DESIGN OF A RECONFIGURABLE DEPLOYABLE STRUCTURE FOR POST DISASTER HOUSING

A Thesis Submitted to
The Graduate School of Engineering and Sciences of
Izmir Institute of Technology
In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

in Architecture

by
Fulya ATARER

December 2014
İZMİR

We approve the thesis of **Fulya ATARER**

Examining Committee Members:

Assoc. Prof. Dr. Koray KORKMAZ
Department of Architecture, Izmir Institute of Technology

Assist. Prof. Dr. Yenal AKGÜN
Department of Interior Architecture, Gediz University

Assist. Prof. Dr. Özgür KİLİT
Department of Energy Systems Engineering, Yaşar University

17 December 2014

Assoc. Prof. Dr. Koray KORKMAZ
Supervisor, Department of Architecture
Izmir Institute of Technology

Assist. Prof. Dr. Gökhan KİPER
Co-Supervisor, Department of
Mechanical Engineering
Izmir Institute of Technology

Assoc. Prof. Dr. Şeniz ÇIKIŞ
Head of the Department of Architecture

Prof. Dr. Bilge KARAÇALI
Dean of the Graduate School of
Engineering and Sciences

ACKNOWLEGEMENTS

I am heartily thankful to my supervisor, Assoc. Prof. Dr. Koray KORKMAZ whose knowledge, encouragement, understanding, valuable advice and sincerity have broadened my mind and supported me to complete my M.Sc. thesis. I am also grateful to my co-advisor Assist. Prof. Dr. Gökhan KİPER whose crucial contributions, valuable advice throughout my study.

I would like to express my sincere appreciation to Prof. Dr. Rasim ALİZADE for his extensive knowledge, vision and creative thinking have been the source of inspiration for me through this work. Additionally, I would like to thank other members of the examining committee; Assist. Prof. Dr. Yenal AKGÜN and Assist. Prof. Dr. Özgür KİLİT, for their valuable suggestions and comments.

I would like to thank special my friends at IZTECH; Gizem PAYER, Feray MADEN and Barış BAĞDADİOĞLU for their help and friendship.

I am thankful all my friends and colleague Department of Architecture in Erciyes University especially; Meltem ULU, Fulya SINACI, Özlem TEPELİ and also Assist. Prof. Dr. Z. Özlem PARLAK BİÇER for their moral support and entertainment.

This journey would not have been possible without the support of my family. First, I would like to express my gratitude to my parents, for their devotion, understanding, and support throughout my life. My special thanks to my husband Sedat ATARER for his endless devotion, understanding, friendship and support at the beginning and during my master thesis, so I dedicate this study to my husband.

ABSTRACT

DESIGN OF A RECONFIGURABLE DEPLOYABLE STRUCTURE FOR POST DISASTER HOUSING

In this thesis, the possibility of constructing reconfigurable deployable structure composed of planar linkage units has been explored.

The first part of the thesis is devoted to literature survey on housing recovery. When the current researches on post disaster housing are investigated, it is observed that most of post disaster housing or temporary buildings in the literature are predefined portable, demountable or relocatable buildings. Deployable buildings serve for a single function.

A study into the existence of alternative forms of a reconfigurable deployable structure has been done. The conditions for the alternative forms to be a multi-functional building have been derived. Reconfigurable deployable structure presented here is a single degrees-of-freedom (DoF) multi-loop linkage which has more than two configurations. The alternative forms that a linkage is constructed with the same links and connections are called configurations or assembly modes of the linkage. During its motion, the linkage may pass from one assembly mode to another, which is called reconfiguration or assembly mode change. Design and position analysis of the linkage mechanism have been implemented in Microsoft Excel® environment. The link lengths can be varied in this environment and the motion of the structure can be simulated by changing input joint parameters. Four different case studies have been designed in Microsoft Excel®.

A reconfigurable deployable structure can be used as a multi-functional shelter or canopy which can take many forms in a few minutes for urgent needs after disasters, military purpose or public needs. Its deployed and retracted (or compact) geometries are explored. As a case study the dimensions of links are presented. Installation process for different functions is explained. The full concept for the structure, from outer covering material to foundation is then detailed. Finally, a sample material cost analysis is performed to determine if the product is financially feasible.

ÖZET

AFET SONRASI BARINMA İÇİN BİÇİM DEĞİŞTİREBİLEN STRÜKTÜR TASARIMI

Bu tezde, düzlemsel mekanizmalardan oluşan biçim değiştirebilen bir strüktür birleşimi incelenmektedir.

Tezin ilk bölümü konut geri kazanımıyla ilgili literatür araştırmasına ayrılmıştır. Literatürdeki afet sonrası barınma ya da geçici konut için yapılan son zamanlardaki çalışmalar incelendiğinde, bunların bütünüyle taşınan yapılar, sökülüp takılabilir yapılar, bütün halinde taşınıp açılıp kapanabilir yapılar olduğu gözlemlenmektedir. Tüm bu geçici konut alternatifleri tek bir fonksiyona hizmet etmektedir.

Biçim değiştirebilen strüktürün alternatif formlarının varlığı üzerine bir çalışma yapılmıştır. Çok işlevli yapılar elde etmek üzere farklı yapılandırmalar oluşturulması için koşullar araştırılmıştır. Burada sunulan biçim değiştirebilen strüktür ikiden fazla konfigürasyona sahip tek serbestlik dereceli çok devreli bir mekanizmadır. Bir çubuk mekanizmanın alternatif formlarına konfigürasyonlar ya da montaj modu adı verilir. Strüktürün hareketi esnasında, bir montaj modundan diğer montaj moduna geçebilmesine ise yeniden yapılandırma ya da montaj modu değişikliği denir. Mekanizmanın tasarımı ve konum analizi Microsoft Excel® ortamında yapılmıştır. Bağlantı uzunlukları bu ortamda çeşitlendirilebilir ve giriş mafsal parametresi değişimiyle mekanizma hareketi simüle edilebilir. Farklı tasarım örnekleri Microsoft Excel®' de incelenmiştir.

Biçim değiştirebilen strüktür sistemi çadır ya da üst örtü olarak birkaç dakika içinde kurulup afet sonrası barınma, askeri amaçlı ve toplum ihtiyaçları için kullanılabilir. Strüktürün açık ve kapalı geometrileri incelenip boyutları sunulmaktadır. Farklı işlevler için kurulum süreci açıklanmaktadır. Strüktür için tüm konsept dış kaplama malzemesinden temeline kadar detaylandırılmaktadır. Son olarak, ürünün mali olarak uygulanabilir olup olmadığını belirlemek için maliyet analizi yapılmıştır.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1. Definition of the Study

Disaster has been defined as appearing physical, economic and social loses for victim people and anthropogenic events that affect the normal life (Ergünay, 1996). Most of people have lost their life qualification due to the disasters like earthquake, hurricane and flood. Therefore, post disaster phase is crucial for disaster victims.

Post disaster consists of 3 stages. These are first aid, recovery and rebuilt. Housing plays a central role in these stages of post disaster. According to Cole (2003), post-disaster housing types in four different groups are emergency sheltering, temporary sheltering, temporary housing and permanent housing. Temporary shelter and temporary house are used in first aid and recovery post disaster stages. Surely, temporary housing is significant for disaster victims. Kronenburg (1995) classifies temporary buildings with variable location or mobility into three specific types. These are portable, relocatable and demountable buildings.

Until today, most of the research on temporary housing has proposed demountable or portable structures and do not offer any significant formal flexibility. However deployable structures can be transformed from a closed compact configuration to a predetermined, expanded form. In the early 1960's, Spanish architect Emilio Perez Pinero pioneered deployable structures. Felix Escrig and Juan Valcarcel improved upon Pinero's work. Now various researchers are doing study on deployable structures. Some of them propose deployable structures as a temporary house for post disaster stages due to more rapid set up. They are folded, packed in the storage and deployed at the site. Today most of the researchers on deployable structures only deal with the study of obtaining predefined forms with mechanisms. Thus, these structures change their geometries only between predefined "folded-deployed" configurations. They cover a space when they are at deployed shape but lose this property when they are at folded configuration.

Reconfigurable deployable structures (RDS) can be transformed from a closed compact configuration to multiple alternative expanded forms for different functions. In literature RDS are multi degrees of freedom (M-DOF) mechanisms. These structures take various geometric configurations with more than one actuator. Besides, some authors use reconfigurable structure to describe movable systems which can attain different stable forms, like a chair which can transform into a ladder (Weaver and et al., 2008). Chair and ladder are two forms for different functions with a single DOF mechanism. Here reconfiguration is assembly mode change for a mechanism. Although single DOF mechanisms are taken two forms, reconfigurable deployable structures can be single DOF. In this way, some single DOF mechanisms can be taken more than two forms. Deployable tents are used for a single function with a single form but the proposed reconfigurable deployable structure concept is multifunctional to create enclosed or semi open spaces with a reconfigurable mechanism. This advantage of proposed RDM will provide public benefit as a shelter or canopy especially at post-disaster situations.

Consequently, it can be claimed that deployable especially reconfigurable deployable structures will subrogate demountable and portable structures based on these definitions.

1.2. Aim of the Study

Primary objective of this dissertation is to propose a reconfigurable deployable structure composed of planar linkage units to meet the temporary multi-functional sheltering needs. Although the reconfigurable deployable structure has single DOF, it can take three different forms to meet urgent needs after disasters, military purpose or public needs.

In this process, the study concentrates on possible ways to assemble planar four bar linkage mechanisms which may pass from one assembly mode to another.

1.3. Scope of the Research

This study utilizes planar four bar linkage to design reconfigurable deployable structure for temporary sheltering. Examination of typologies, position analysis of the RDM, parametric design of the case studies, cad modeling form the content of the thesis.

Links material, connection details and cost analysis of the reconfigurable deployable structure are other scopes of this study. Covering material of such kind of deployable structures is an additional research problem that is not within the scope of this study.

1.4. Methodology of the Research

This study employs “Simulation and Modeling” as the primary research methodology. Simulation and modeling includes all prototyping works, mathematical models in Microsoft Excel® and computer simulations with Solid Works.

Firstly, a thorough and critical literature survey was conducted and the study exposed common deployable and reconfigurable deployable structures.

Secondly, simple physical models were constructed to evaluate the transformation capabilities of the reconfigurable deployable mechanism.

Thirdly, several mathematical algorithms were developed by using Microsoft Excel® in order to assess the improvements over the previous design schemes and to product several case studies. Finally, a case study was selected and modeled by using Solid Works.

1.5. Organization of Thesis

The present thesis consists of six chapters.

Chapter 2 comprises the background of the study with disaster stages, housing recovery after disaster and type of temporary building according to classification of Kronenburg.

Chapter 3 is a literature survey about deployable and reconfigurable deployable structures. It includes classification of deployable structure according to morphological features. Then the kinematic properties and examples of these classes are presented.

Chapter 4 is concerned with the kinematic design of a reconfigurable deployable structure. Firstly, parallelogram four bar mechanism is utilized by connecting two parallelogram loops. Then the general case of four-bar loops without parallelogram proportions is analyzed. The position analysis of the mechanism is modelled in Microsoft Excel® and several different case studies are designed.

Chapter 5 presents a case study of the overall construction of the RDS, technical drawings and a cost analysis.

In Chapter 6, the main achievements of the research are summarized, together with suggestion for future works.

CHAPTER 2

HOUSING RECOVERY AFTER DISASTERS

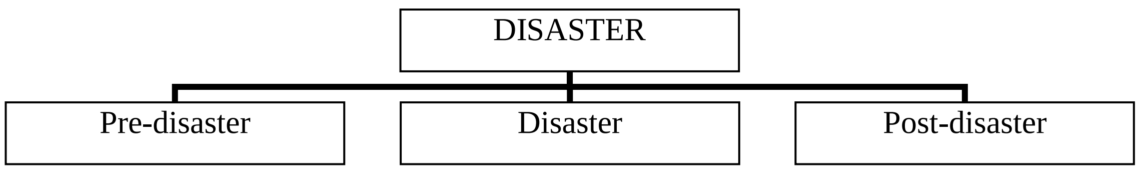
2.1. Disaster

Disaster is defined as a non-routine event that goes over the capacity of the affected area to respond to it in such a way as to save lives, preserve property and to maintain the social, ecological, economic and political stability of the affected region (Pearce, 2000). Ergünay (1996) has defined the disaster as occurring physical, economic and social losses for people and stopping or interrupting the natural and anthropogenic events that affect the normal life and human activities.

The natural disasters that occur in Turkey are earthquakes, landslides, floods, rock falls, fires, avalanches and strong winds. Among those, earthquakes are the most frequent and the most destructive disasters that strike the country, because Turkey is on Alp-Himalayan seismic belt. 61% of the damages are caused by earthquakes, 15% by landslides, 14% by floods, 5% by rock falls, 4% by fires and 1% are damaged by disasters such as avalanches, strong winds (Acerer, 1999).

Disasters change physical environments which lead to some difficulties on communities' living conditions. The majority of the buildings are damaged in disasters. Some buildings collapse and some cannot be used any more. Thus, people become homeless and face with sheltering problems. Immediate help of accommodation is put up after any kind of disasters by governments and/or by private institutes.

Basically, disasters are viewed the following 3 phases:



Pre-disaster phase consist of planning and preparedness. Namely, pre-disaster phase is designed to structure the disaster response prior to the occurrence of a disaster. This phase involves evaluating the potential disaster risks of community, vulnerabilities, and the likelihood for a disaster to occur. According to Herrmann (2007), successful disaster response requires a community and its health care system to:

- Define and anticipate disaster risk and hazards,
- Prepare the material resources and skilled personnel to respond to these risks and hazards,
- Develop comprehensive plans to deploy these resources to assist the community and its recovery,
- Learn from disasters and translate the lessons learned into invaluable future preparedness.

Post disaster phase is sub divided into three phases.

1. Phase of immediate aid
2. Rehabilitation
3. Reconstruction

Phase of immediate aid is the real implementation of the disaster plan which is of vital importance for rescuing the plenty of lives. Rehabilitation and reconstruction phases play a significant role bring back to normal life.

2.1.1. Phase of Immediate Aid

Phase of immediate aid includes works of the first 24 hours period after the occurrence of the disaster. This phase is characterized by the measures taken to reduce the harmful effects of a disaster in order to limit its impact on human health, community function and economic infrastructure. In phase of immediate aid, emergency and temporary shelters are used because they are stocked, carried and set up easily and fast. This phase is important to satisfy basic human housing need and protection from climate.

2.1.2. Rehabilitation

Phase of rehabilitation focuses primarily on emergency relief: saving lives, providing first aid, meeting the basic life requirements of those impacted by disaster and providing mental health and spiritual support and comfort care. In this phase, temporary housing, which provides better living conditions than the emergency and temporary sheltering, must be used. The most important function of accommodation is that it protects disaster victims from harmful external influences during phase of rehabilitation and provides family's security. People begin to return normal life.

2.1.3. Reconstruction

Reconstruction phase focuses on the stabilization and returning the community and health care system to its pre-impact status. Phase of reconstruction can begin days or in some cases months after disaster strikes. This phase can range from rebuilding damaged buildings, building new permanent houses and repairing an infrastructure of community to relocating population. Therefore, disaster victims get back to normal life. According to Akünal (1986), permanent housing aims to be a final solution after disasters to provide housing individually which would fulfill the needs of the inhabitants in relatively much longer period of time.

As it is seen, each phase presents unique opportunities for individuals, communities, and hospitals to focus on preparing for respond to and recover from disaster.

2.2. Housing Recovery

Following a devastating natural disaster, restoring housing is one of the most important aspects of community recovery. Housing is not only the shelter, it is also a critical component of the local economy and social fabric (Zhang and Peacock, 20 09). The process of housing recovery varies among households. Households move in and out of sheltering and housing locations either in many circumstances, so the sheltering and housing of victims is not static. Cole (2003) describes post-disaster housing types in four different groups. These four housing recovery phases are emergency sheltering, temporary sheltering, temporary housing and permanent housing.

2.2.1. Emergency Sheltering

Emergency sheltering is a makeshift haven for victims seeking safety for short periods of time, after evacuating their homes during the height of the disaster (Bolin and Stanford, 1998). It is a tent or a shelter made of panels. This type may offer weak selection or a forcefully imposed location for the site as a result of the conditions being lived. The contextual characteristics of this kind of shelter are totally different from the other two as a result of its fundamental aim that is to house people for a very short period just after the disaster.

2.2.2. Temporary Sheltering

Emergency shelters go by the name of temporary shelters. In some instances emergency shelters become temporary shelters as victims remain at the emergency shelter until they move to new house. Both public and private temporary shelters are provided to the victims after the disaster has ceased. Actually, many studies have shown that public shelters are used as temporary sheltering after disasters. Public shelters are pre-planned for mass care sheltering arrangements in public or other large buildings like secure school or library. They provide victims sleeping arrangements, medical services, and provisions for temporary subsistence.

2.2.3. Temporary Housing

Temporary house is built shortly after the occurrence of disaster. It offers better living conditions than the emergency and temporary sheltering (Gürsu, 1986). Temporary housing includes the reestablishment of household routines. Therefore, after the using temporary housing, they move permanent housing. Mobile homes and demountable system are effectively used for temporary housing in this time. In addition, vacant apartments and houses, dormitory rooms, the homes of family, friends and neighbors and public building are sources of temporary housing for victims.

2.2.4. Permanent Housing

In the phase of permanent housing, disaster victims may repair or rebuild their pre-disaster houses or move to other permanent housing location within or outside the community. In some cases, temporary housing, such as caravans can become permanent housing. Permanent houses aim not only to serve as housing units or basic protection but also to satisfy all necessary requirements regularly.

