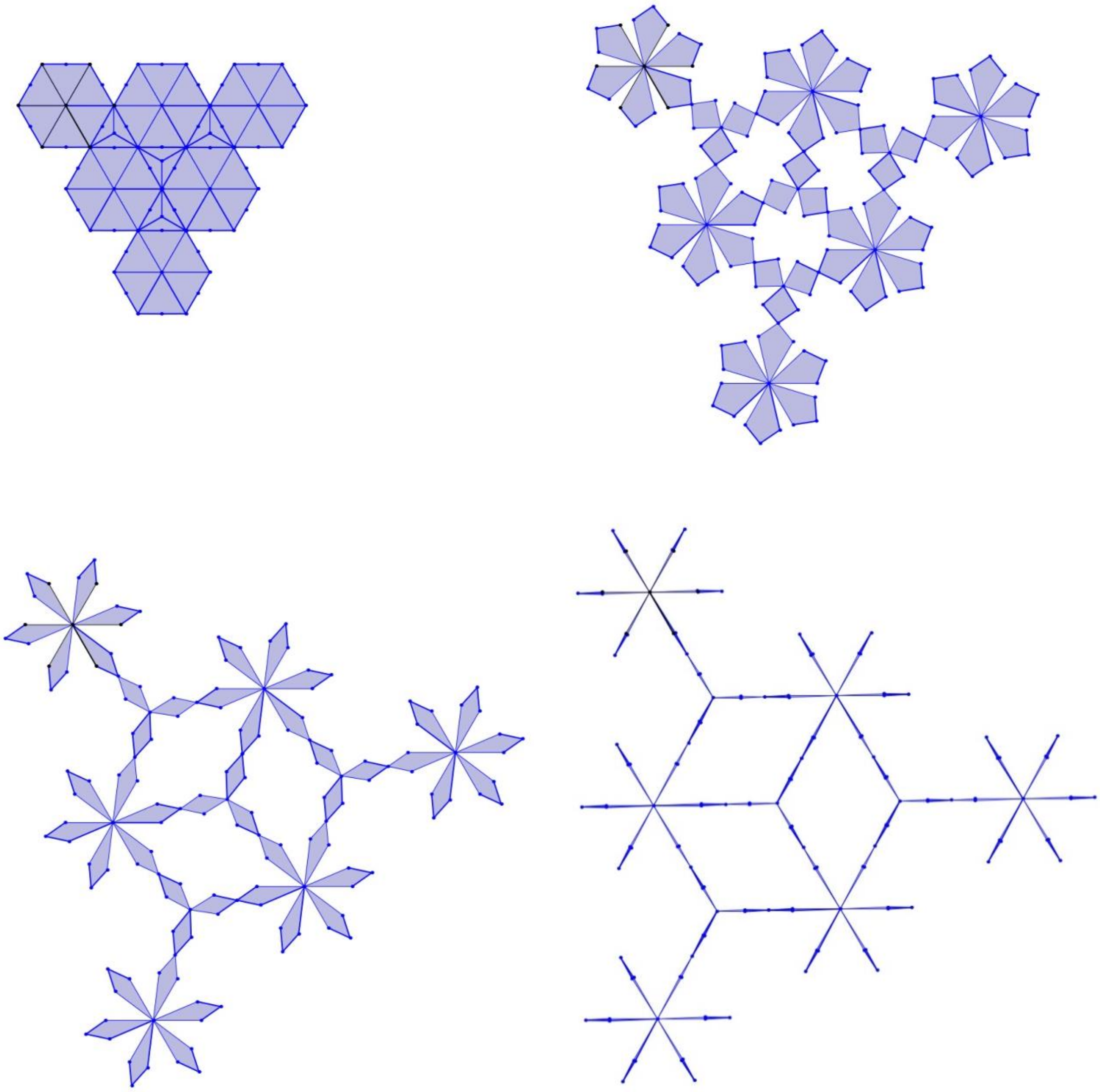


Figure 5.12. The deployable 3.6.3.6 semi-regular tessellation with planar modules in 4 positions

The Deployable 3.4.6.4 Tessellation

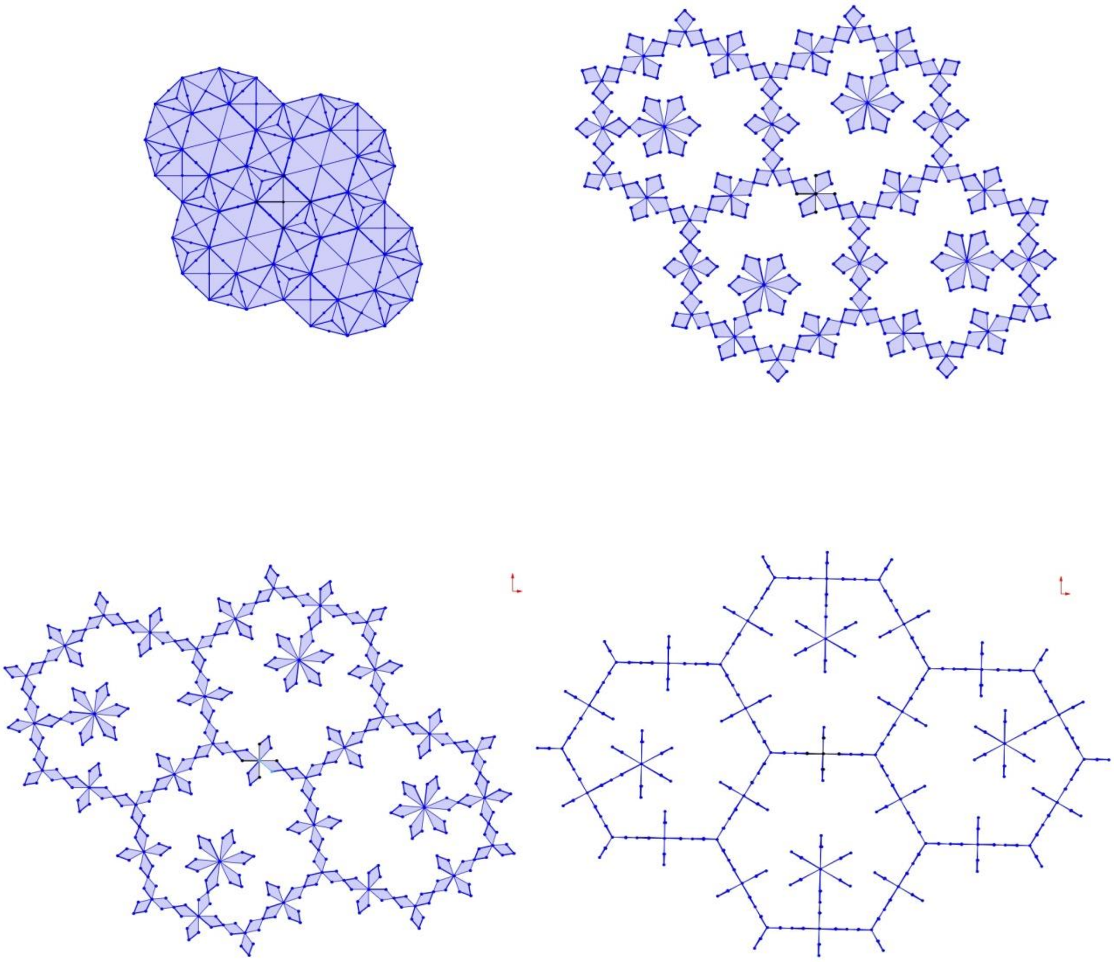


Figure 5.13. The deployable 3.4.6.4 semi-regular tessellation with planar modules in 4 positions