According to Ervan (1995), people's desires and needs can be collected in 3 groups. These are physiological, social and psychological.

Physiological: Provided by persistence of human life which are basic desires and needs (food and beverage, relaxation and sleeping).

Social: Caused by living together that are desires and needs (relationship between families, hygienic conditions, disposal of waste materials).

Psychological: Living in safety desires and needs in extraordinary environment (stay away from danger, out of jeopardy, feel at peace).

People's basic needs play an important role in the design of temporary housing. Balkan classifies people's actions. These are passive and active specific actions and passive and active general actions.

Passive specific actions are sleeping, relaxation, living, reading, speaking, writing, listening radio, watching TV, need to use the toilet.

Active specific actions are eating food and beverage, brushing teeth, getting a shave, washing hand and face, changing clothes, taking shower.

Passive general actions are domestic economy, drying laundry, stocking food, communication with relative, neighborhood.

Active general actions are cleaning house, washing laundry and dishes, ironing, cooking, stitching, childcare, patient care.

2.3. Temporary Buildings

Temporary means that it is intended to be used for only a limited period of time (Longman dictionary). Temporary building is a physical modification to facilities which can be in a disaster area or a public area intended to be in place for a short period of time. Structure of a temporary building provides a modular shelter which can be quickly set up and taken down.

Therefore, temporary housing needs to have these properties:

- Setting and dismantle are easy
- Different areas of application
- Lightness
- Packaging, transportation, storage are easy
- Counter to aftershock resistance and durability
- Counter to using resistance and becoming long-lasting
- Create a livable internal environment against climatic conditions
- Fire safety
- Protection against harmful animals
- Providing the necessary daily requirements for life (Acerer, 1999, Sey and Tapan, 1987).

Kronenburg (1995) defines that temporary buildings are dismantled and reassembled and moved as components or complete units. These buildings with variable location or mobility are classified into three specific types:

1. Portable Buildings
2. Relocatable Buildings
3. Demountable Buildings

According to Kronenburg, “Buildings with variable Location or mobility” action takes place before using the structure. This primary action is necessary in order to obtain initial form of the structure. Portable, relocatable and demountable structures belong to this group.

2.3.1. Portable Buildings

Portable buildings are designed to be transported whole and intact. They are also called moveable or transportable. Sometimes they include the method for transport within their own structure (wheels, hull) and can be carried – a few can be described as self-powered (Kronenburg, 1995).

Portable buildings have been in use since humankind first began to build, yet because of their impermanent nature it is only recently that they have begun to be perceived as architecture (Kronenburg, 2003). Figure 2.1 shows one of the first examples of portable buildings. Medieval Tartar Yurts is transported whole and intact with the animals. It is a tent made of sheep skin. Other example is Conestoga wagon which was used extensively during the late 18th century and the 19th century in the United States and Canada (Figure 2.2). In 1919, fist caravan sample called Aerocar was designed by Glen Curtis Figure 2.3. The first commercial portable building was introduced in the United Stated in 1955 by Porta-Kamp (Figure 2.4). In the UK, the first portable building was in 1961 under the brand named Portakabin (Figure 2.5).

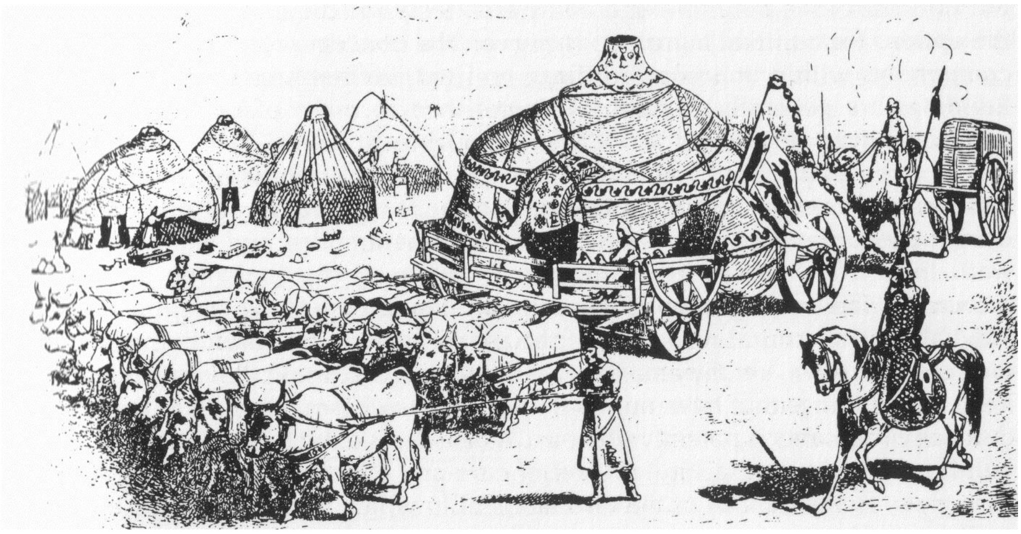


Figure 2.1. Medieval Tartar Yurts and Wagons Moving Camp
(Source: Kronenburg, 1995).

Figure 2.2. Conestoga Wagon
(Source: Wikipedia, 2012)

Figure 2.3. Glen Curtis' Aerocar
(Source: Hemmings, 2009).

Figure 2.4. Example of Porta-Kamp
(Source: Sistersonthefly, 2014).

Figure 2.5. Example of Portakabin.

An example from present day is expandable mobile mini house designed by Stephanie Bellanger, Amaury Waitine, François Gustin and David Dethoor. It has an ingenious expanding floor plan that features a bathroom, living room, bedroom, kitchen, and office when this house is expanded, it can draw an arc of about 252 degree (Figure 2.6).

Figure 2.6. Expandable mobile mini house
(Source: Inhabitant, 2013).

2.3.2. Relocatable Buildings

Relocatable buildings are transported in parts but are assembled at the site almost instantly into usable built form. These are almost always carried but in a few limited cases may have part of their transportation system incorporated into their structure (Kronenburg, 1995). The main advantage of this type is that it can provide space almost as quickly as the portable building without restriction in size imposed by transportation. Relocatable buildings can offer more flexibility and a much quicker time to occupancy than conventionally built structures.

Figure 2.7. AT&T Global Olympic Village
(Source: Kronenburg, 2003).

The athletic and related facilities for the 1996 Olympic Games in Atlanta, USA, are resourced in three ways- approximately one-third are new permanent construction, and one-third (about 150,000 square meters) utilized temporary and relocatable buildings and interior adaptations (Figure 2.7). They are made from standard rental items such as scaffolding, with additional specially designed modular elements such as printed fabric panels, tensile membranes, and above-ground concrete ballasting. Owing to the vast numbers of people that would use the complex and the nature of the site, which is reclaimed inner-city land, temporary concrete foundations are built for the reusable buildings. Other sample is Carlos Moseley Music Pavilion (Figure 2.8). It consists of four main elements a tripod like truss system, a tensile canopy, a folding stage, and a series of collapsible amplification towers. The three trusses are hinged in the centre for transportation and when they arrive on site they are folded out to their full length of 26 meters (Figure 2.9). In order to be capable of accurate three dimensional positioning the base of each truss has been designed to pivot vertically and rotate around a pin (Kronenburg, 2003).

Figure 2.8. Carlos Moseley Music Pavilion
(Source: Kronenburg, 2003).

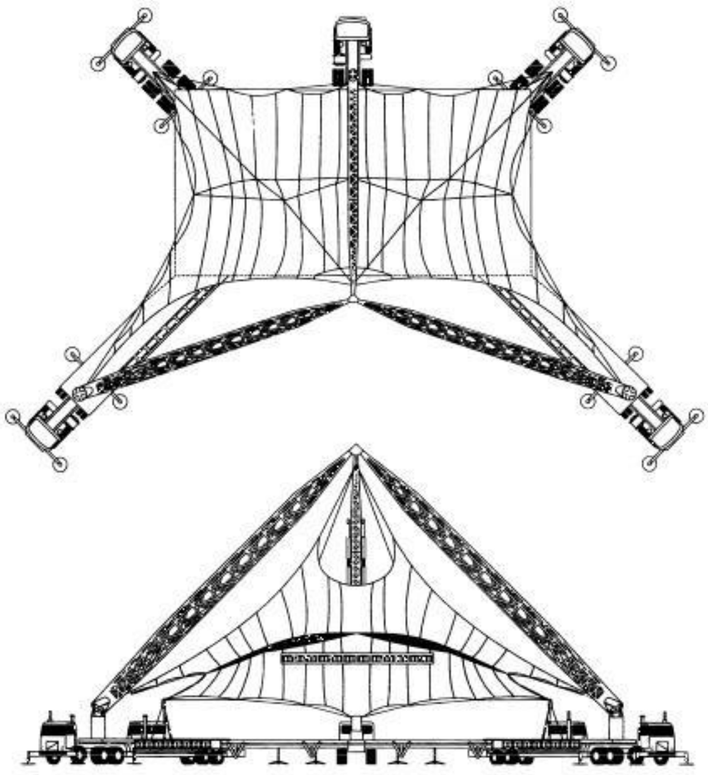


Figure 2.9. Carlos Moseley Music Pavilion, plan and audience elevation
(Source: Kronenburg, 2003).

The Transportable Maintenance Enclosure project which is a kind of relocatable building resulted from a search by the US Army to find a quickly deployable large area maintenance shelter, primarily for helicopters (Figure 2.10). Transportable Air-supported structures can be very light to transport and fast to erect; however, the most common pattern is the low pressure air-filled space which is entered through an air lock. The TME utilizes PVC-coated polyester membranes to form structural arches, four vertical ones in the center and two which are inclined at the ends. These tube-like structures are 1075 mm in diameter and span 9 meters with a height of 6 meters. Though they must be very airtight and resistant to puncture the relative area in which leaks may occur is reduced as the intermediate membranes between the arches need not be airtight (Figure 2.11). The building takes less than one and a half hours to deploy but once in position can be inflated in just twenty minutes (Kronenburg, 2003).

Figure 2.10. Transportable Maintenance Enclosure (TME)
(Source: Kronenburg, 2003).

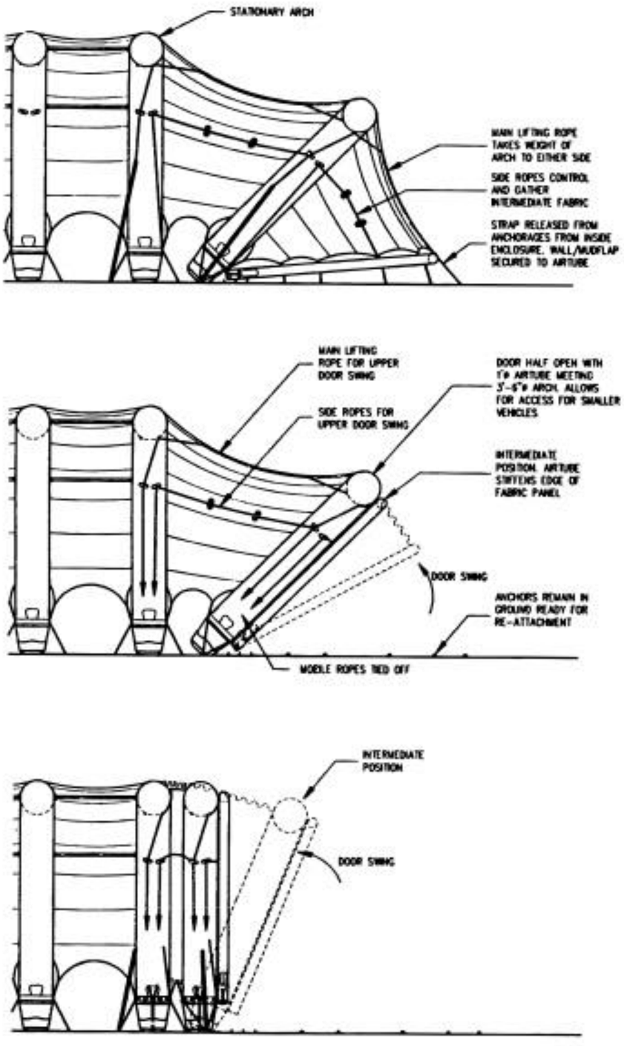


Figure 2.11. TME, computer rendering image and assemble schema
(Source: Kronenburg, 2003).

2.3.3. Demountable Buildings

Demountable buildings are transported in a number of parts for assembly on site. They are much more flexible in size. They have some of the limitations that site operations bring to a conventional building and depending on the size, complexity, and ingenuity of the system, are not as instantly available (Kronenburg, 1995). First examples of demountable buildings are tent, tipi and yurt (Figure 2.12). At the same time, when North American nomadic tribes of Great Plains used tipi, Asian nomads used yurt as their home. Traditional yurts consist of an expanding wooden circular frame carrying a felt. A yurt is designed to be dismantled and the parts carried compactly on camels or yaks to be rebuilt on another site. A tipi is a conical tent, traditionally made of animal skin and wooden poles. The construction of a tipi starts with tying together three of the poles at the skin's radius from their bases using a tripod lashing.

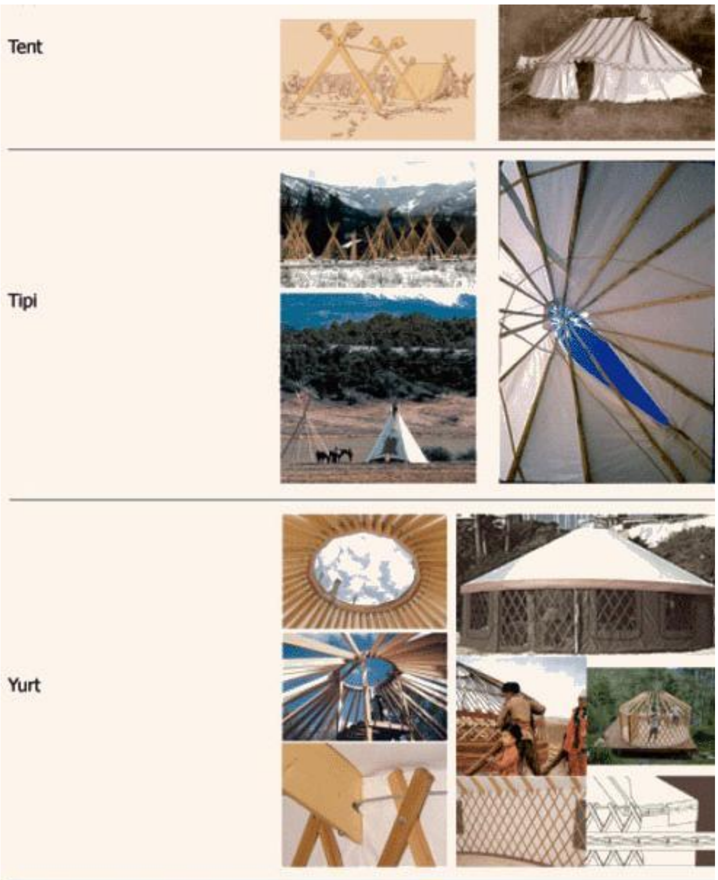


Figure 2.12. First samples of demountable buildings (Source: Kronenburg, 1995).

Demountable buildings must have these properties; (Ervan, 1995).

1. Their components must be separated easily in order to assemble again.
2. They should have packing, transportation and storage properties.
3. They must be less depreciation and also maintain easily.
4. They should produce unit components in industry and people can do only assembly in disaster area.
5. Their assembly need not to any special knowledge, equipment and expert. They can assemble easily few disaster victims and one manager.

Figure 2.13 shows a schema of a demountable building.

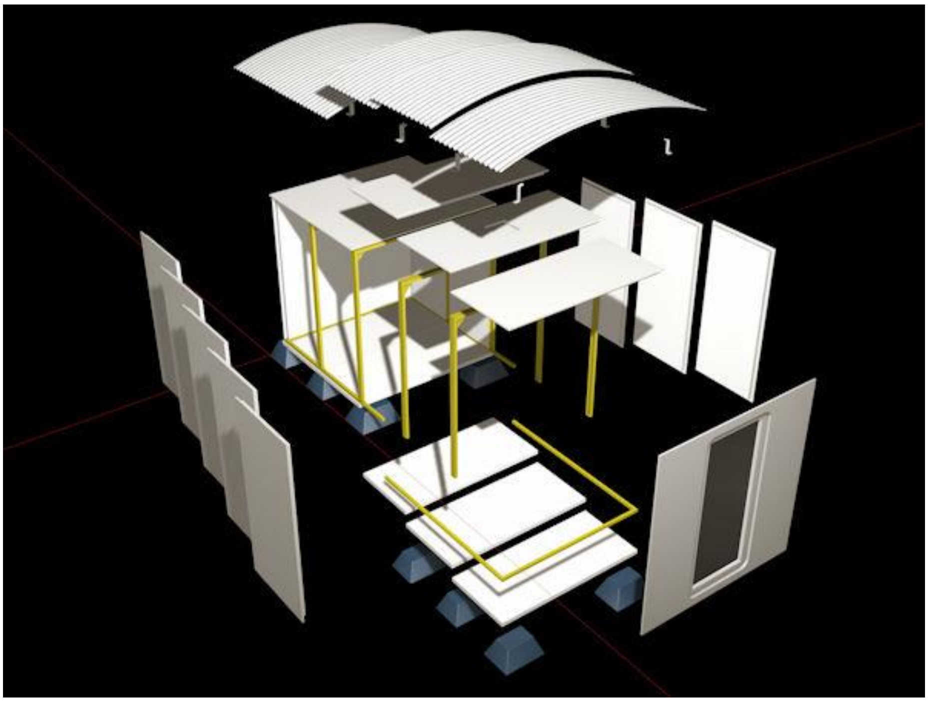


Figure 2.13. A schema of demountable buildings.