The Deployable 4.8^2 Tessellation

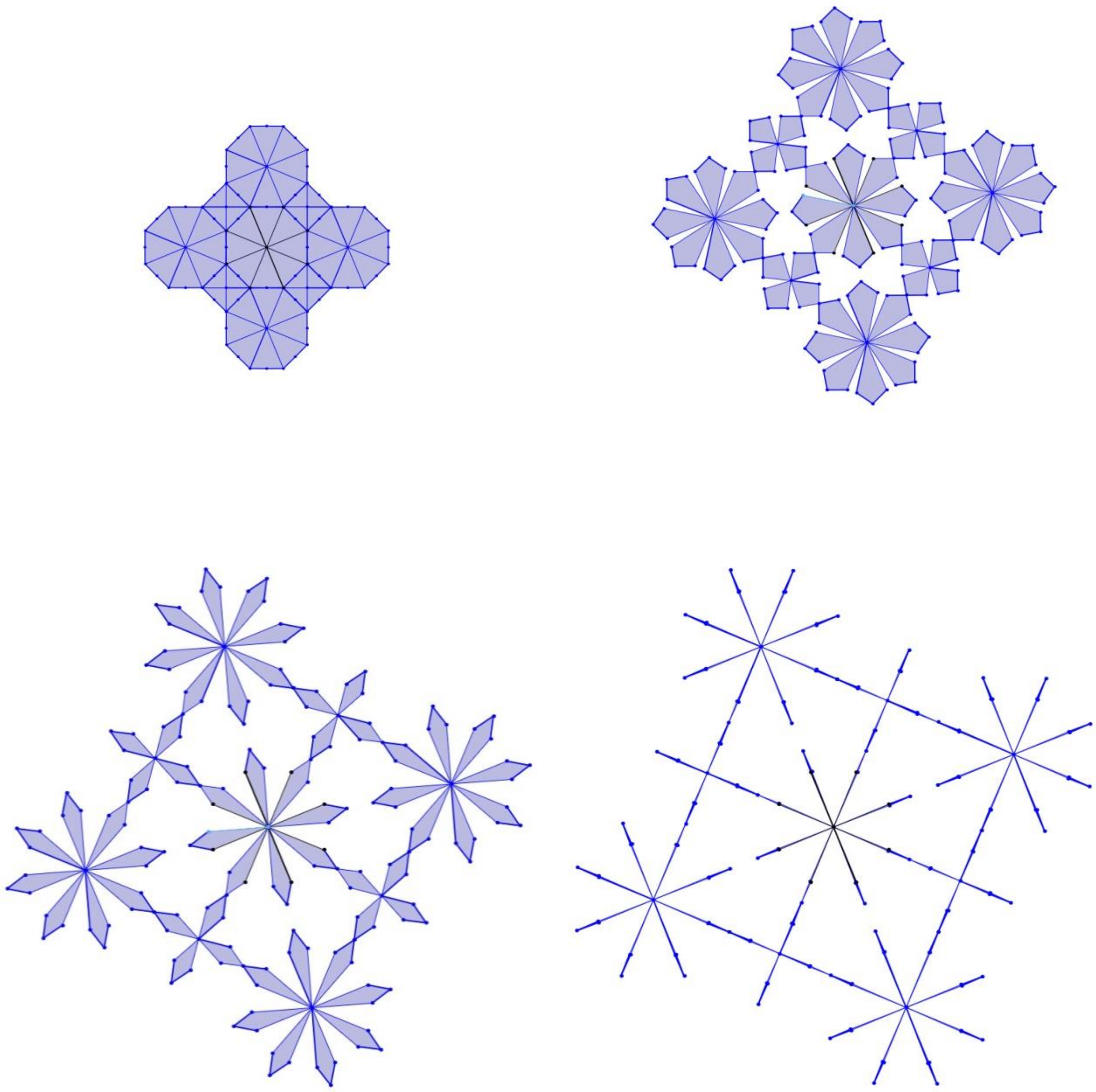


Figure 5.14. The deployable 4.8^2 semi-regular tessellation with planar modules in 4 positions

The Deployable 3^2.4.3.4 Tessellation

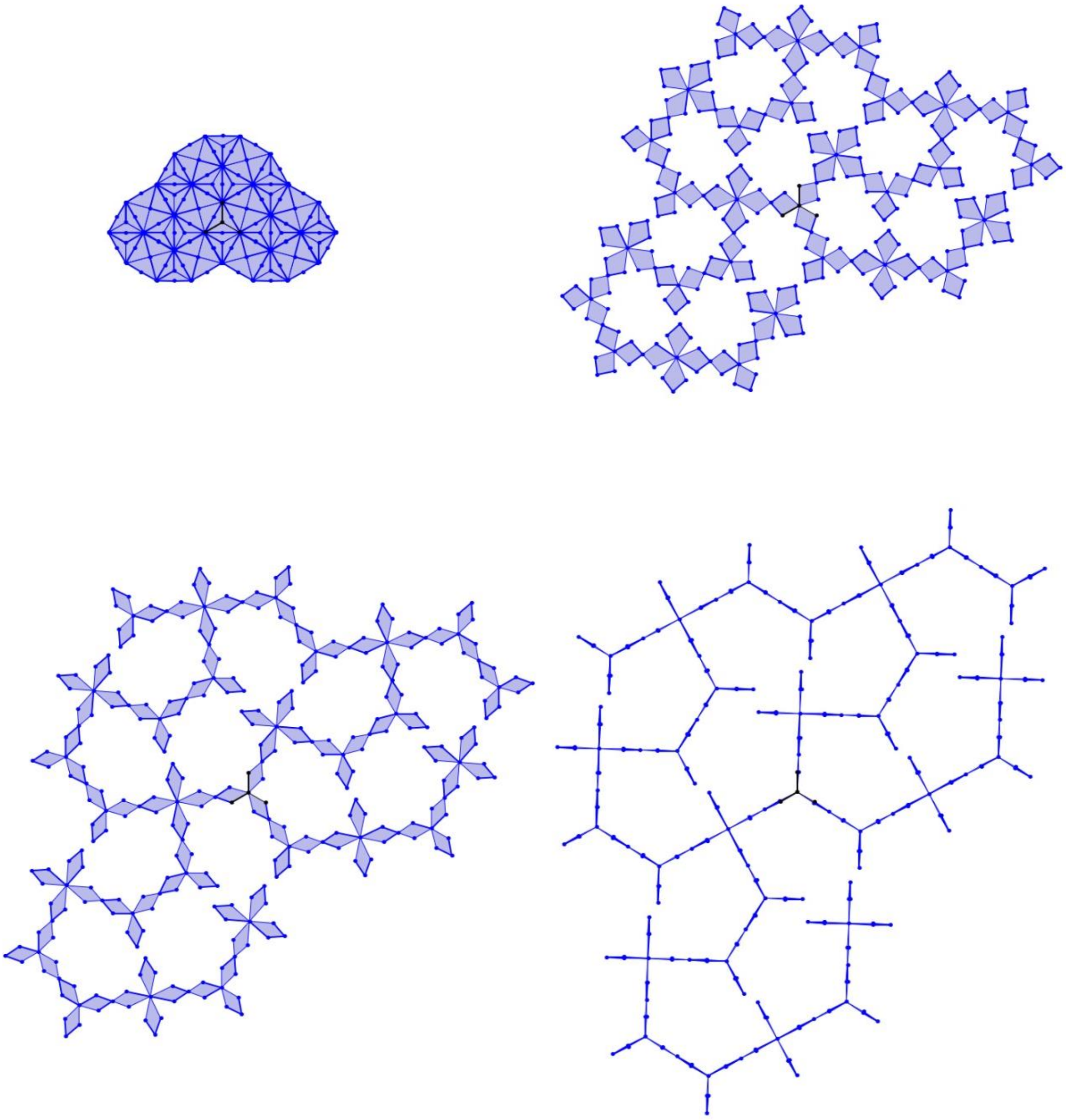


Figure 5.15. The deployable 3^2.4.3.4 semi-regular tessellation with planar modules in 4 positions