An example for demountable buildings is The DH1 Disaster House. There are not any necessaries using extra combining elements to assemble the disaster building called The DH1 instead of using plywood with socket (Figure 2.14). It is designed by Gregg Fleishman. The DH1 project began in early 2006. Built in model form, full size would have been 14' square. Each of four roof surface sections was formed with two 4 x 8 sheets, supported by a sectional frame. A bit too fussy, perhaps, the solution was set aside more for being too uninteresting. The wall slope did borrow from the "rhombi cube" at 19.5 degrees and this angle was carried over to the DH1. A structural floor was added to the DH model and roof and floor module 1.5m. The 5' module is visible in the exterior in the pair of doors on each face and the roof panels. The corner wall assemblies are made with two vertical 4 x 8 sheets and a corner beveled part and provide both vertical and lateral support (Greggfleishman, 2013).

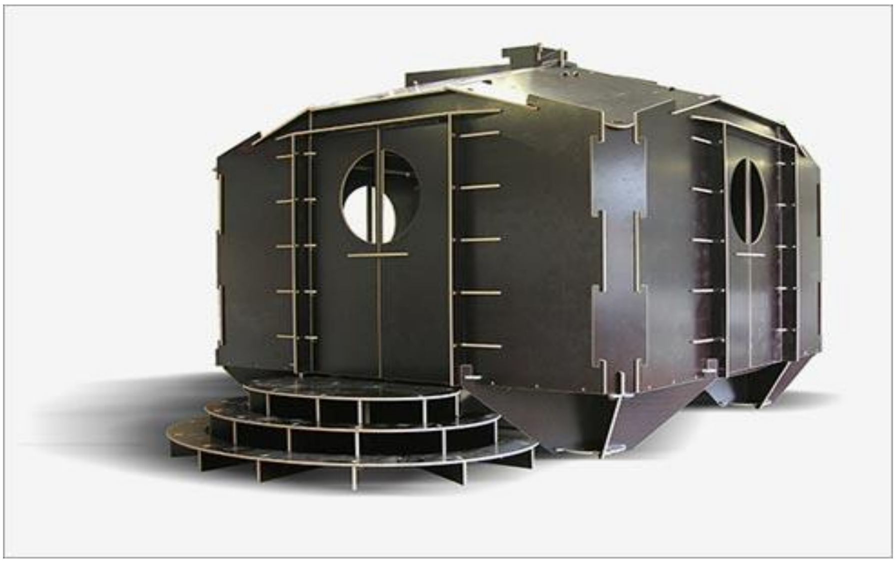


Figure 2.14. The DH1 Disaster House
(Source: Greggfleishman, 2013).

Abod House is designed by BSB Design in South Africa in 2007. It is set up fast and easy and has expandable construction when disaster occurs (Figure 2.15). It has kitchen niche, bed and seating area. Figure 2.16 shows set up schema of Abod House. It can be set up only one day by four people.

Figure 2.15. Abod House
(Source: Abodshelters, 2013).

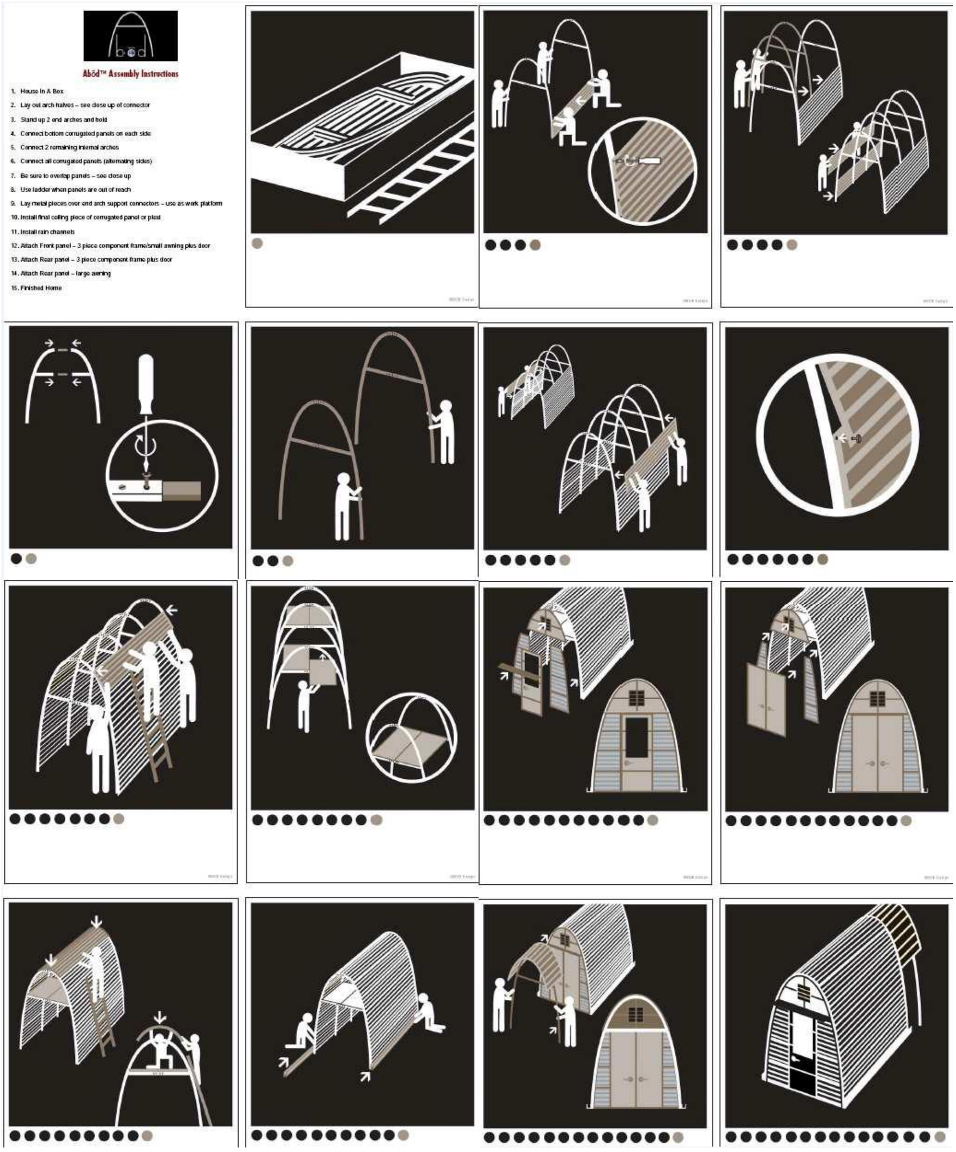


Figure 2.16. Set up Schema of Abod House
(Source: Abodshelters, 2013).

CHAPTER 3

DEPLOYABLE STRUCTURES

Gantes (1994) defines deployable structures as 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. It is clear that the term implies a transition, both in location and in geometry, from a compact stowed condition to final functional state (Hanaor and Levy, 2001). There are many applications of single DOF (degrees of freedom) deployable structures for temporary buildings or emergency shelters. It is the speed and ease of erection, ease of transportation and minimal skill required for erection make the deployable structures an alternative for temporary architecture. There are many different types of deployable temporary shelter designs in the world. Design alternatives include classical tents, inflatable tents, structures comprising folded plates or bar structures.

3.1. Classification of Deployable Structures

Hanaor and Levy (2001) classifies deployable structures according to morphological features and kinematic properties in Figure 3.1. The columns of the table represent the morphological aspects and the rows the kinematic properties, which are of primary significance in the context of deployable structures.

The kinematic properties are closely related to deployment technology. Two subcategories are considered for each of the main classification categories. The two major morphological features are lattice structures (skeletal) and continuous (stressed-skin) structures. It should be noted that in the context of space enclosures, all structures have a functional covering surface. The difference between the two classes of structures mentioned above is that in lattice structures, the primary load-bearing structure consists of discrete members, whereas in continuous structures the surface covering itself performs the major load-bearing function. Hanaor and Levy have proposed a third class called hybrid structures combine lattice and continuous components with approximately equal roles in the load-bearing hierarchy.

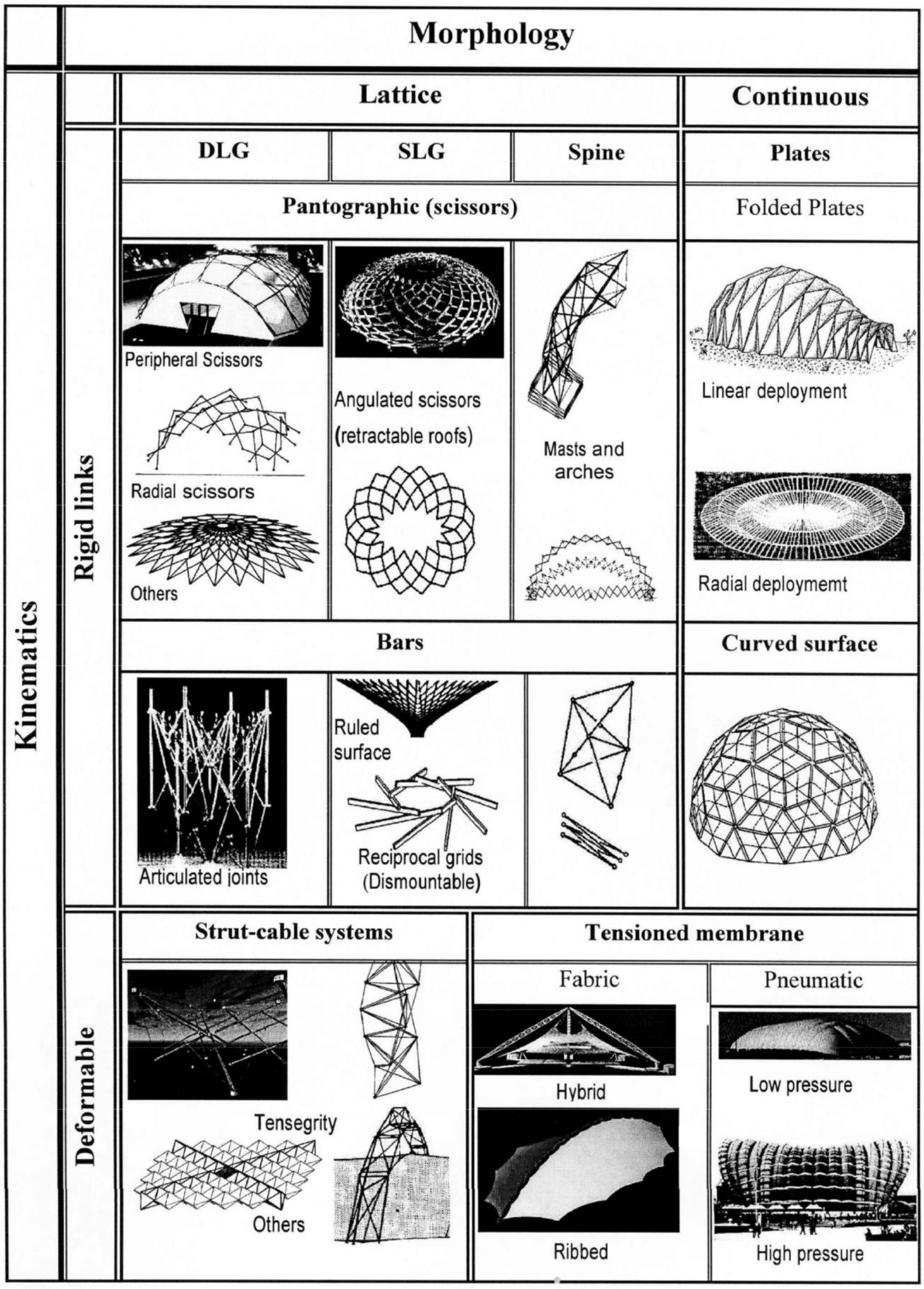


Figure 3.1. Deployable Structure Classification Chart
(Source: Hanaor and Levy, 2001).

The two major kinematic subcategories are systems comprised of rigid links (bars or plates) and systems containing deformable components which lack flexible stiffness (strut-cables or tensioned membrane).

As regards to using this schema, deployable buildings can be separated four groups in point of structures. These are scissors, bar, plate, strut-cable and tensioned membrane structures.

3.1.1. Scissors Structures

Scissors mechanism is the most commonly used mechanism for deployable buildings. In a scissor mechanism, there are three pivot joints for each rod, one on each end and one toward the middle (Figure 3.2). The deployable roof base on scissor grids was constructed by the Spanish architect Emilio Perez Pinero in 1961. He designed and presented his "Itinerant Theatre" in London (Figure 3.3). This theater is the first deployable space frame, using the scissor mechanism with tensile membrane to create shelter (Escrig, 2013). The theatre is a cover for an 8.000 s.q.m. made with aluminum in structures of scissors of four arms (Escrig et al., 1996). Pinero realized that if the interior pivot point on a rod was not at the midpoint, then it is possible to create a shell-shaped surface.

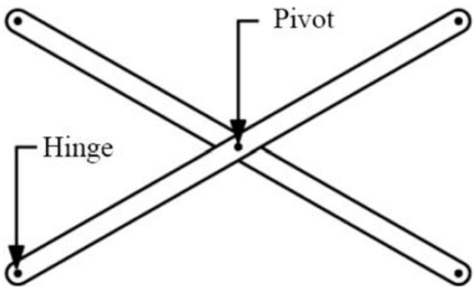


Figure 3.2. Scissor mechanism.

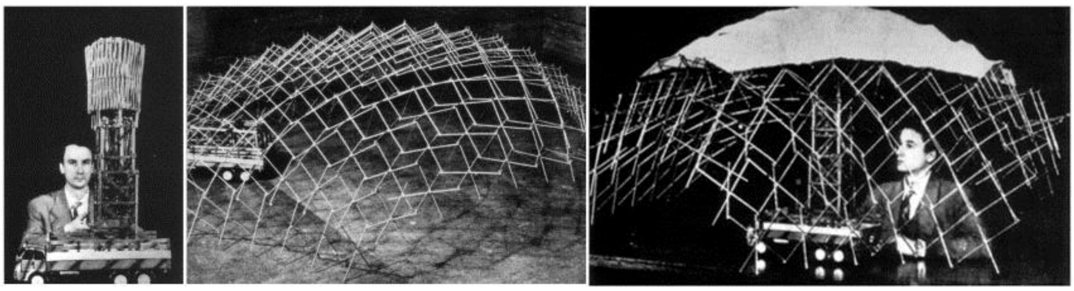


Figure 3.3. Emilio Pérez Piñero's Deployable Theatre
(Source: Robin, 1996).

The first dome structure of this type was introduced by T. Zeigler in 1974. Several pop-up displays and pavilions are constructed in accordance with his patents.

Felix Escrig Pallares improved upon Pinero's work and continued the study of scissor mechanisms with Sanchez and Valcarcel in Spain. They considered the geometric shapes that incorporate rigid-plate roofing elements. Their first designs were like the roof for Saint Francisco square and an assembly of eight umbrellas in 1982.Another their design was that their first attempt to complete a deployable closed polyhedral and design great deployable dome made with scissor mechanism. The main achievement of this team was to cover swimming pool in San Pablo sports area in Seville (Figure 3.4) (Escrig, 2013). Escrig adopted the geometry described of spherical segment of 6x6 quadrilaterals two of them in a common place (Escrig et al., 1996).

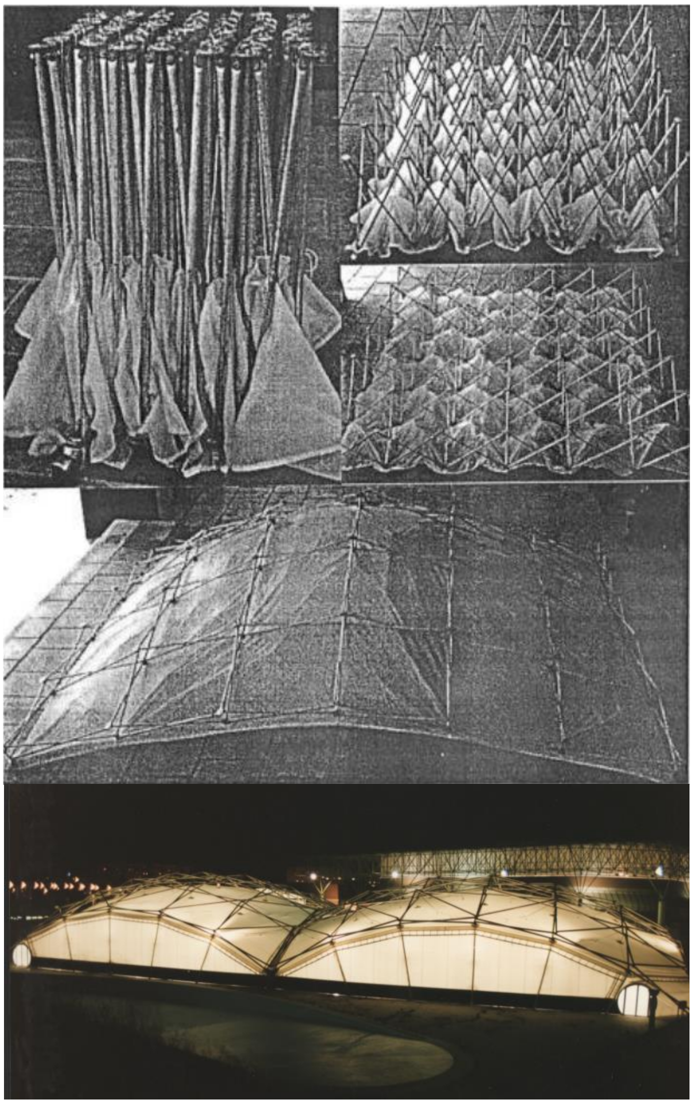


Figure 3.4. Escrig's Swimming Pool Cover Coat
(Source: Escrig et al., 1996).

Chuck Hoberman is another important reference in this kind of studies. He is a mechanical engineer who has concentrated on the study of deployable structures. He is the inventor of angulated scissors (eccentric scissors). By using the angulated scissors, Hoberman has designed the deployable single DOF Iris Dome and Hoberman Arch (Figure 3.5). A prototype for the Iris Dome was built for an exhibition at the Museum of Modern Art in New York in 1994. The Hoberman Arch was constructed for the Winter Olympics in Salt Lake City in 2002. Both of these mechanisms are constructed from a number of angulated elements arranged on concentric circles.

Figure 3.5. Left one is Hoberman's Arch in the Salt Lake (2002). Right one is Iris Dome in Germany (2000) (Source: Hoberman, 2013).

Other builder is Carlos Henrique Hernadez who designed and built the Venezuela Pavilion at the EXPO 92 in Seville. It is based in the accordion system. He has studied experimental shelters called STRAN 1 and 2 using scissor mechanism (Figure 3.6). His recent design is foldable rigid triangular sheets in Caracas in 2002. Luis Sanchez Cuenca is the other remarkable researcher who developed a complex geometric theory for building any kind of deployable surfaces. In his proposal, he has created generate arbitrary forms using scissor mechanisms.

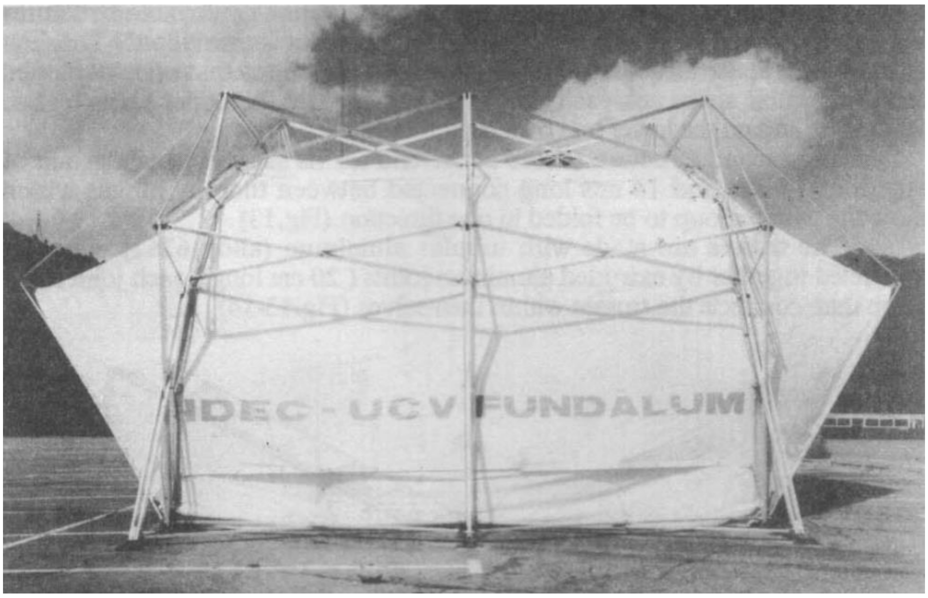


Figure 3.6. Experimental Shelter STRAN-1
(Source: Escrig, 2013).

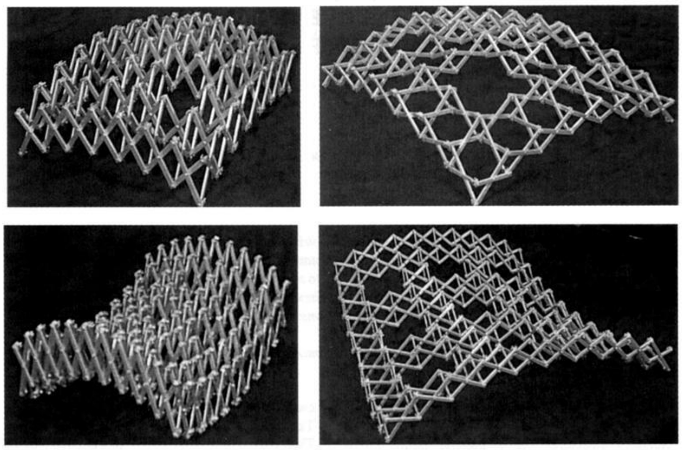


Figure 3.7. Deployable double curvature scissor hinge structures by Travis Langbecker
(Source: Langbecker, 2003).

Langbecker has designed several single DOF synclastic and anticlastic deployable structures with translational units (Figure 3.7). In order to increase stiffness and deployability feature, he added numerous rigid units and joints to his design (Langbecker, 2003).

Matthias Rippmann and Werner Sobek's research is one of the studies of Institute for Lightweight Structures and Conceptual Design (ILEK) at University of Stuttgart. Their study has developed a new Scissor-like Element (SLE) which has various hinge points, and allows bar connections at different points (Figure

3.8). By switching the locations of hinge points, different shapes can be constituted. He has proposed a single DOF deployable exhibition wall (Rippmann, 2007).

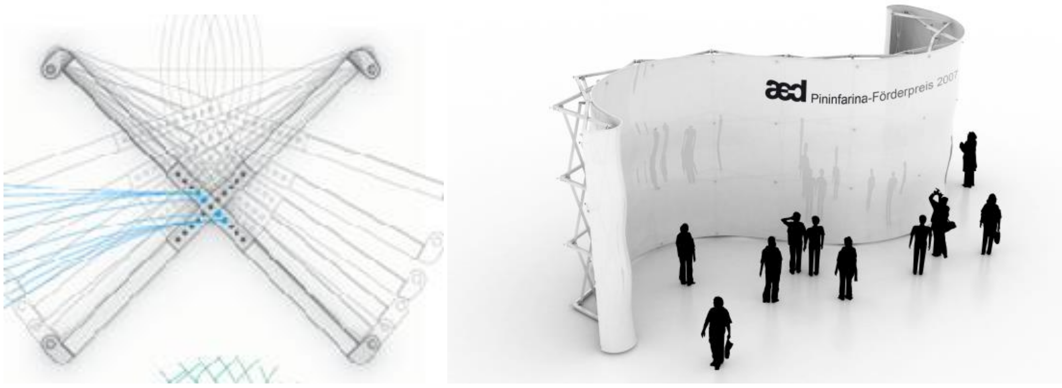


Figure 3.8. SLE with various hinge points and proposed exhibition hall.
(Source: Rippmann, 2007).

Tom Van Mele has researched the scissor-hinge structural mechanisms. One of his case studies is scissor hinged retractable roof over a sports facility. Retractable roof is in the shape of barrel roof but cut into two single DOF half arches (Figure 3.9). However his design requires additional retractable supportive elements like a strut, an arch, because scissor structural mechanisms are not convenient for long span To avoid a permanent structure that remains over the area even when the roof is open, each of the 'half' scissor-arches should be supported by a moveable supporting structure (Mele, 2008).

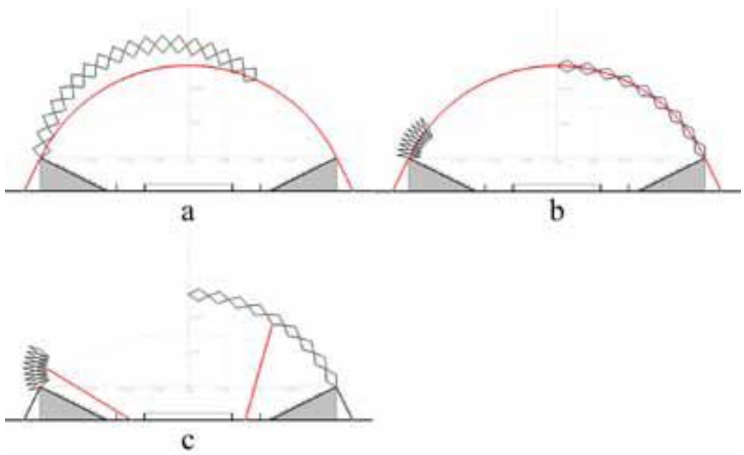


Figure 3.9. Tom Van Mele's visualization for retractable membrane roof.
(Source: Mele, 2008).

3.1.2. Bar Structures

In science of mechanism, movable bar structures are named linkage mechanisms. Frei Otto is the first in charge to propose the greatest and elegant umbrella structures supported on a single mast. Umbrellas are a kind of linkage mechanisms which are also rigid, stable bar structures when necessary. Mahmoud Bodo Rash has followed Frei Otto. He designed large scale umbrellas (25.5m on each side) for pilgrims visiting the Prophet's Holy Mosque located in Al-Madinah (Kingdom of Saudi Arabia) in 1971. The large scale umbrellas are deployable bar structures covered with tensioned membranes (Figure 3.10). The cross section of the aluminum arms of the umbrella structure is of triangular shape, so that the arms, when collapsed, form a closed casing of hexagonal cross section.

Figure 3.10. Deployable Umbrellas for the Piazza of the Prophet’s Holy Mosque, Madinah, SA. (Source: Otto, 2013).

In his early career Santiago Calatrava pioneered the application of linkage mechanisms in architecture. In 1981 he presented his PhD thesis “On the foldability of trusses” (Figure 3.12). Having completed his studies, he worked with small projects. Instead of scissor mechanisms he preferred to use articulated arms (linkage mechanism) in his designs. Based on slider crank mechanism, Calatrava designed three foldable entrances for Ernsting store in 1983 (Figure 3.11). Entrance doors transform to eaves.

Figure 3.11. Foldable entrance for Ernsting store
(Source: Designtheorykje, 2013).

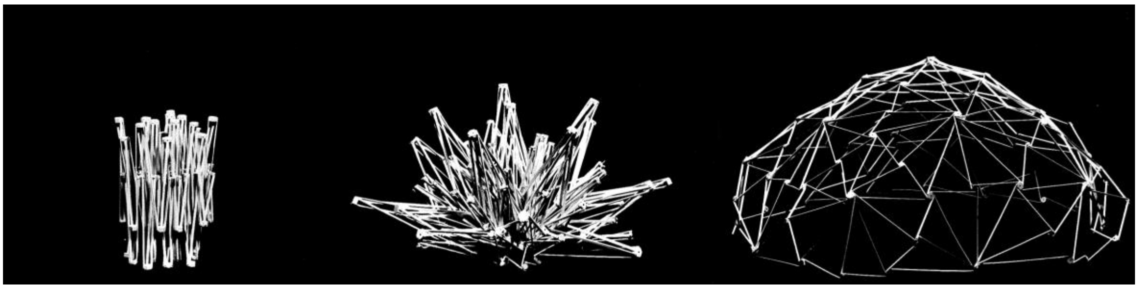


Figure 3.12. One of model from Ph.D. Thesis “On the foldability of trusses”

The roof of the Emergency Service Centre designed by Calatrava is another linkage mechanism. The symmetrically constructed, lens-shaped skylight of the Centre, surrounded by a spectacular folding shade, gives the impression of a fresh, half- open flower in the green of the garden. Folding shade consist of two foldable coverings constructed with aluminum slats (Figure 3.13).

Figure 3.13. Deployable roof of Emergency Center
(Source: Miestai, 2012).

Rapidly Deployable Shelter (RDS) by Hoberman Associates (Figure 3.14) provides “quick-up” structures for modular expansion that are durable, efficient, and easy to assemble and disassemble. With easier deployment and minimal time-consuming secondary connections, the RDS system uses fewer, larger, and more robust parts than competitive products. The unique patented system is durable, affordable tents that withstand high winds, resist snow loads up to 10 pounds per square foot, and can be set up in minutes. Figure 3.15 shows linkage bar mechanism of the rapidly deployable shelter. The mechanism consists of four parallelogram bar linkages. The planar mechanism demonstrated in Figure 3.16 is used as a module and several such planar modules are combined with parallelogram loops in order to obtain spatial assemblies as in Figure 3.14.

Figure 3.14. Rapidly Deployable Shelter
(Source: Hoberman, 2006).

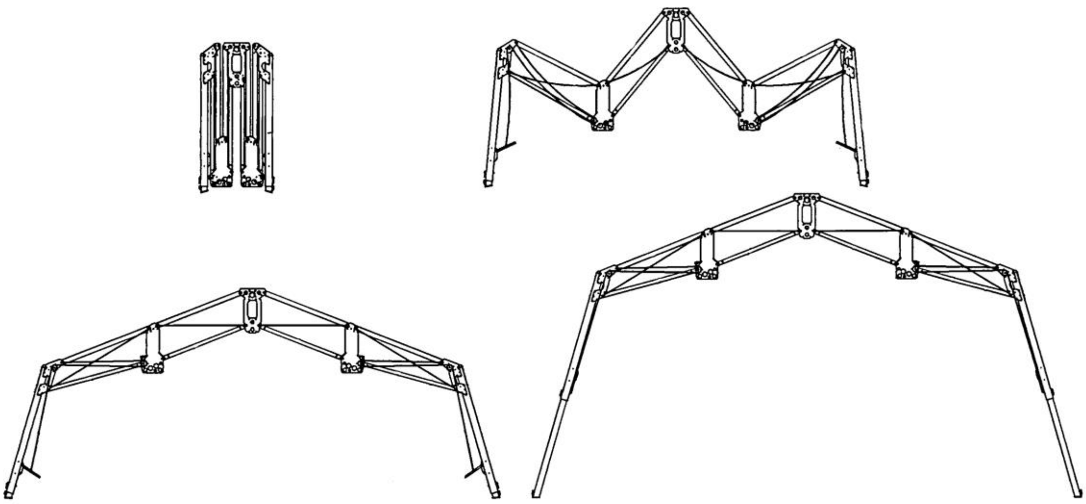


Figure 3.15. The Schema of Rapidly Deployable System
(Source: Hoberman, 2006).

Another significant researcher is Yan Chen. She developed many cylindrical deployable structure composed of modified Bennett linkages. First of all Chen identifies a basic element from Bennett linkage with skew square cross-section bars to obtain compact folding and maximum expansion (Figure 3.16). In her dissertation Chen shows that the construction of a Bennett linkage with compact folding and maximum expansion is not only mathematically feasible, but also practically possible. By using mathematical tiling technique, Chen has constructed the deployable structures (Figure 3.17).

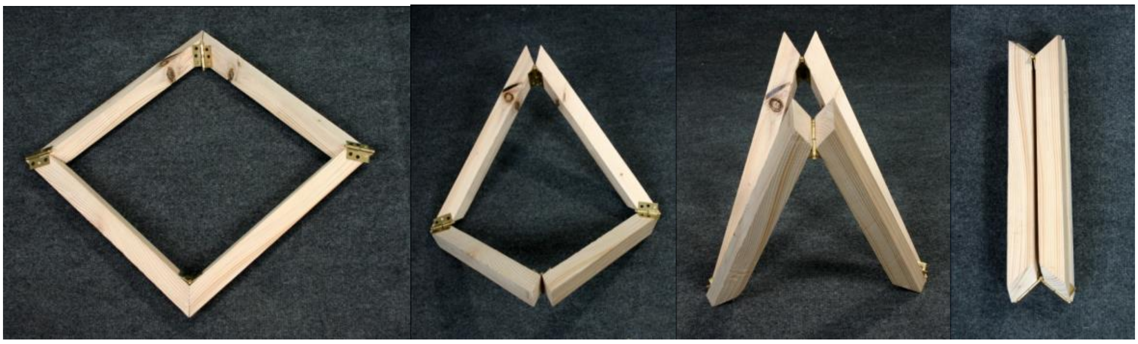


Figure 3.16. Yan Chen's modified Bennett mechanism

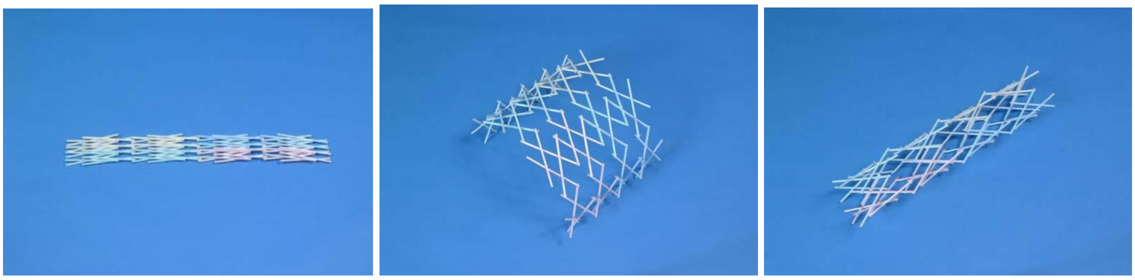


Figure 3.17. Deployment sequence of a deployable arch
(Source: Chen, 2003).

3.1.3. Plate Structures

Plate structures have surfaces and base on origami which is the ancient art of paper folding. Traditional origami usually involves only straight folds on a (square) planar piece of paper; tearing, cutting or gluing are not allowed. Once folded, the origami constitutes a developable surface that can be unfolded as a flat plane (it is isometric to a planar surface). Differences from bar structures, they do not need to any cover coat because their rigid elements called plates comprise surfaces. Transformable polyhedral surfaces with rigid facets, i.e., rigid origami, are useful for designing kinetic and deployable structures. Several designs of rigid-origami structures have been proposed from around 1970's. Foster and Krishnakumar (1986) presented a family of foldable, portable structures which are based on the Yoshimura buckle pattern for axially compressed cylindrical shells (Gantes, 2001). Foldable plate structures consist of a series of triangular plates, connected at their edges by continuous joints, allowing each plate to rotate relative to its neighboring plate. A plate linkage with appealing characteristics is the one with an apex angle of 120°. From Figure 3.19 it can be seen that the width of the collapsed configuration is identical to the plate length (Temmerman, 2007).