The Deployable 3.12^2 Tessellation

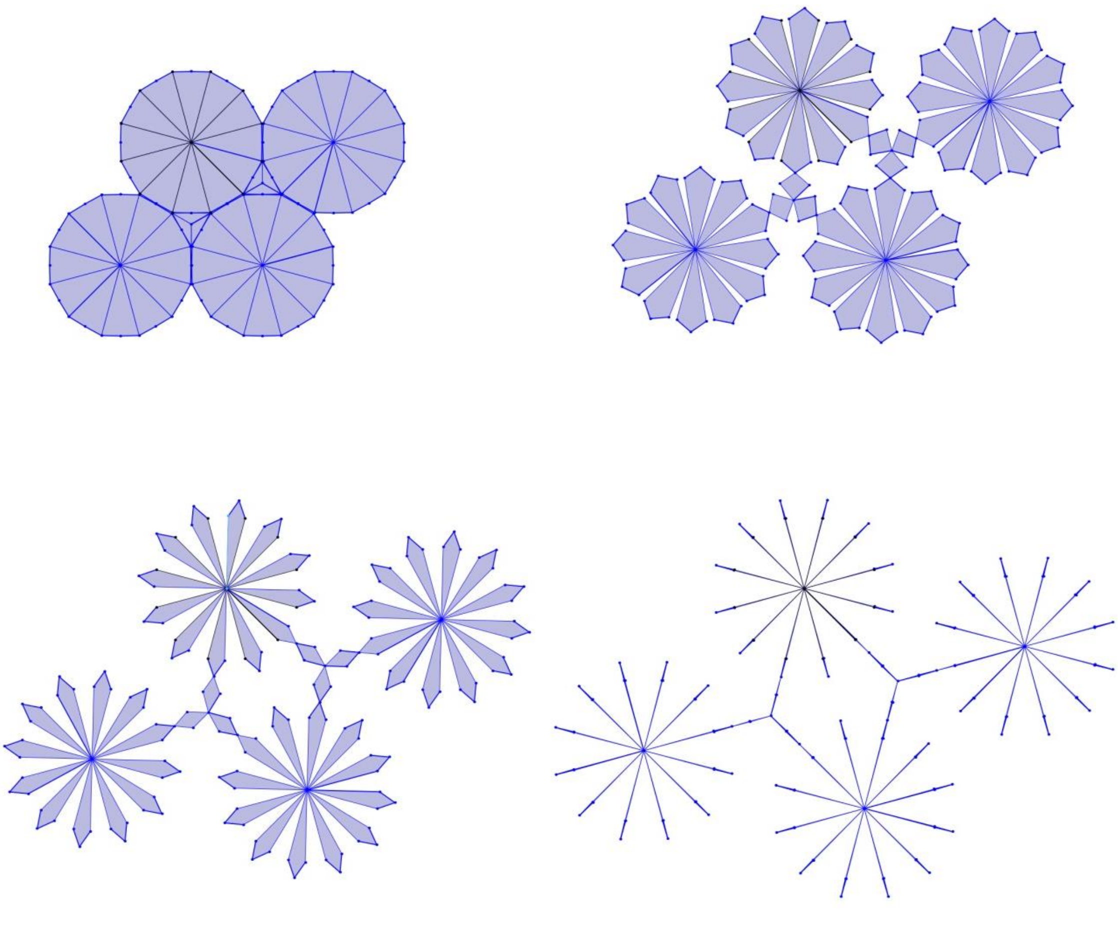


Figure 5.16. The deployable 3.12^2 semi-regular tessellation with planar modules in 4 positions

The Deployable $3^3.4^2$ Tessellation

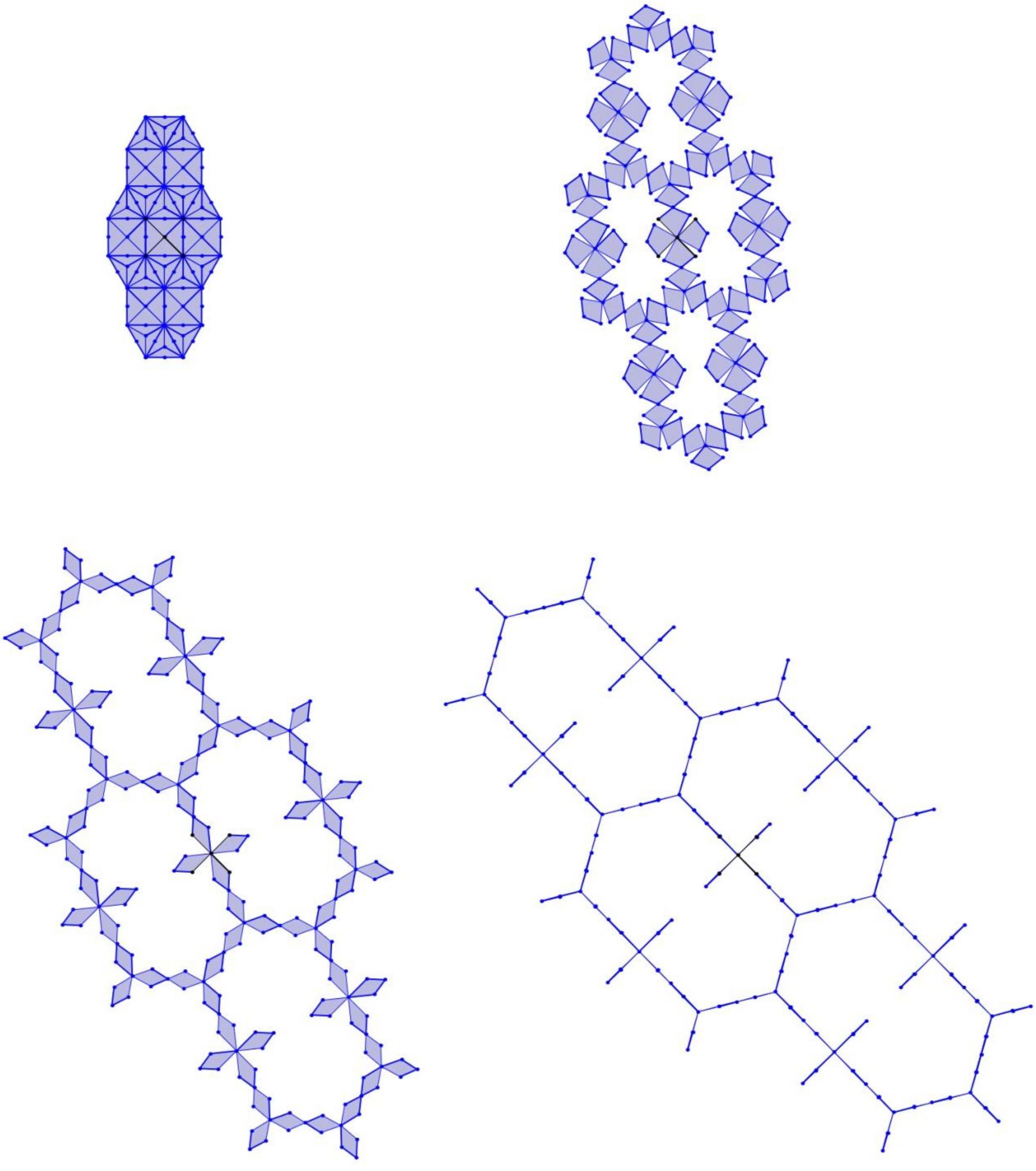


Figure 5.17. The deployable $3^3.4^2$ semi-regular tessellation with planar modules in 4 positions

The Deployable 4.6.12 Tessellation

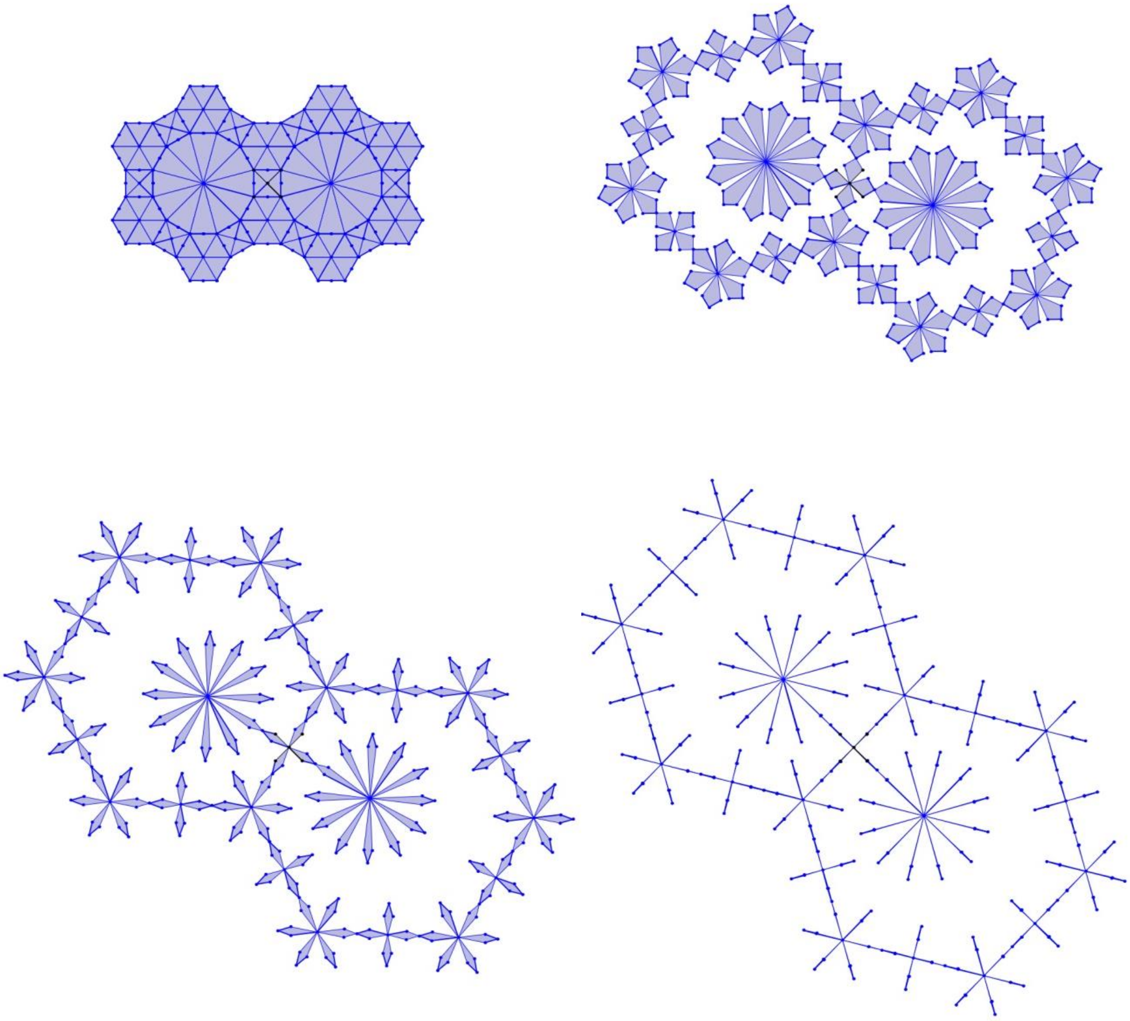


Figure 5.18. The deployable 4.6.12 semi-regular tessellation with planar modules in 4 positions

The Deployable $3^4.6$ Tessellation

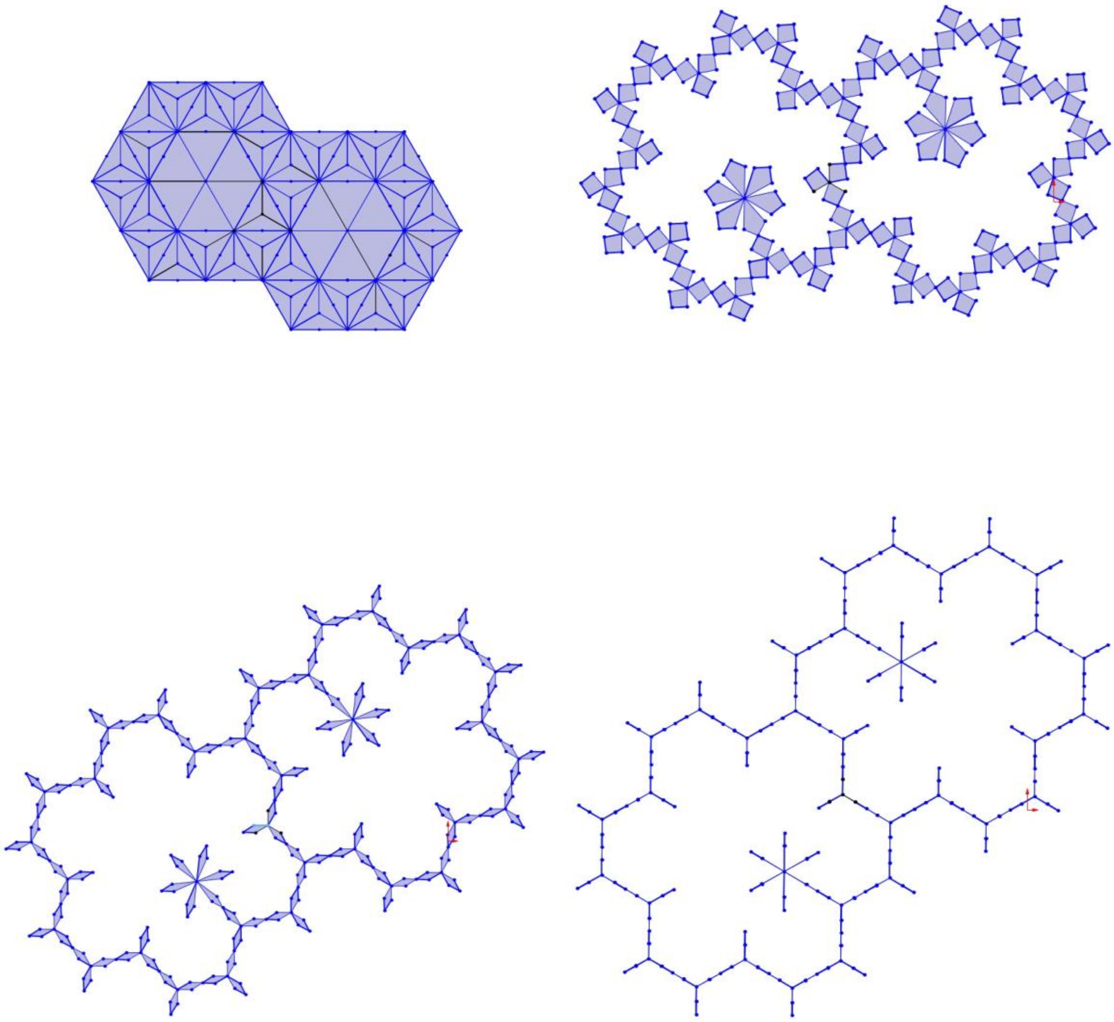


Figure 5.19. The deployable $3^4.6$ semi-regular tessellation with planar modules in 4 positions

The plano-spherical configurations are modeled to show the design in various Archimedean tilings. The plan of the selected tilings and number of polygons are shown in Figure 5.20.

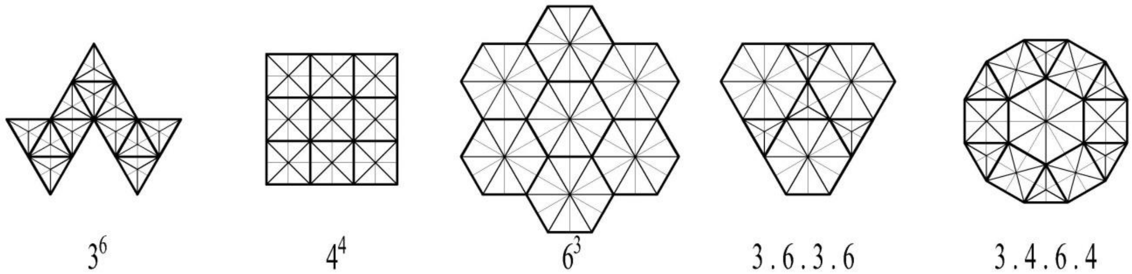
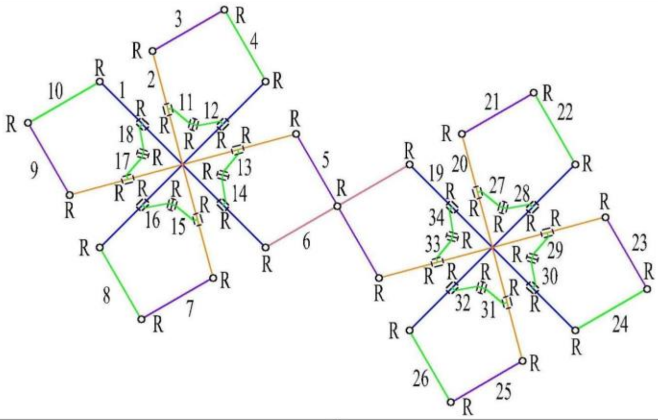
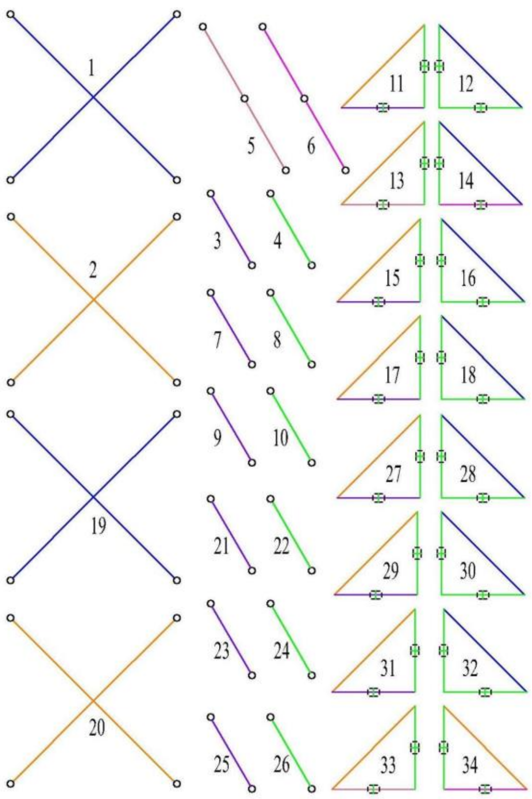
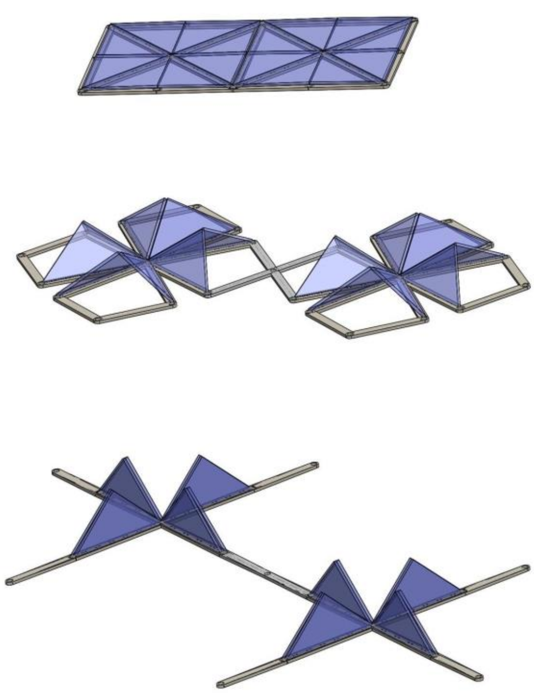