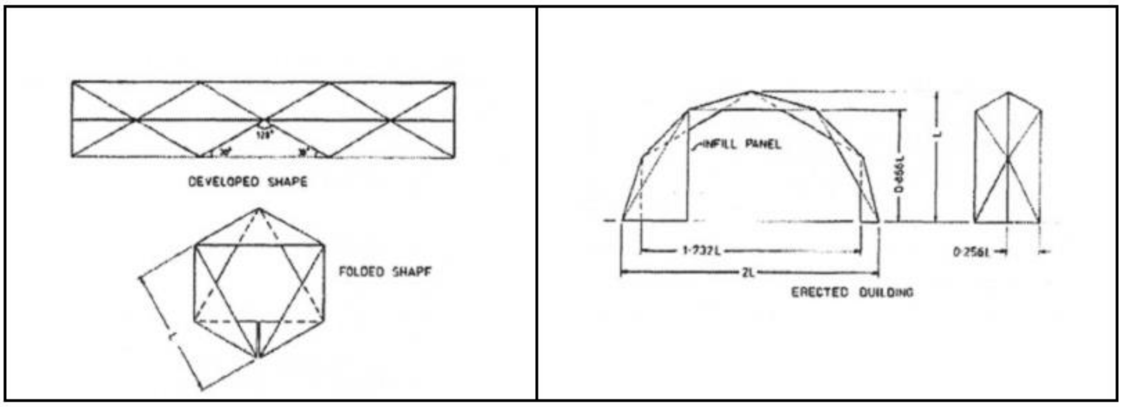


Figure 3.18. Building with apex angle of 120° by Foster
(Source: Temmerman, 2007).

Using the 120°-structure can also be circularly deployed, by holding the bottom elements together and only deploying the middle section. As the structure deploys, it undergoes a linear expansion in the longitudinal direction and a variation of the curvature in the transverse direction. The example in Figure 3.20 could be used for a temporary stage shell. Due to the fact that these structures are basically a mechanism, a number of constraints have to be considered to make them statically determinate.

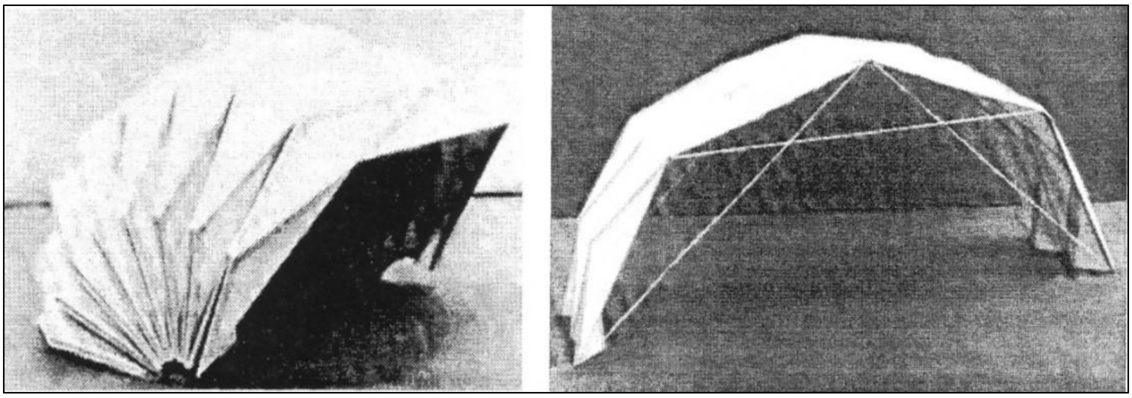


Figure 3.19. Temporary stage shell with 120° modules by Foster.

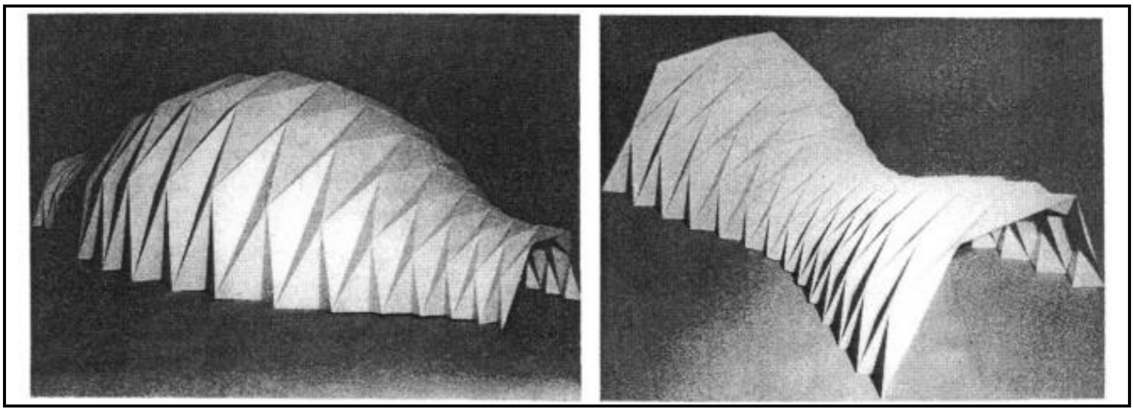


Figure 3.20. Doubly curved folded shapes.

Further expanding this concept, the geometry of single and double curvature foldable plate structures, such as domes, conics, and hyperboloids have been studied by Tonon in 1993 (Figure 3.20). Another interesting idea, although not of immediate use for an architectural application, is brought forward by Guest and Pellegrino in 1994, treating the folding of triangulated cylinders, later expanded by Barker and Guest in 1998 (Figure 3.21). On the other hand, using a plane foldable geometry, Hernandez and Stephens have proposed a folding aluminum sheet roof for covering the terrace of a pool area. The fold pattern consists of trapezoidal plate elements which give rise to a plane corrugated surface in 2000 (Figure 3.22) (Temmerman, 2007). Another researcher called Tachi worked on origami structures and he mentions that actual designs of architectural space with origami have been unachieved because there is lack of design ability in the existing methods in 2010. Therefore, he works on alternative methods on origami structures and computational design of origami.

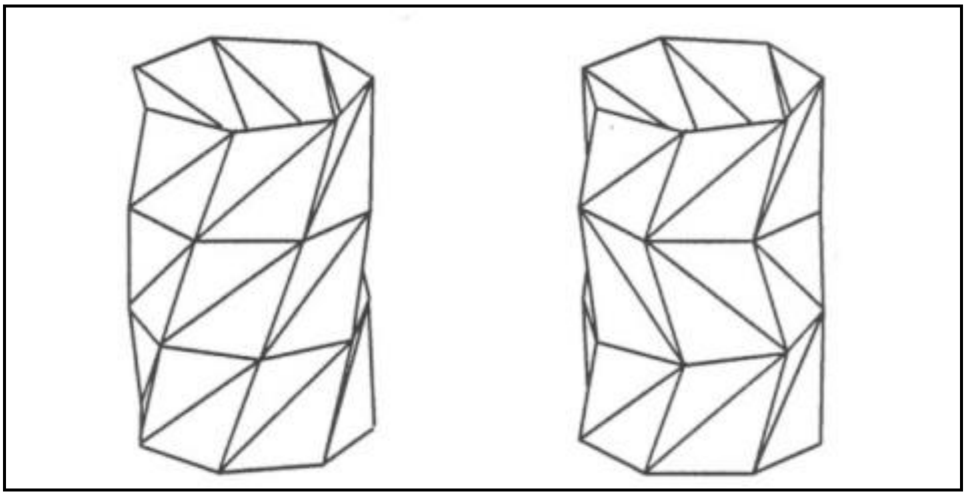


Figure 3.21. Left one is fold pattern; Right one is fold pattern with alternate rings to prevent relative rotation during deployment (Source: Tachi, 2010).

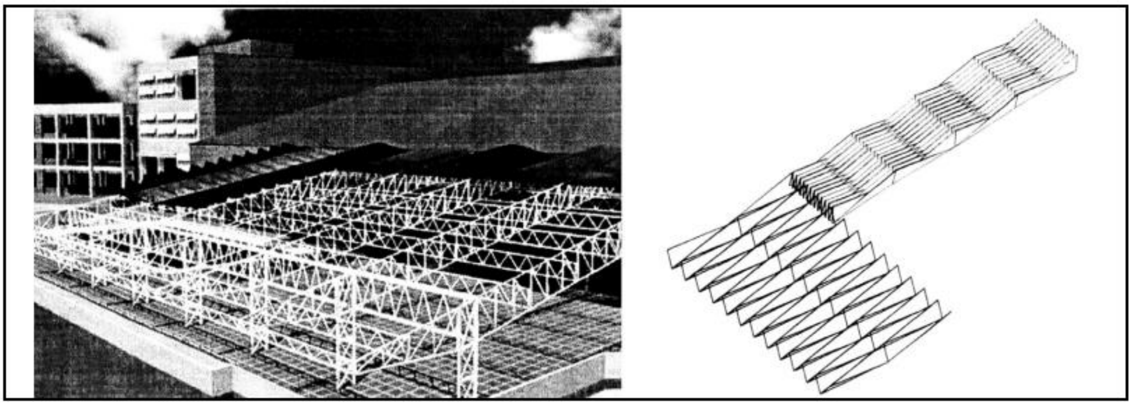


Figure 3.22. Folding aluminum sheet roof for covering the terrace of the pool area of the International Center of Education and Development in Caracas, Venezuela.

Escrig and Sanchez studied a dome using origami in 2011. The module square plan can be extended to polygons with more sides thus increasing the size of the set and setting other aesthetics. The advantage of this type of solution is to fold very compact intermediate without leaving gaps, so they are ideal for the purpose of transportation and packaging (Figure 3.23). After few years, Miwa Takabayashi has developed this study and designed a pavilion in Seville (Figure 3.24).

.

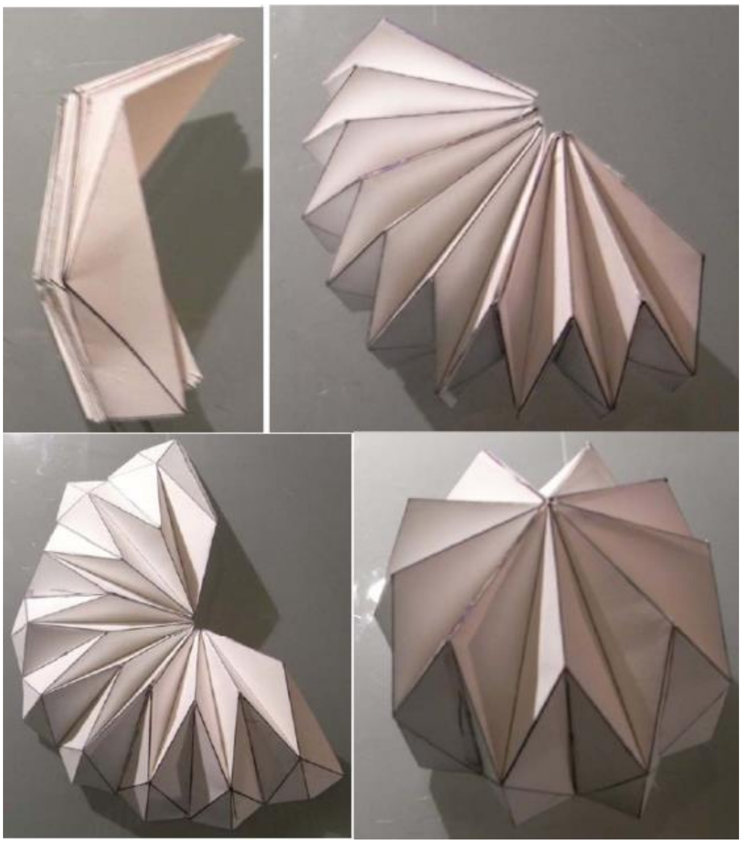


Figure 3.23. Escrig & Sanchez's dome by using origami.

Figure 3.24. Miwa Takabayashi's Pavilion
(Source: Miwaart, 2013).

Rentaro Nishimura designed another pavilion in Cambridge with origami. It is a kind of squinch. Figure 3.25 illustrates this pavilion.

Figure 3.25. Rentaro Nishimura's Pavilion
(Source: Madesignsuite, 2009).

3.1.4. Strut Cable Structures

Strut cable structures possess, a self-equilibrated system providing stability and stiffness to the structure which is a most important advantage in construction over conventional deployable structures. The concept of cable-strut is extended from that of tensegrity. Tensegrity systems are a stable three-dimensional space frame assembly of cables and struts where the cables are continuous but the struts are discontinuous and do not touch one another. The word tensegrity comes from the contraction of tensile and integrity (Motro, 2003). These experimental systems are a fascinating concept developed by sculptor Kennet Snelson, and later patented and explored by Buckminster Fuller in 1962. Snelson and Fuller's goal is creating maximal efficiency structures (Fuller, 1975). Moreover, tensegrity structures are stable 3-dimensional mechanical structures which maintain their form due to an intricate balance of forces between disjoint rigid elements and continuous tensile elements.

The simplest tensegrity unit is the tensegrity tripod designed by Fuller in 1962 (left side of Figure 3.26). And also Fuller designed tensegrity dome using this module in

Figure 3.27. Other tensegrity networks can be derived from geodesic polyhedral which are designed by Hugh in 1976 (middle and right side of Figure 3.26). As it is seen, tensegrity structures have no redundant parts. Tensegrity modules can be joined to create structural elements as beams and columns. Strut cable structures are used in various kinds of deployable architectural applications like shelter systems, domes, roof structures and towers. They can be used plenty of applications besides architecture such as installations, sculptures, toys, furniture and etc.

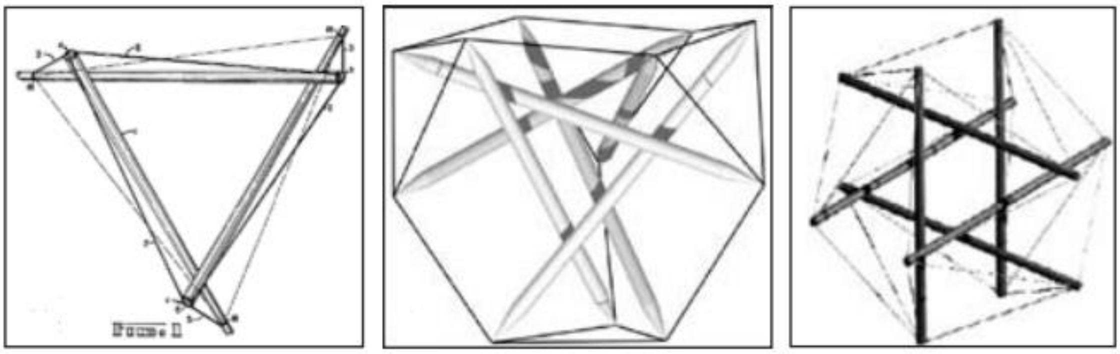


Figure 3.26. Different tensegrity systems
(Source: Fuller, 1975).

Figure 3.27. Fuller's Tensegrity Dome
(Source: Fuller, 1975).

The first to have illustrated the possibilities of generating double-layer tensegrity grids is David George Emmerich in 1965 (Robbin, 1996). Emmerich's works inspired researchers about tensegrity systems. For instance, René Motro has studied tensegrity structures and folding tensegrity systems in 1970s. Hanaor, an Israeli engineer has studied double-layer tensegrity grids and the deployable examples in his research (Robbin, 1996). Deployment or folding is very promising application field for tensegrity systems. Tensegrity systems can be folded and unfolded by modification of element lengths. Length changes can be applied to both struts and cables. Over the last decades, the tensegrity concept has received significant interest among scientists and engineers throughout disciplines such as architecture, civil engineering, biology, robotics and aerospace (Tibert, 2002). Designed by Schlaich, Bergermann and Partners, the Rostock tower (Germany) built in 2003 is probably the highest tensegrity tower (62.3 m). The tower is composed of a continuous assembly of six ``simplex" modules (Figure 3.28).

Figure 3.28. Rostock Tower in Germany
(Source: Tensegrity, 2013).

Tibert and Pellegrino compared the stiffness of a deployable tensegrity mast with a conventional mast in 2003. They identified lack of stiffness during deployment and weak deployed bending stiffness as obstacles to practical applications.

Tristan d'estree Sterk who is the founding partner of a group called The Office for Robotic Architectural Media & The Bureau for Responsive Architecture (Orambra) in Northfield, Illinois had used tensegrity structures successfully as architectural element in The Prairie House in 2010. Figure 3.29 shows

Sterk's study in The Prairie House. These systems are parametric structures and surfaces that are actuated with thermal memories.

Figure 3.29. Sterk's The Prairie House
(Source: Orambra, 2012).

Orambra works on designing structures that can change its shape and volume in order to prevent energy lost within the structure. These systems are parametric structures and surfaces that are actuated with thermal memories. In this design, they use tensegrity prototypes in the projects like Prairie House (Figure 3.30).