Figure 5.20. The plan of the modeled tilings

The same assembly method with the planar configurations is used in mutual links between two deployable polygons. For example, the assembly of two deployable squares that are each assembled of four identical plano-spherical units is shown in Table 5.9. The links no. 5 and 6 are the mutual ternary (3 nodes) links. Link no.1 is a fixed link and link no. 2 is the input link that rotates 90° ($\frac{2\pi}{4}$ rad) from the deployed position to the compact position of the mechanism. Considering these parameters $n = 34$, $j_1 = 47$, the independent loop calculation is $L = 47 - 34 + 1 = 14$. There are 14 independent loops, two of them are plano-spherical ($\lambda = 5$), six of them are planar ($\lambda = 3$) and six of them are spherical ($\lambda = 3$). Considering these parameters $j_1 = 47$, $L = 14$, the mobility calculation is $M = 47 - (5x2) - (3x6) - (3x6) = 1$.

The motions of deployable tessellations from the deployed positions to the compact positions are modeled in 3 positions in the current study. The deployable tesselation of 3^6 is shown in Figure 5.21, the 4^4 is shown in Figure 5.22, the 6^3 is shown in Figure 5.23, the 3.6.3.6 is shown in Figure 5.24, the 3.4.6.4 is shown in Figure 5.25.

Table 5.9. Kinematic properties of the assembly of two plano-spherical *deployable squares*

<table>
<tr><td colspan="2">Assembly of Two Square Modules — Plano-Spherical</td></tr>
<tr><td colspan="2">Kinamatic Diagram</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Links</td><td>Motion Sequence</td></tr>
<tr><td></td><td></td></tr>
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The Deployable 3^6 Tessellation

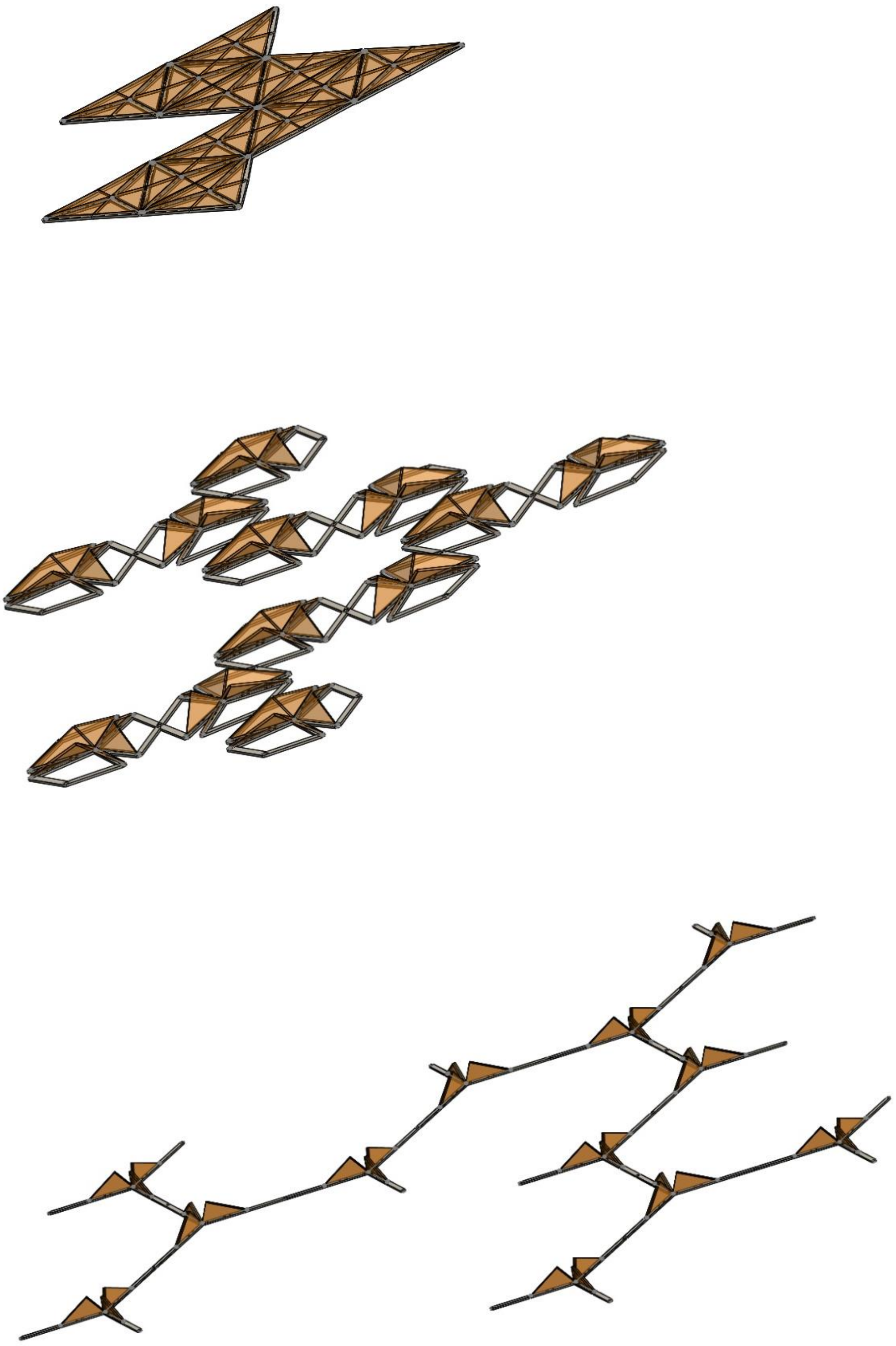

Figure 5.21. The deployable 3^6 regular tessellation with plano-spherical modules in 3 positions