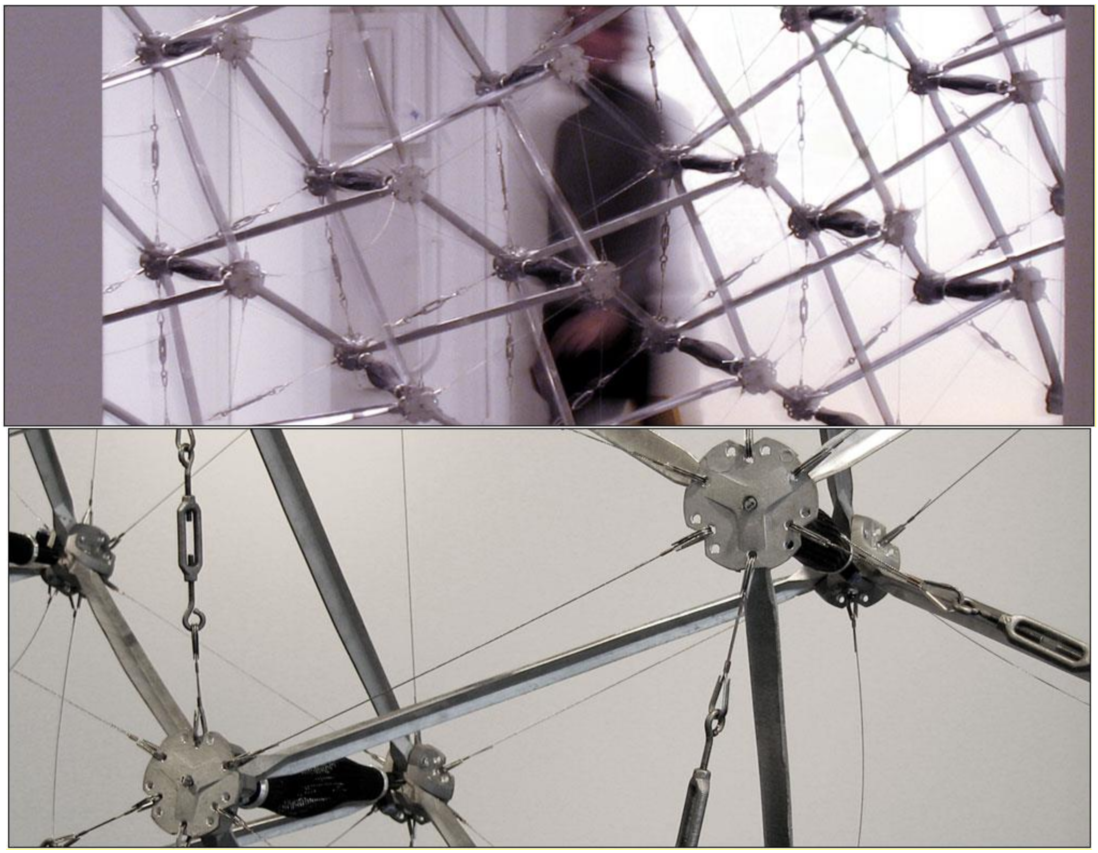


Figure 3.30. Parametric structures and surfaces
(Source: Orambra, 2012).

3.1.5. Tensioned Membrane Structures

Tensioned membranes are divided 2 varieties which are fabric and pneumatic systems. Though tensioned membrane structures have rigid components, they are more flexible than rigid systems.

Cable membrane convertible roof is designed into the historical castle for the open-air theatre by Bodo Rasch. He is a German architect and an engineer and had worked with Frei Otto in Wiltz in Luxemburg in 1988 (Figure 3.31). The support structure of the roof runs around the spectators and stage areas. The structure consists of tubular steel supports, guy ropes and a ring rope. Folded membrane is parked in the area behind the spectators so it does not interfere with their views. In bad weathers the roof is moved into place with the help of mechanism and automatically got its final position. The whole roof structure which covers an area of 1200 square meters. It can be removed at the end of the theatre season and then rebuilt without difficulty.

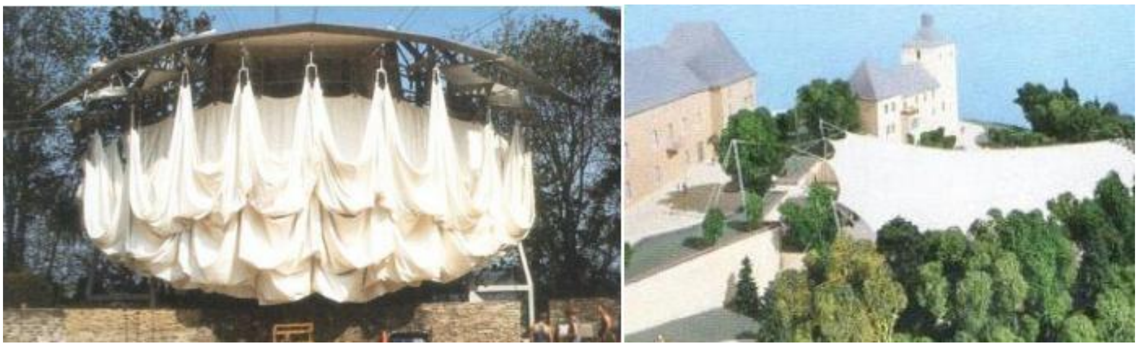


Figure 3.31. Cable membrane roof for the open-air theatre in Wiltz,Luxemburg (Source: Otto & Rasch, 1995).

The Olympic Stadium in Montreal, Canada designed by The French architect Roger Tailibert was to open for the 1976 Olympic Game, but the retractable roof was finished only in 1988 (Figure 3.32). The structure was replaced with a non-retractable spatial steel roof structure. The central playground and the race tracking field are covered by 20 000 m² PVC/Kevlar folding membrane roof which is opened and closed by 28 stray cables connected to 175 m inclined tower. This complex has become one of the Montréal's landmarks.

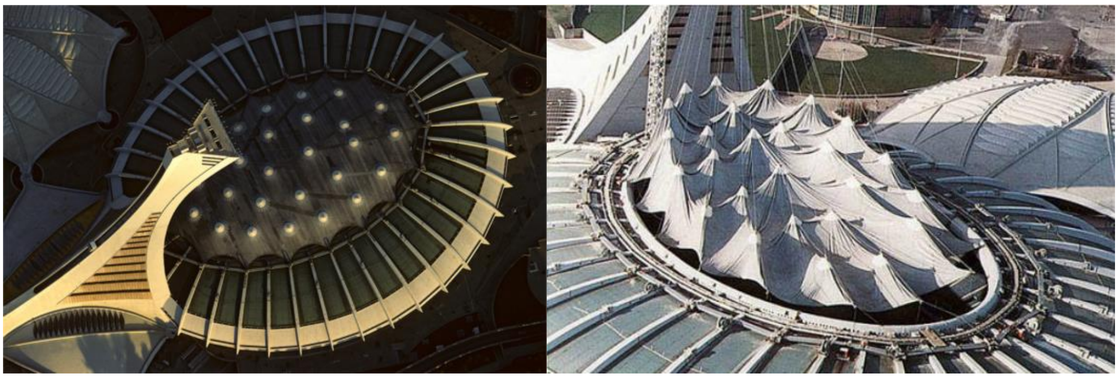


Figure 3.32. Olympic Stadium in Montreal
(Source: Taillibert, 2013).

At the same time, a similar, but more successful design was evolved in 1988, Zaragoza, Spain for the roofing of the bullfighting Arena. It is designed by the German firm Scleich, Bergman and Partners. The roof is separated to an 83 m diameter fixed and a 23 m diameter central convertible membrane roof. The area of the fixed roof is 4.400 m² and the area of movable part is 1.000 m². When the roof is open, it hangs bunched up in the center, when is to be closed, 16 electric motors draw the bottom edge of the membrane out to the lower tension rim.

Cadillac Mobile Theatre is very efficient sample for fabric systems although it is not foldable (Figure 3.33). The theatre would have to enclose space completely, protect the occupants from rain and wind and excess heat and also have a black-out facility to allow complete control of the internal visual environment during the day and night. The Cadillac building was also required to be much more flexible in its final form, capable of use for a wide range of events from pop concerts to trade shows. The theatre requires just two trucks for transportation, one to carry the roof structure – triangular roof beams which fold in half for transportation – and one to carry the membrane roof and walls, foundation plates and air conditioning plant. The 1000 square meter membrane is assembled from only three fabric panels when stressed form a complex saddle shape called a 'hypar'. The use of just three main panels reduces site assembly time and the risk of rainwater leaks at the joints. These are formed using a double lace line that uses polyester rope with twin rain flaps to protect the joint from water ingress. The membrane is hoisted from the center by a cable that passes inside one of the trusses.

Figure 3.33. Cadillac Mobile Theatre
(Source: Kronenburg, 2003).

The supporting medium of pneumatic structures is compressed air or gas that creates tension forces on the elastic membrane, thus ensures the strength and the stability of the structure (Friedman & Farkas, 2011). The balloon is the most well-known classical pneumatic structure. In construction the first pneumatic structures appeared in the 1950’s. Pneumatic structures are divided into two types are air supported and inflated structures.

Mush-balloon designed by Tanero Oki Architects for EXPO ‟70 in Osaka, Japan; is an example for kinetic air supported pneumatic structures (Figure 3.34). It is an inverted shaped balloon, suspended by 45 wire ropes that pass from the top of a pole through the center of the balloon. The balloon is made of an upper and lower fabric. These fabrics are braced by inner ropes.

Figure 3.34. Mush-balloon for EXPO’70 in Osaka
(Source: Tensinet, 2013).

Giving an example in these days pneumatic system is Ark Nova is the best of recent times. From the outside it resembles a giant, plushy purple jelly bean, while from the inside it looks more like a glowing, colored seashell. Actually, this balloon-like form is the world's first inflatable concert hall, entitled "Ark Nova." It made from an elastic shell that can be quickly inflated and dismantled (Figure 3.35).

Figure 3.35. Ark Nova
(Source: Huffingtonpost, 2013).

3.2. Reconfigurable Deployable Structures

In this thesis, structures with multi-form are called reconfigurable deployable structures. These structures are commonly built with multi-degree of freedom mechanisms whereby they can offer wide range of form flexibility compared to deployable structures.

First example is the flexible street lamps in Schouwburgplein, Rotterdam. They are designed by Adriaan Geuze for an interactive public space. Every multi-form lamp is a sort of bar structure as shown figure 3.36. These lamps transform from one configuration to another during day and seasons in the public square to obtain an interactive public space. The lamps have two hydraulic pistons to achieve various geometries. Although this sample is reconfigurable, they are not deployable because they cannot be fully compact.

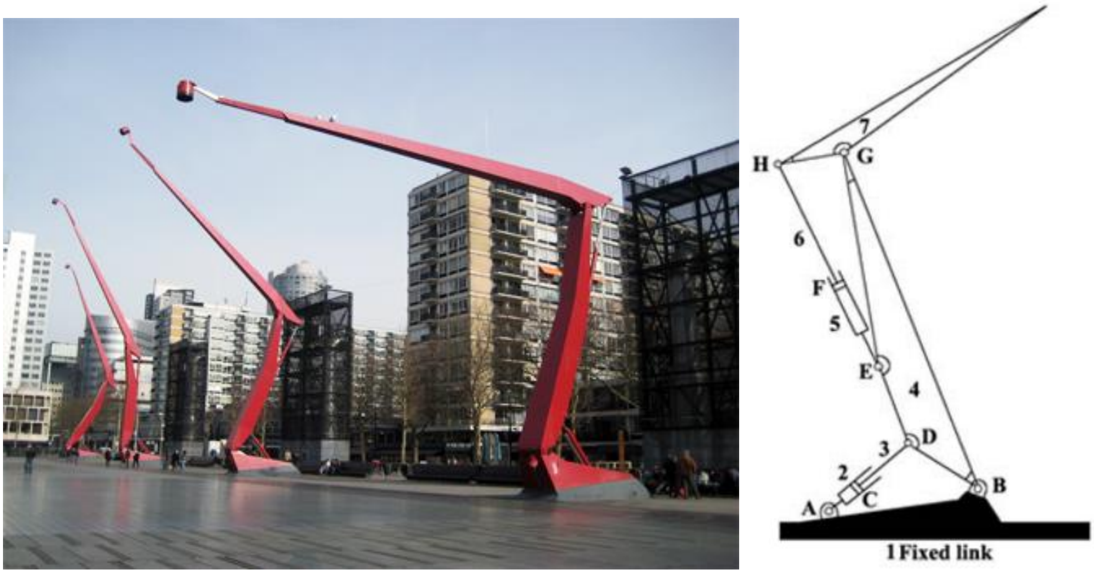


Figure 3.36. Street lamps at Schouwburgplein
(Source: West-8, 2014).

Another example is Rolling Bridge from Grand Union Canal in London. This bridge was designed by Anthony Hunt with Packman Lucas before had been conceived by British designer Thomas Heatherwick (Figure 3.37). The bridge consists of seven pairs of bar mechanism actuated with seven pairs of hydraulic pistons (Figure 3.38). When extended, it resembles a conventional steel and timber 12 meters long footbridge. To allow the passage of boats, the bridge curls up until its two ends join, to form an octagonal shape (Heatherwick-Studio 2009). In fact The Rolling Bridge can take various forms. Since the pistons work at the same time, the bridge is deployable.

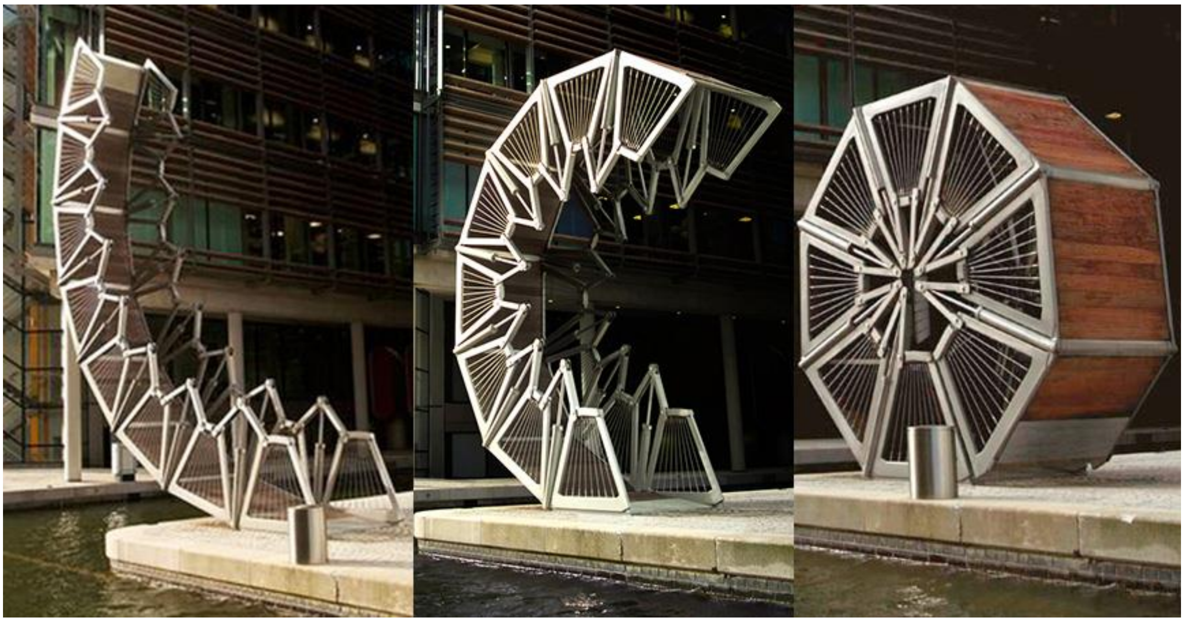


Figure 3.37. Opening steps of Rolling Bridge
(Source: Heatherwick-Studio, 2014).

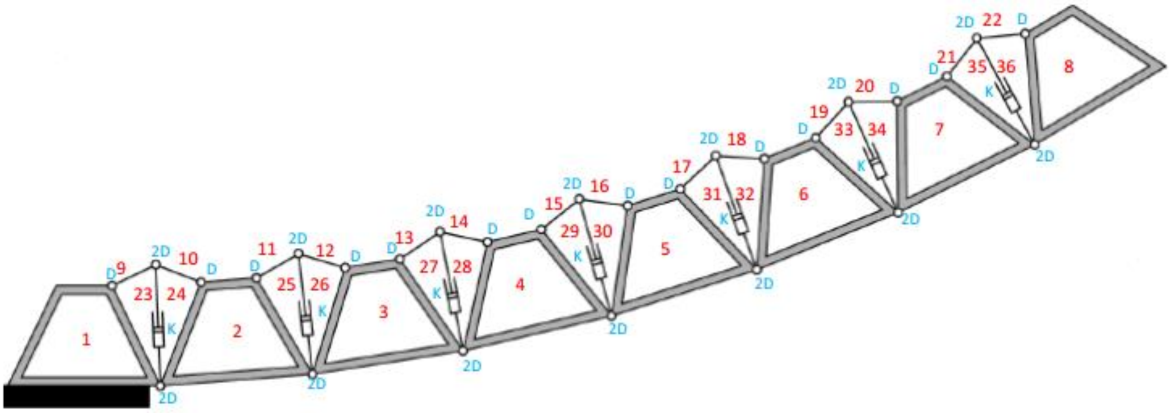


Figure 3.38. Kinematic diagram of Rolling Bridge.

Kokawa's (1995) expandable cable scissors arch (CSA) is another example for reconfigurable structures (Figure 3.39). CSA is different from the typical scissor-hinge structures because this structure is more innovative and can change its geometry without changing the span length. The structure consists of two arch scissors connected with hinges and extra zigzag cables with pulleys. The form of the structure is changed during winding up or winding back by a winch.