The Deployable 4^4 Tessellation

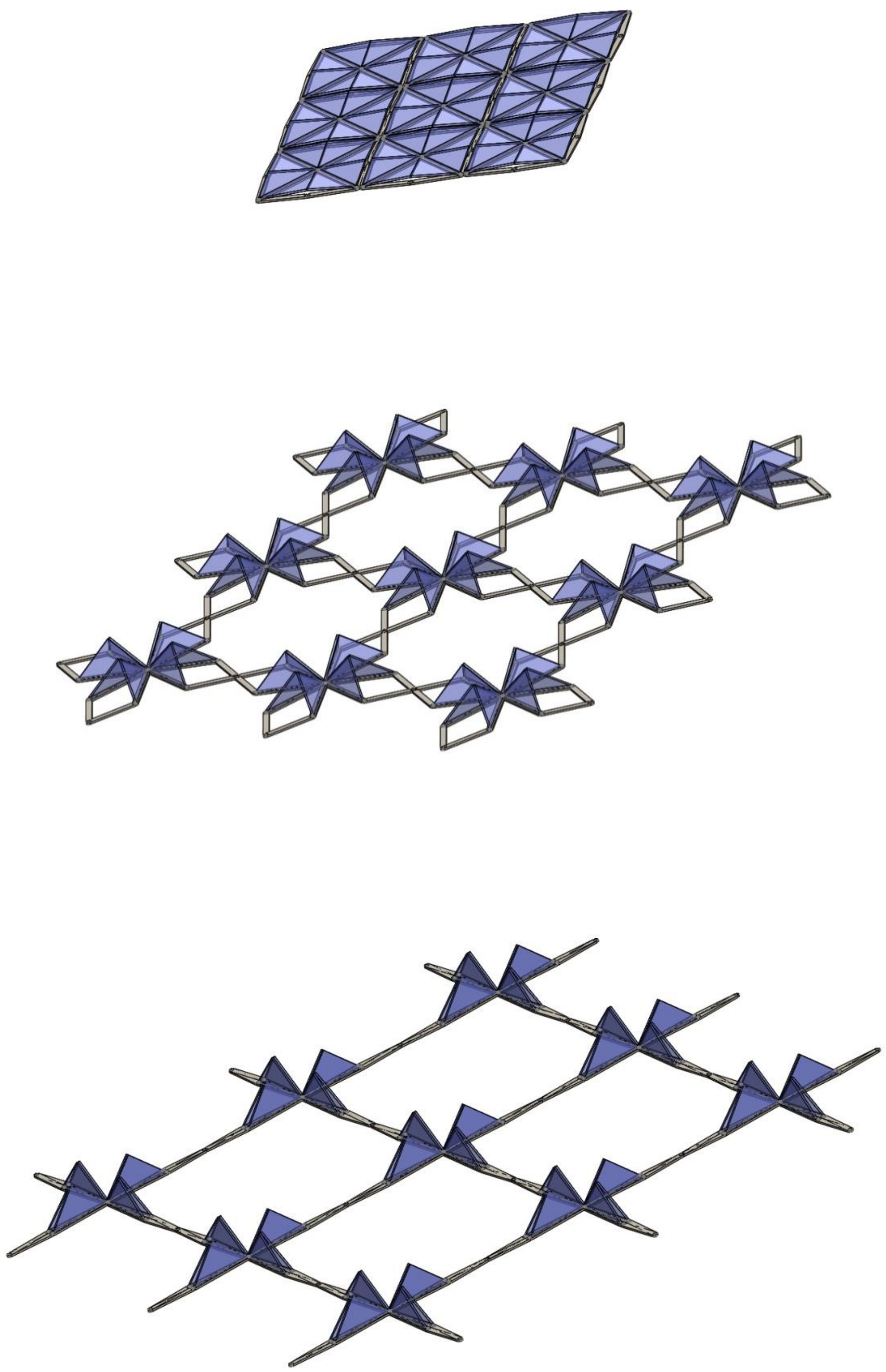

Figure 5.22. The deployable 4^4 regular tessellation with plano-spherical modules in 3 positions

The Deployable 6^3 Tessellation

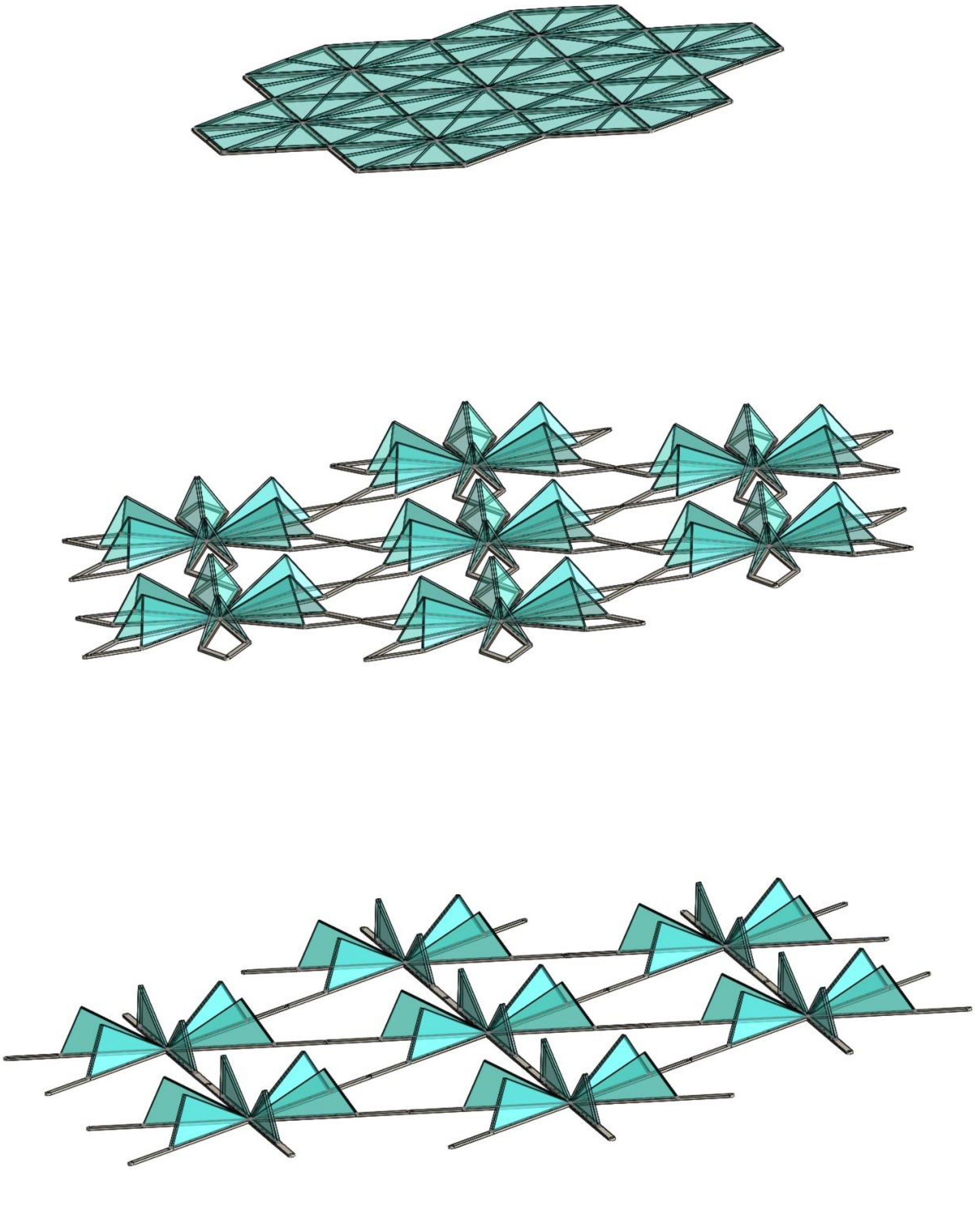

Figure 5.23. The deployable 6^3 regular tessellation with plano-spherical modules in 3 positions

The Deployable 3.6.3.6 Tessellation

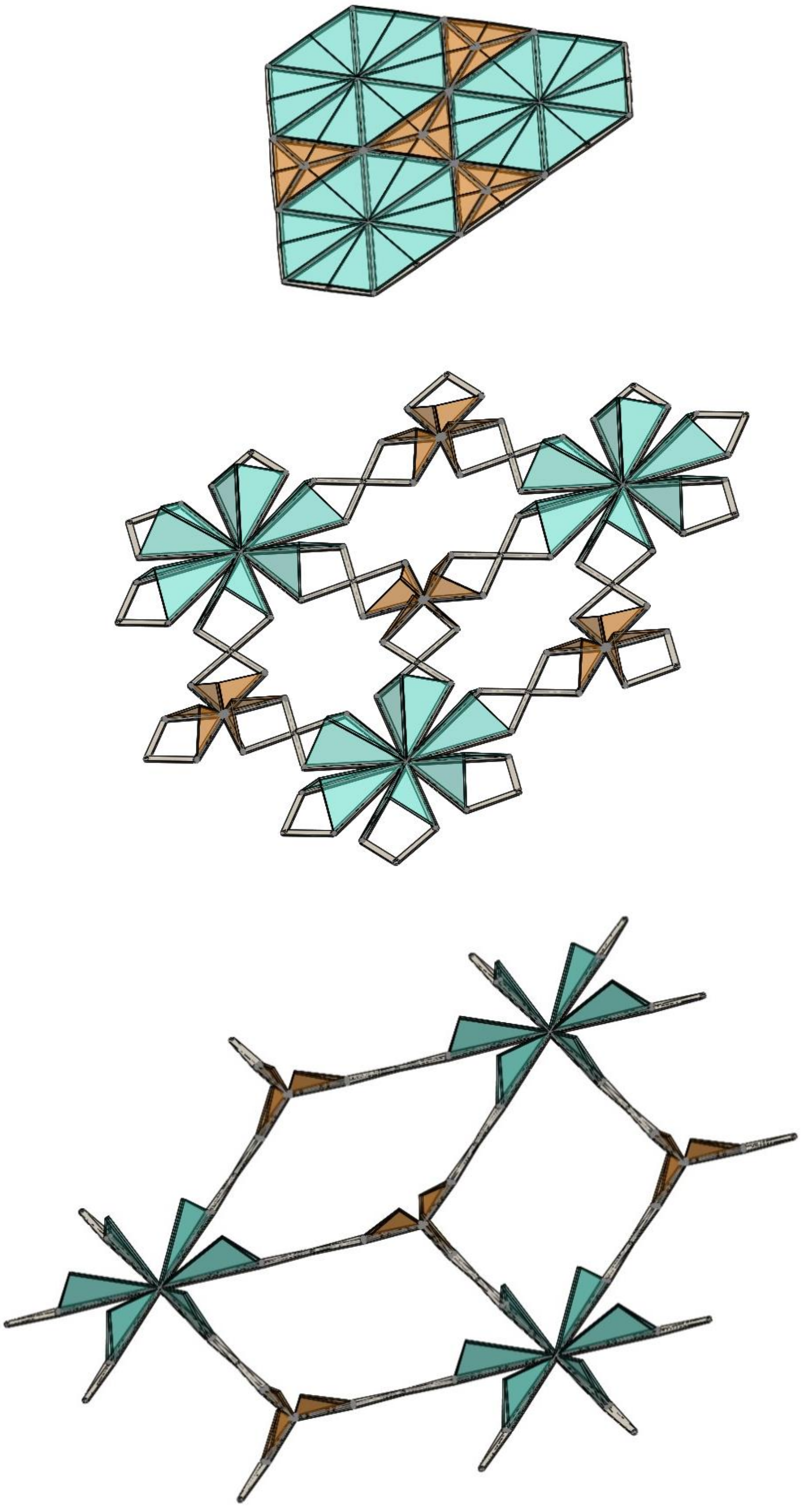

Figure 5.24. The deployable 3.6.3.6 regular tessellation with plano-spherical modules in 3 positions

The Deployable 3.4.6.4 Tessellation

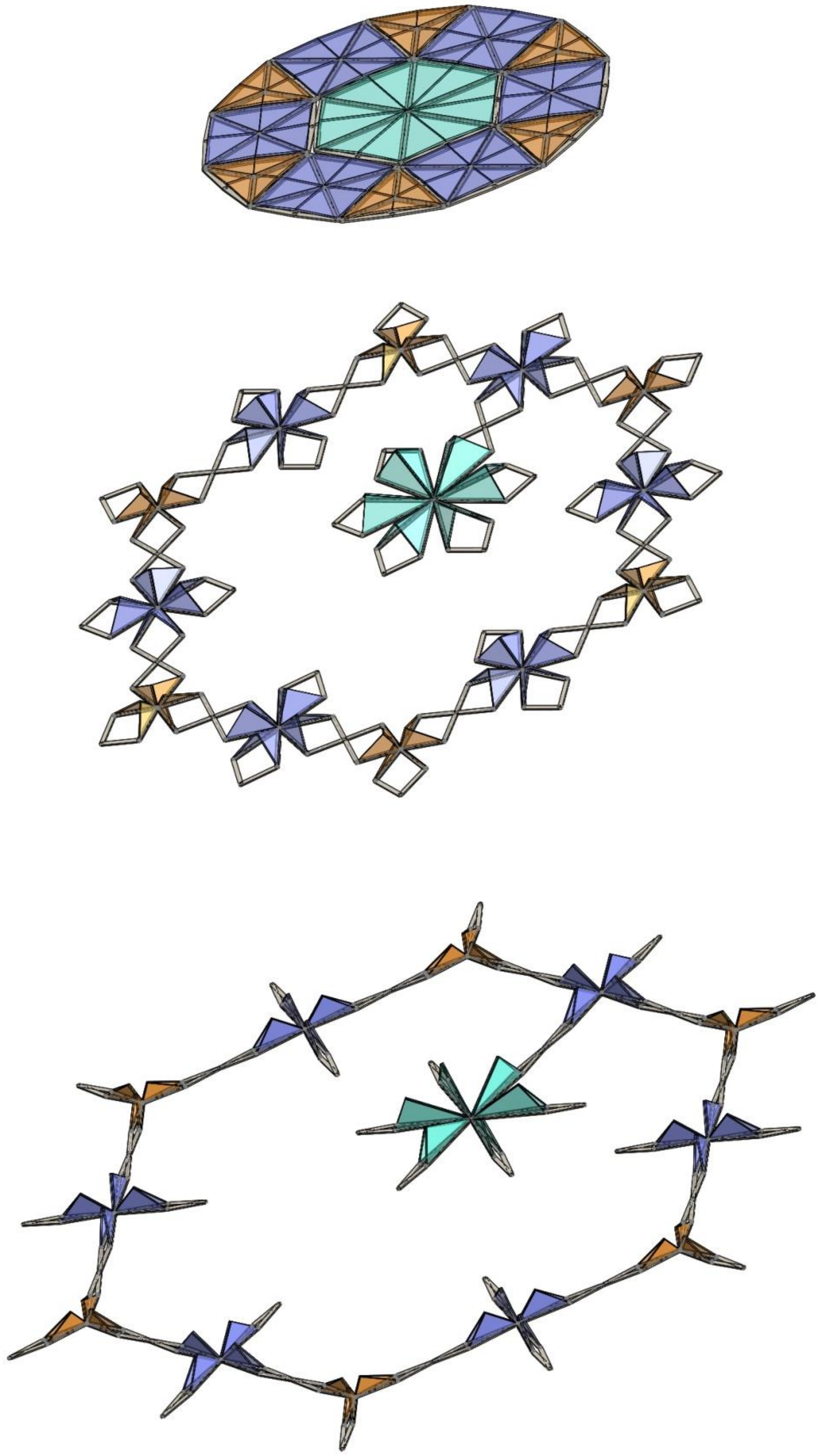

Figure 5.25. The deployable 3.4.6.4 regular tessellation with plano-spherical modules in 3 positions

CHAPTER 6

CONCLUSION

Movable products with certain mechanisms are analyzed based on the knowledge obtained from kinetic art, architecture and deployable structures in this study. Movable designs of the pre-industrial revolution period are first investigated. Second, mechanism science; including the modern technical knowledge, fundamentals of the design, types of mechanisms, and design methods, are examined. The kinematic structural analyses of the extant examples are subsequently revealed. Finally, a novel mechanism design method using a polygonal 1 DoF deployable surface design in a modular approach is proposed. The study that consists of the historical background and contemporary works with a design proposal indicates the mechanical bases and processes of designs as well as knowledge of both artists and architects.

The invention of mechanical systems is one of the factors that affected the developmental process in architecture. The invention of the wheel, for example, resulted in the first examples of caravans as nomads generating durable huts on carts in place of portable tents to carry their home together. Clocks affected shaping clock towers, whereas water wheels affected the design of aqueducts. The construction machines that were also designed by architects, allowed them to build new structures. Today, machinery plays an active role in the formation of industrial buildings. Besides the significant effect of machinery had on shaping buildings, examples in which buildings and building components were used in the transmission of motion as a mechanism part, were seen in the early examples. For instance, drawbridges were the first examples of today's movable bridges, and windmills were the first examples of rotatable architecture. Architects also designed several automats, clocks, and water wheels. As the famous Roman architect Vitruvius stated, architects of that period were defined as experts with multidisciplinary knowledge that worked in a wide range of fields. The projection of inventions in motion studies and design is seen in the works of several architects and artists such as Hero of Alexandria, Leonardo da Vinci, Villard de Honnecourt, and Leon Battista Alberti, etc. Thus, architects and artists were accepted as developers and masters of mechanical and technical knowledge.

Motion is a field that was studied long before the formation of kinematic science, which is the examination of motion without regard to the affecting forces. The urge to understand the origin of forces that generate motion, mainly terrestrial and celestial body motion, was more of the underlying process of motion studies throughout history. Numerous products are designed considering gravity, free fall, throwing and floating actions, balance, air pressure, water pressure, and magnetism. Today, two types of motion, rotation and translation, are accepted as basic motions, and the combination of these motions is complex motion. Even in the Roman period, architect Vitruvius defined two types of motion in hoisting machines as rectilinear and circular. The parabolic curve that is generated by the action of throwing was stated as vertical and horizontal by Galileo.

The research accumulated as mentioned provided the basis for creating mechanical systems to organize daily life dynamics, construct buildings, and understand the world. Generated products indicate that the technology was far beyond the scientific knowledge related to those. Modern kinematic science, on the other hand, enabled the development of the concept of motion for mechanism design. The study of motion is provided by the geometry of mechanisms, without respect to the affecting forces, is examined. Applying kinematic science to the areas of art and architecture is seen as an increasing mobility level in structures and products when chronologically considered.