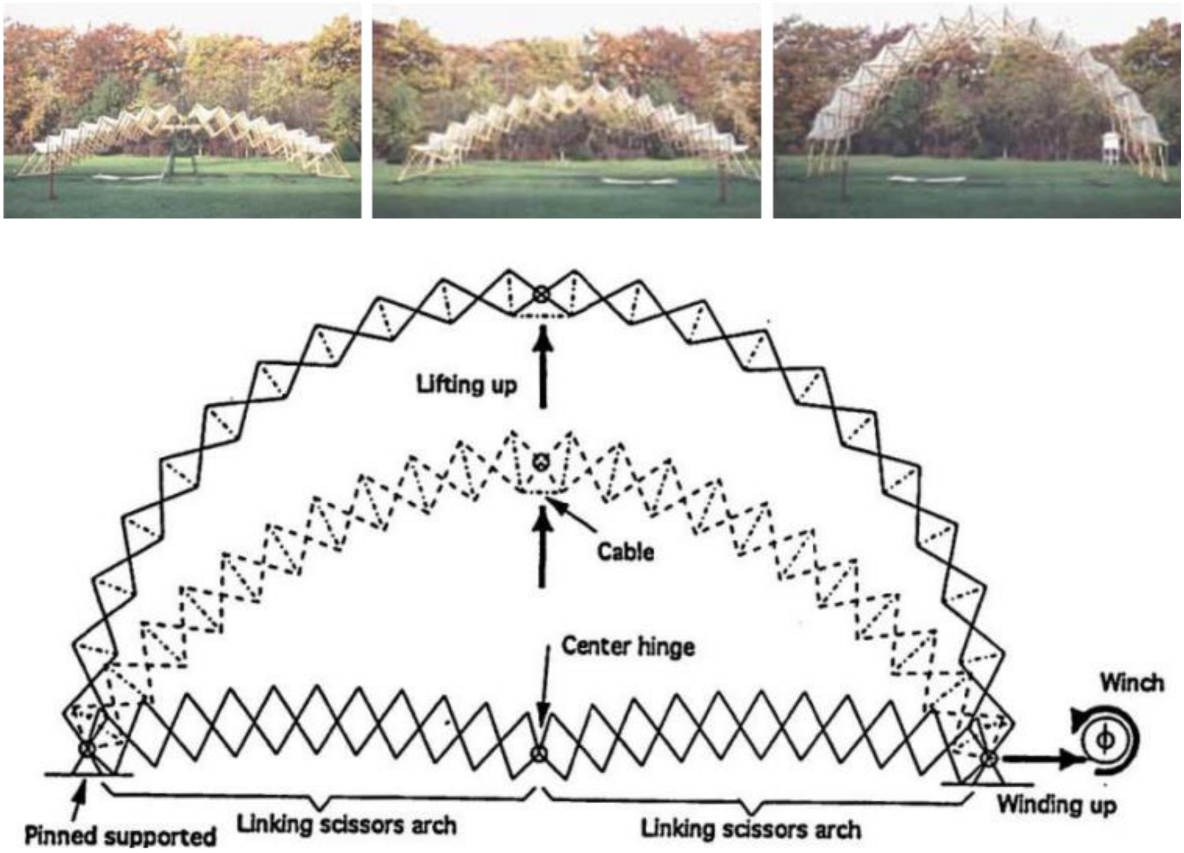


Figure 3.39. Kokawa's expandable scissors
(Source: Kokawa, 1995).

Yenal Akgün has studied with scissor-hinge mechanism and has achieved an endeavor approach which expands the adaptability and form flexibility in the fields of deployable structures. Although, scissor-hinge structures have been only used as the portative building components until now, he proposed a multi DOF structure that can be used as permanent adaptive building structures. His research is on planar and spatial versions of modified scissor-hinge structures (Figure 3.40). Planar version presents various curvilinear geometries. The spatial version of the structure can constitute remarkable form flexibility from curvilinear to double-curved shapes.

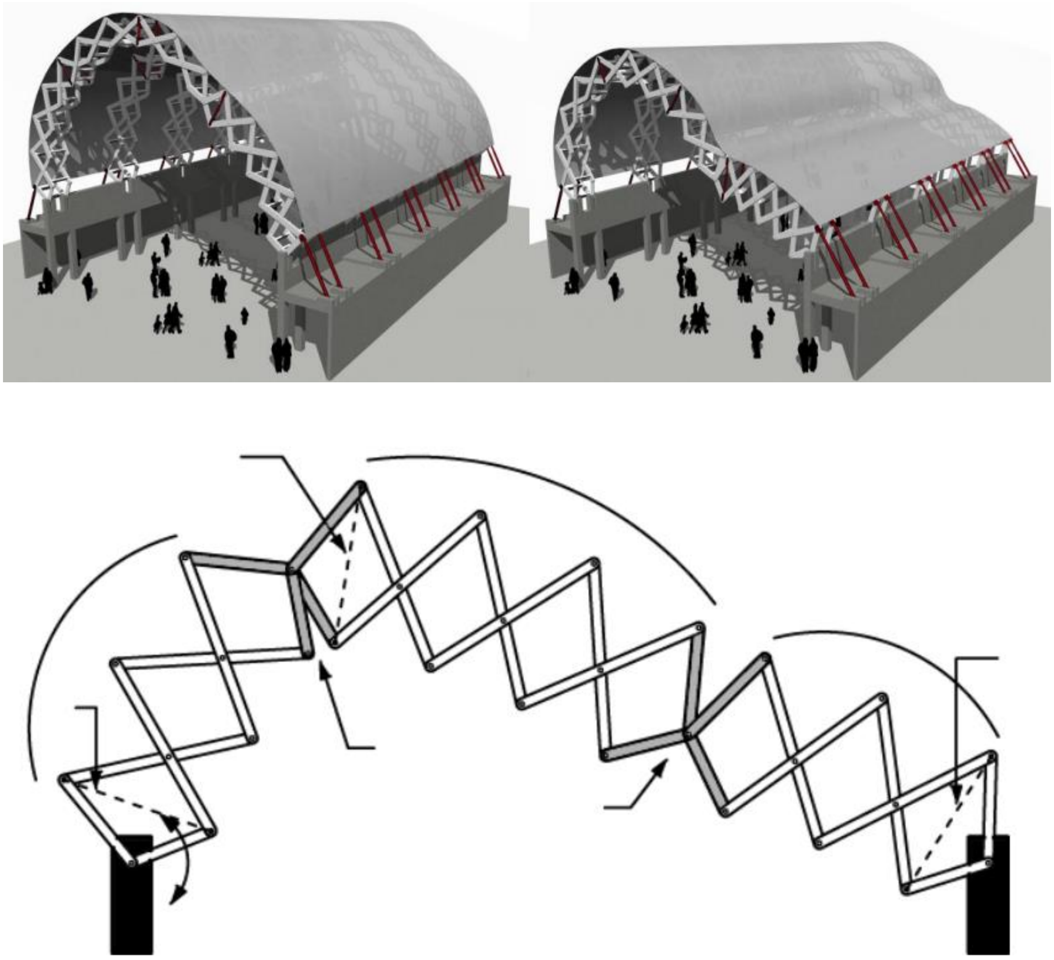


Figure 3.40. Planar version of Akgün’s studies
(Source: Akgün, 2010).

CHAPTER 4

A RECONFIGURABLE DEPLOYABLE MECHANISM DESIGN[1]

The term "reconfigurable" is used for several different meanings in the literature. Reconfigurable deployable structures can be transformed from a closed compact configuration to multiple alternative expanded forms. Some authors use reconfigurable structure to describe movable systems which can attain different stable forms, like a chair which can transform into a ladder (Weaver et al., 2008). Reconfiguration is assembly mode change for a mechanism. The word reconfiguration comes from configuration. The word configuration is also used for different concepts in various studies. Mason (2001) defines a configuration of a system as the location of every point in the system, so that one can define the configuration space as a metric space comprising all configurations of a given system. On the other hand, Kuo et al. (2009) use the configuration definition of Merriam-Webster Dictionary as "relative arrangement of parts or elements". In this thesis configuration is used interchangeably with assembly mode.

Reconfigurable deployable structures may take various forms with multi DoF mechanisms. However some reconfiguration can be achieved with single DoF mechanisms passing from one assembly mode to another.

The RDM design introduced in this chapter consists of several reconfigurable planar linkage modules which are assembled parallel to each other to obtain spatial assemblies.

Most parts of this chapter were published in:
[1] F. Gürcü, K. Korkmaz, G. Kiper, New Proposals for Transformable Architecture, Engineering and Design "Design of a Reconfigurable Deployable Structure" p. 145-149 Transformables 2013- Seville, Spain.
G.Kiper, F. Gürcü, K. Korkmaz, E. Söylemez, New Trends in Mechanism and Machine Science: From Fundamentals to Industrial Applications, Springer, "Kinematic Design of a Reconfigurable Canopy" p. 167-174, EUCOMES 2014- Guimaraes, Portugal.

4.1. Planar Linkage Module

The alternative forms that a linkage can be constructed with the same links and connections are called configurations or assembly modes of the linkage. During its motion, the linkage may pass from one assembly mode to another, which is called reconfiguration or assembly mode change.

This study makes use of reconfigurable loops in planar linkage modules of a canopy design. Figure 4.1 shows a four bar mechanism in two different configurations. The four bar mechanism may change the configuration through the dead-center position. Figure 4.2 illustrates assembly mode change and dead center of a parallelogram mechanism.

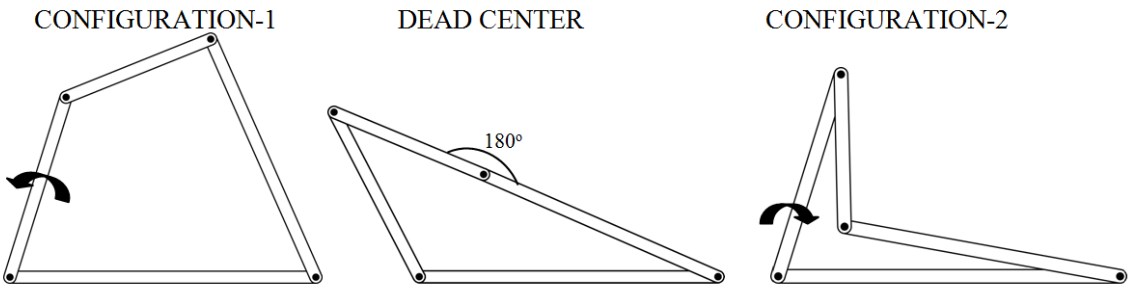


Figure 4.1. Assembly mode change through the dead center.

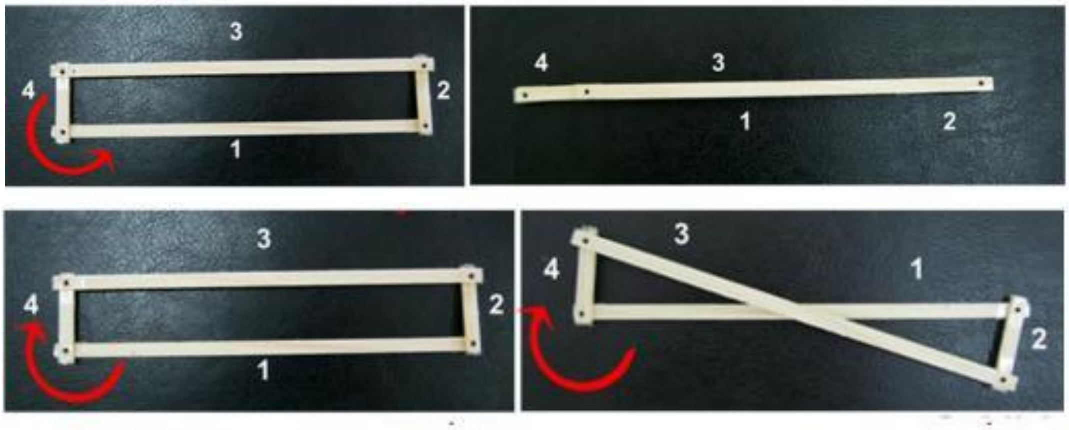


Figure 4.2. Assembly mode change and dead center for parallelogram mechanism.

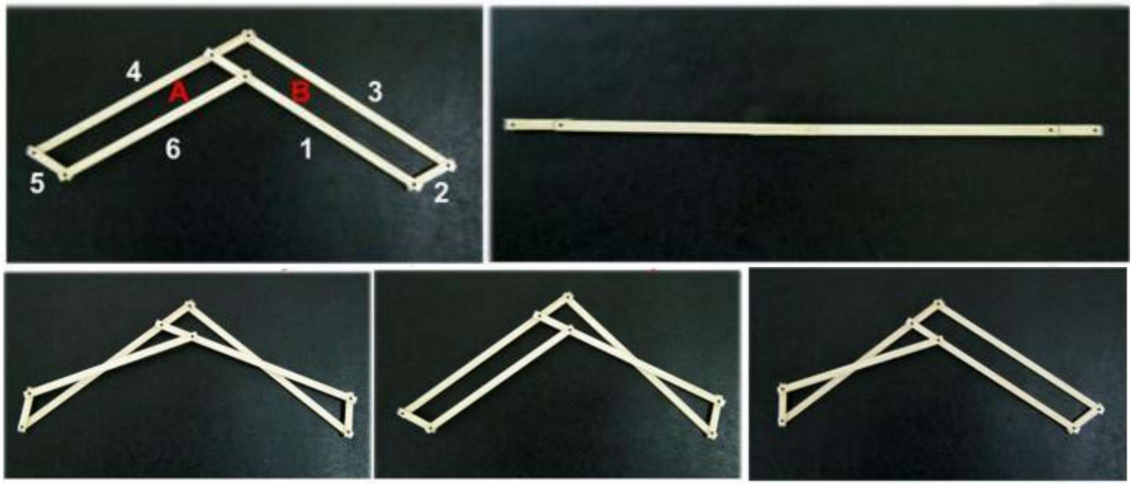


Figure 4.3. Connecting two parallelogram linkages.

The proposed reconfigurable mechanism comprises two four-bar loops. It has single degree-of-freedom with 2 ternary, 4 binary links and 7 joints. A special case, where the four-bar loops are parallelograms is illustrated in Figure 4.3. Utilizing this mechanism, a reconfigurable structure is designed. It has 4 alternative configurations. Thanks to this feature, the reconfigurable canopy concept is multi-functional to create closed and semi open spaces (Figures 4.4-4.5). Moreover, it is deployable, i.e. it can be folded into a compact form and moved to some other place.

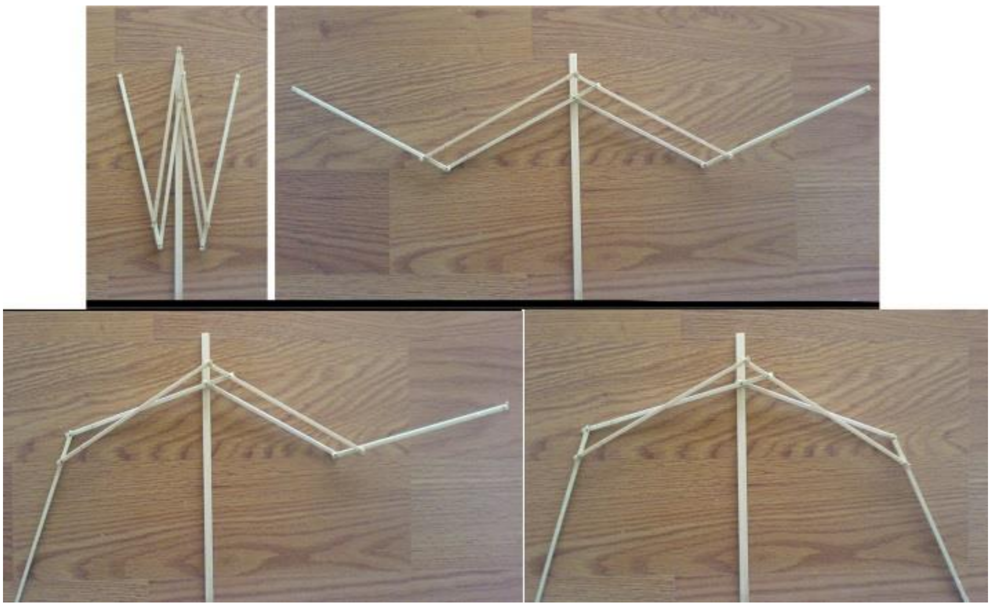


Figure 4.4. Planar linkage unit in compact, open and closed form.

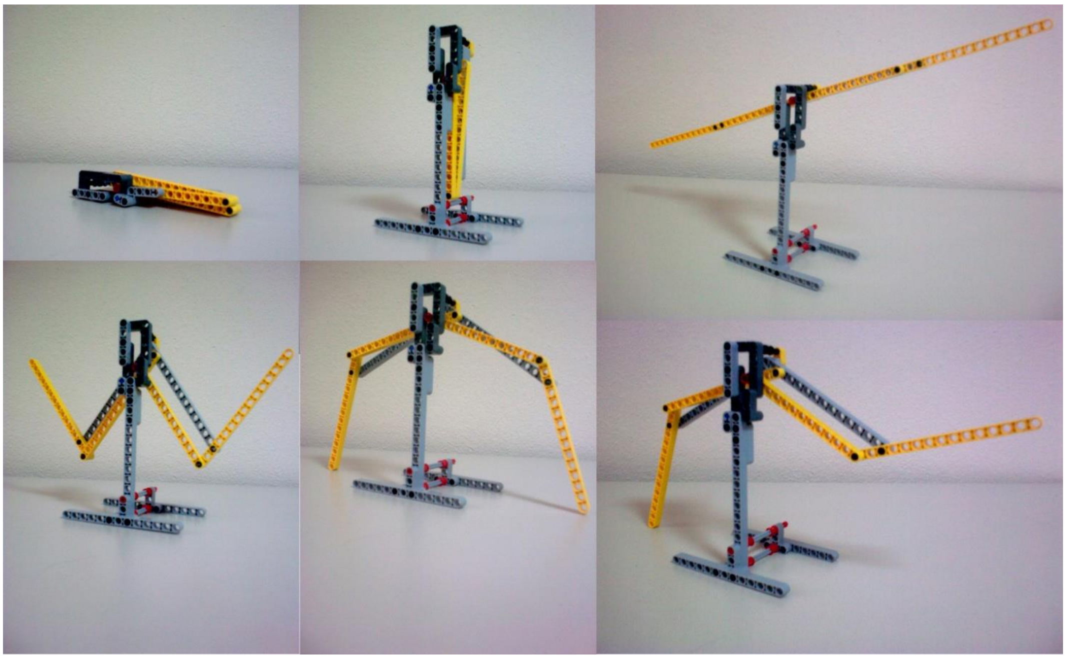


Figure 4.5. Planar linkage unit constructed with Lego Technic®.