Improvement of systems and methods enabled contemporary machines to differ from early machines in terms of complexity and multi-functionality. Actuators were also improved from the first systems operated by the human, animal, or natural forces to the pneumatic, hydraulic, or gear motors are driven by electricity, gasoline etc. The progress in computer technology allowed a generation of smart systems and sensors that are responsive to light, heat, sound, or motion and are used in machinery design. The development of technology and mechanism science since the Industrial Revolution resulted in broader use of mechanical expressions in products.

The concept of movement that equips a designers' unique work gives an excellent opportunity to create unique dynamic designs of the fourth dimension in architecture. Application of mechanism design and knowledge to architecture gave rise to the development of the concepts of *Kinetic Architecture* and Deployable Structures in the field of architecture and *Kinetic Art* in the field of arts. These structures developed with mechanism design principles that were capable of moving, carried forms of buildings or building components that changed with relation to time and space. Such widespread products as *action origami* and *kirigami*, *pop-up* engineering, automata, movable sculptures, interior architecture components, furniture, urban objects, fountains, industrial design products of landscape architecture, bridges, buildings, and building components are designed in movable and adaptable forms every day.

In this study, design approaches and the fundamentals of mechanisms with the determinants of the resulting motion are examined based on existing examples in the fields of art and architecture. Links and joints that generate mechanisms, junction procedures, and drawing processes of kinematic diagrams, mobility formulas that indicate the required actuator number are examined.

Lower pairs are preferred over higher pairs as joint types in art and architecture due to their longer life span. Surface contact enables the maintenance the lubricating grease between the pairs, making those, especially the revolute joints, advantageous for heavy loads. The significant role in the widespread use of revolute pairs in art and architecture is their characteristic of having a single DoF. The advantage of higher pairs, on the other hand, is the reduced number of components required in a mechanism.

The most commonly used mechanisms in architecture are examined in two categories in the current study. The examination is conducted concerning the pair variable (linkage, cam, gear mechanisms) and the motion plane (planar, spherical, spatial mechanisms).

Planar linkages are the most commonly used mechanisms in architecture. The capability of rigid bars to resist heavy loads enables lower pairs and bar links to be used as well as plate links. Durability against environmental conditions is another factor. The simplicity in terms of calculation and assembly is another advantage of planar mechanisms over spatial and spherical mechanisms. Various 3D designs are revealed by combinations or repetitions of planar mechanisms.

Gear mechanisms, though not frequently, are also used in architecture. Their advantages over linkages in terms of being smaller and easier to pack enable gear and cam mechanisms to be widely used in sculpture and automata designs. Cam mechanisms provide the opportunity to arrange the timing of the motion. Cams and gears which are easily affected by environmental conditions and not as successful in transmitting forces as they are in transmitting motion, are mostly used in interior design. Dead-loads of sculptures that include cam mechanisms are carried by hanging cables attached to the ceiling in numerous works of Margolin. Spherical mechanisms, on the other hand, are used in action origami designs with rigid plates. In spatial mechanisms, however, overconstrained mechanisms are mostly preferred in architectural work due to the stiffness they provide. Spatial mechanisms are mostly used in the work of literature rather than being built. For example, despite the use of the Sarrus mechanisms in the dissertation, repetitions of planar mechanisms are used in the applications of Calatrava.

The mobility and connection methods of certain movable products are analyzed concerning their primary units in the present study. Kinematic structural analyses are revealed with kinematic diagrams, joint and link types and numbers, mobility formulations of primary units. The kinematic principles of movable products are examined to understand the essential characteristics of artwork and architectural products. The mobility analyses of primary units also reveal the mechanical properties of the whole product since symmetrical repetitions of these units are used to generate the final products.

Kinematic structural analyses of primary units that comprise cam mechanisms and linkages are conducted. Conducted analyses revealed that the mutual links and joints that are used to generate these primary units as four-bar assemblies have a significant effect on mobility. The cam mechanism of *The Fingers Mk III* is 1 DoF in case a single cam is connected to a follower, whereas *The Redwood* is 2 DoF when 2 cams are connected to a follower with additional links and joints. The *Helix* project is developed with the same principles of *The Redwood,* except that cams are replaced by bars. A similar oscillating motion is produced by the connection angles of bar links. Linkages, on the other hand, are 1 DoF when 2 four-bar linkages are combined with 2 mutual links (*Strandbeest, Open View)* and have greater mobility in case a single mutual link is used (crane-shape *Lights, The Rolling Bridge*). *The Klann Mechanism* is topologically derived from the *Steffenson Mechanism* which has a six-bar linkage with 1 DoF. *The Acrobat,* which is capable of standing stable in every position due to the balance among weights, is 5 DoF.

A proposal of a novel deployable, modular, easily transportable and adaptable surface design with 1 DoF that is capable of being controlled with a single actuator is developed on the basis of the information obtained from previous research and analyses. Kinematic diagrams, calculations with CAD drawings and models are used to reveal the kinematic structural syntheses in which link and joint types along with numbers and mobility analyses of the designs are included. The number and type selection of links and joints in the process of structural design is directly affected by the load-bearing capacity. Bar and plate links are used for surface covering and motion transmission.

Rigid links are connected with revolute joints in order to resist heavy loads. Plate link shapes are preferred in case an advantage of covering is required.

The triangular primary unit is an assembly of a planar 4-bar loop and a spherical 4-bar loop. The unit is topologically a Bennett variation of Sarrus's overconstrained 6-bar, 1 DoF plano-spherical mechanism. The unit is then symmetrically rotated in the repetition of regular convex polygons with respect to the number of sides of the polygon. Using two mutual links and joints provides a stable DoF value. The binary mutual links in the assembly are turned into ternary, quaternary, etc. links. Deployable polygons are then repeated for covering the surfaces with no gaps or overlaps. The selection of adjacent polygons to be assembled in the 1-uniform tessellations is essential in terms of generating no collision during deployment. The redundant joints are revealed in closed-loop assemblies.

6.1. Main Contributions

The current study that includes technical examination and information on various fields such as mathematics, geometry, physics, and astronomy, is holistic, multidisciplinary research that brings art, architecture and mechanism science together on a historical basis. The study is unique in terms of revealing numerous outstanding pieces of art and architecture that are affected by motion in a single document.

Since the essence of the information used by engineers and architects are the same, the required information is gathered from the literature of machinery theory to be applied to architecture because of the lack of architectural sources. Types of mechanisms that are generated differ from each other with respect to utilization and purpose. The load-bearing capacity has a significant role in the structure design. The selection of link types depends on purposes such as motion transmission and covering. The products can have their form as their outstanding characteristic. Focal points of engineering, architecture and art may differ from each other. For example, the transmission of motion from a point to another may be the essence in mechanical engineering while the first and final positions can be in architecture and each moving piece or the motion itself may be in art. Velocity and acceleration have minor importance in kinetic architecture. Thus, priorities in the process of mechanism design vary among different fields of work. Information from the field of mechanical engineering is collected based on architectural application in the current study which intends to strengthen the interdisciplinary bond between mechanical engineering and architecture. The present study is intended to serve as a guide in the process of movable design for artists and architects with the fundamental principles of kinematics and applied examples.

The novel method of surface design developed in the current case study provides a proper solution for generating a surface that is adaptable to applied pressure. The design is an adaptable form that is responsive to environmental, functional, visual, and social needs; easy to transport through its compact form. The modular characteristic provides adaptability to polygonal surfaces. The fully planar configuration in the deployed position is advantageous in terms of its capability of fully closing a planar surface that is widely used in architecture. The 3D dynamic perceivable form is observed in motion. A mechanism type that can resist heavy loads is selected. The unit is adaptable to all regular convex polygons by virtue of its triangular shape in the deployed position. It can be used as a single module, as well as assemblies in various combinations in surface design. The current modular approach and method of assembly provide the opportunity of many 1 DoF configurations that are driven by a single actuator to be designed.

6.2. Recommendations for Future Works

Movable designs have the potential of changing the environmental, functional, and social needs in society. Thus, such designs are suggested to be developed, improved, and applied in future research.

The present study includes numerous daily examples, fundamental principles of art and architectural design, examinations and analyses with respect to selected examples. Revealed information may serve as a baseline for future kinematic structural analyses of artists and architects.

Kinematic principles and design processes are also revealed to serve as a guide for future designers. Revealed information may result in proper studies when combined with required imagination, creativity, experience and aesthetics in perspective.

A novel polygonal surface design proposal is revealed on the basis of analyses conducted in the present study in which using polygons is limited with uniform tessellations. Since there is no limit in designing surfaces that consist of repetitions of regular convex polygons with this method, various dimensions and materials can be used in design depending on the final product. Future researchers are encouraged to develop new designs using variations of this design method.

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