4.2. Position Analysis

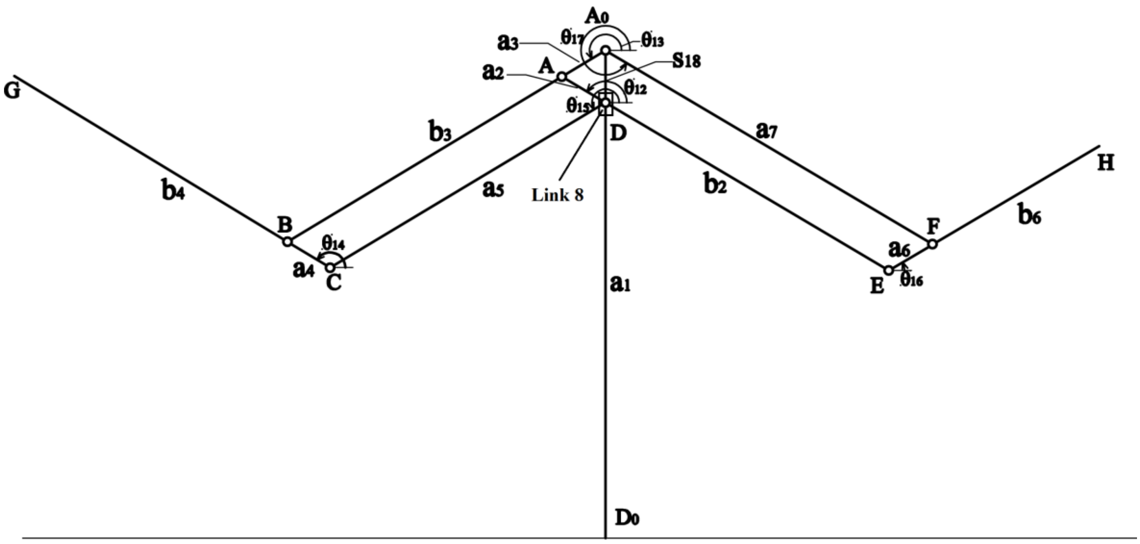


Figure 4.6. Kinematic diagram of the planar mechanism.

In order to understand the kinematic analysis of the reconfigurable mechanism, first mobility of the system should be found. Kinematic diagram of the mechanism is shown in Figure 4.6. In this study, Grübler's equation for planar linkages is used (Söylemez, 2009). According to this formula,

$$M = 3(\ell - 1) - 2j = 3(8 - 1) - 2 \cdot 10 = 1 \tag{4.1}$$

where M = DoF or mobility, ℓ = number of links and j = number of joints. This mechanism consists of the following design parameters (constant link lengths):

$|A_0D_0| = a_1$, $|AD| = a_2$, $|DE| = b_2$, $|AA_0| = a_3$, $|AB| = b_3$, $|BC| = a_4$, $|BG| = b_4$,

$|DC| = a_5$, $|EF| = a_6$, $|FH| = b_6$, $|A_0F| = a_7$

Variable joint parameters are θ_{12}, θ_{13}, $|A_0D| = s_{18}$, θ_{14}, θ_{15}, θ_{16}, θ_{17}.

A parametric model of this mechanism is constructed in Microsoft Excel® environment. See (Söylemez, 2008) for use of Excel® in mechanism applications. For the position analysis, the user defined functions for solutions of planar mechanisms developed by Söylemez (2009) are used. The function library for these functions is available online (Söylemez, 2014). For the analysis of a slider-crank mechanism (Figure 4.7), two functions are used. The SliderCrank function gives the slider displacement s for given link lengths, configuration information and input angle θ_i. The SliderCrankCoupler function gives the angle of coupler link θ_c for given link lengths, configuration information and input angle θ_i. The configuration parameter is +1 when the slider is on the right of the crank and –1 when the slider is on the left. The format of the functions are as follows:

s = SliderCrank(Crank, Coupler, Eccentricity, Config, θ_i)

θ_c = SliderCrankCoupler(Crank, Coupler, Eccentricity, Config, θ_i)

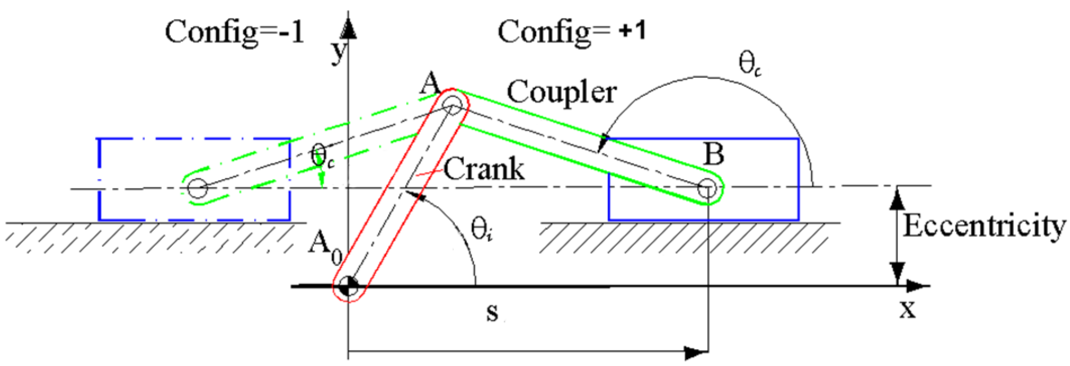


Figure 4.7. The slider-crank mechanism
(Source: Söylemez, 2009).

Similarly, for the analysis of a four bar mechanism, the FourBar and FourBarCoupler functions are employed. These functions respectively give the angle of the two passive moving links, which are the rocker angle θ_r and coupler angle θ_c, for given link lengths, configuration information and input angle θ_i. The configuration parameter is +1 for open configuration and –1 for cross configuration (Figure 4.8). The formats of the functions are as follows:

$$\theta_r = \text{FourBar}(\text{crank, coupler, rocker, fixed, config}, \theta_i - \alpha) + \alpha$$

$$\theta_c = \text{FourBarCoupler}(\text{crank, coupler, rocker, fixed, config}, \theta_i - \alpha) + \alpha$$

Here, α is the angle of the fixed link with respect to the positive x-axis of the fixed coordinate system.

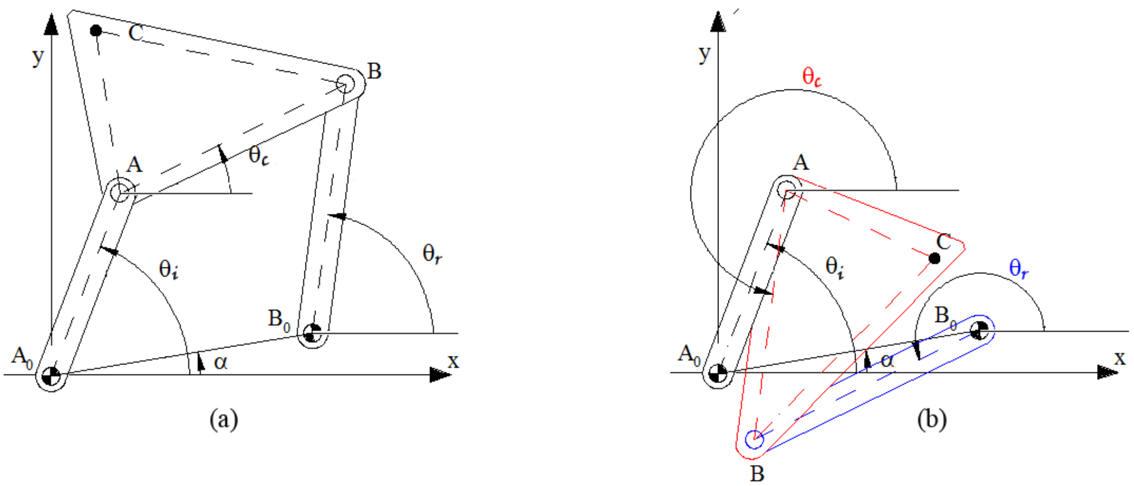


Figure 4.8. The four bar mechanism in (a) open and (b) cross configuration (Source: Söylemez, 2009).

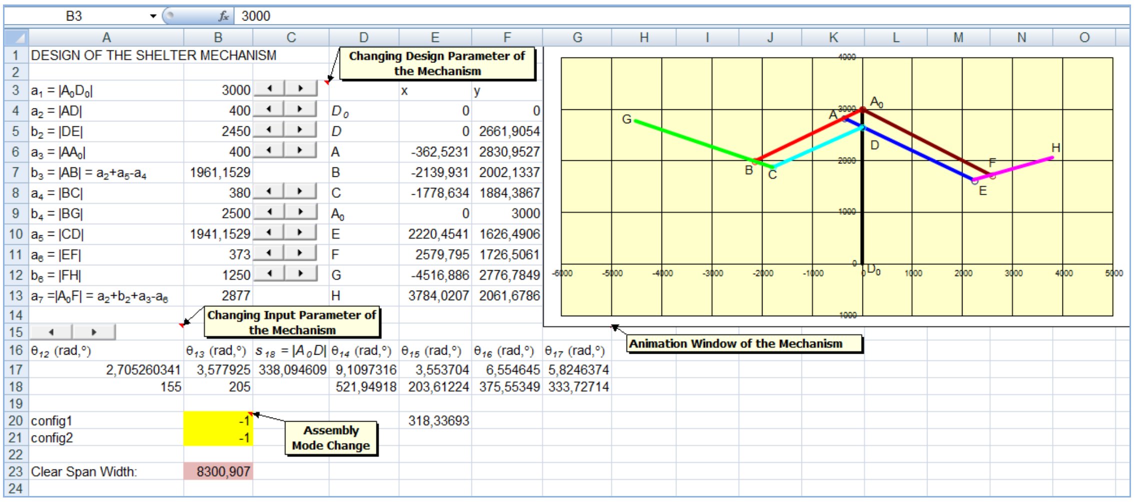


Figure 4.9. Design of the Reconfigurable Mechanism with Microsoft Excel®.

Figure 4.9 illustrates the computer model of the reconfigurable mechanism with Microsoft Excel®. First of all, link length parameters a_1, a_2, b_2, a_3, b_3, a_4, b_4, a_5, a_6, a_7 are specified. Determination of the link length values is discussed in the parametric design section. Variable joint parameters are θ_{12}, θ_{13}, s_{18}, θ_{14}, θ_{15}, θ_{16}, θ_{17}. The input angle θ_{12} can be varied using the associated spin button. Other joint parameters are calculated by using the functions of Söylemez (2009).

θ_{13} is found by using SliderCrankCoupler function:

$$\theta_{13} = \text{SliderCrankCoupler}(a_2;\ a_3;\ 0;\ 1;\ \theta_{12} - \text{pi}()/2) + \text{pi}()/2$$

$|A_0D| = s_{18}$ is found by using SliderCrank function:

$$s_{18} = \text{SliderCrank}(a_2;\ a_3;\ 0;\ 1;\ \theta_{12} - \text{pi}()/2)$$

θ_{14} and θ_{16} are found by using FourBarCoupler function:

$$\theta_{14} = \text{FourBarCoupler}(a_3;\ b_3;\ a_4;\ a_5;\ s_{18};\ \text{config1};\ \theta_{13} + \text{pi}()/2) + \text{pi}()/2$$

$$\theta_{16} = \text{FourBarCoupler}(b_2;\ a_6;\ a_7;\ s_{18};\ \text{config2};\ \theta_{12} + \text{pi}()/2) + \text{pi}()/2$$

θ_{15} and θ_{17} are found by using FourBar function;

$$\theta_{15} = \text{FourBar}(a_3;\ b_3;\ a_4;\ a_5;\ s_{18};\ \text{config1};\ \theta_{13} + \text{pi}()/2) - \text{pi}()/2$$

$$\theta_{17} = \text{FourBar}(b_2;\ a_6;\ a_7;\ s_{18};\ \text{config2};\ \theta_{12} + \text{pi}()/2) + \text{pi}()/2$$

config1 and config2 are the two configuration parameters for the ABCD and A_0AEF loops, respectively.

Table 4.1 lists the joint coordinate expressions. It is important to calculate the opening span and also plot the mechanism. As the input angle (θ_{12}) is varied by the help of its spin button, the motion of the mechanism is simulated.

Table 4.1. Parameters of joints X and Y coordinates.

	X	Y
D_0	0	0
D	0	a_1
A	$a_2 \cos(\theta_{12})$	$a_1 - s_{18} + a_2 \sin(\theta_{12})$
B	$(a_3 + b_3) \cos(\theta_{13})$	$a_1 + (a_3 + b_3) \sin(\theta_{13})$
C	$a_5 \cos(\theta_{15})$	$a_1 + a_5 \sin(\theta_{15})$
A_0	0	$a_1 - s_{18}$
E	$b_2 \cos(\theta_{12})$	$a_1 - s_{18} - b_2 \sin(\theta_{12})$
F	$a_7 \cos(\theta_{17})$	$a_1 + a_7 \sin(\theta_{17})$
G	$(a_3 + b_3) \cos(\theta_{13}) + b_4 \cos(\theta_{14})$	$a_1 + (a_3 + b_3) \sin(\theta_{13}) + b_4 \sin(\theta_{14})$
H	$a_7 \cos(\theta_{17}) + b_6 \cos(\theta_{16})$	$a_1 + a_7 \sin(\theta_{17}) + b_6 \sin(\theta_{16})$

Deployed width is another design parameter and it depends on the difference of x coordinates of points H and G when the y coordinates are equal to zero:

$$|HG|_X = \left[a_7 \cos(\theta_{17}) + b_6 \cos(\theta_{16})\right] - \left[(a_3 + b_3)\cos(\theta_{13}) + b_4 \cos(\theta_{14})\right] \quad (4.2)$$

4.3. Parametric Design

The crucial part of the overall design process of the reconfigurable deployable shelter is its geometric design. In order to have a fully compact configuration, the mechanism must obey a general deployability condition (Maden et al., 2011). The deployability condition is that all joints of the loops are collinear in the folded configuration. To satisfy this condition the four bar loops ABCD and A_0AEF do not have to be parallelograms. The deployability conditions for these two loops are as follows:

$$\text{For loop ABCD: } a_2 + a_5 = a_4 + b_3 \tag{4.3}$$

$$\text{For loop } A_0\text{AEF: } a_3 + (a_2 + b_2) = a_6 + a_7 \tag{4.4}$$

There are also some inequality constraints as design requirements. The main design requirement is reconfigurability. Reconfiguration is obtained through the dead center position when links DC and CB are collinear for loop ABCD and AE and EF are collinear for loop A_0AEF. In order to have this collinearity the following reconfigurability conditions should be satisfied:

$$\text{For loop ABCD: } a_4 + a_5 \leq b_3 + a_2 \tag{4.5}$$

$$\text{For loop } A_0\text{AEF: } a_2 + b_2 + a_6 \leq a_7 + a_3 \tag{4.6}$$

Combining the reconfigurability conditions (4.5) and (4.6) with the deployability conditions (4.3) and (4.4):

$$a_4 \leq a_2 \tag{4.7}$$

$$a_6 \leq a_3 \tag{4.8}$$

Reconfiguration of the two loops has to occur simultaneously, because if one of the loops reaches the dead center position before the other one, the other loop does not reach its dead center position. When the two loops simultaneously reach their dead center positions, the two loops are instantaneously positioned as in Figure 4.10.

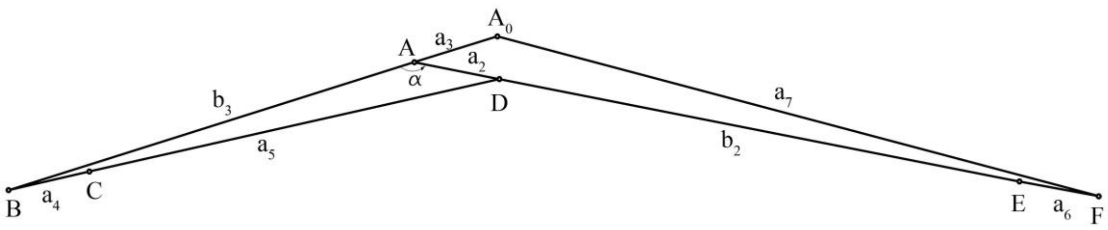


Figure 4.10. The four-bar loops in dead center position.

Writing cosine theorem for triangles ABD and A_0AF:

$$(a_4+a_5)^2 = a_2^2 + b_3^2 - 2a_2b_3\cos\alpha \Rightarrow \cos\alpha = \frac{a_2^2 + b_3^2 - (a_4+a_5)^2}{2a_2b_3} \quad (4.9)$$

$$a_7^2 = a_3^2 + (a_2+b_2+a_6)^2 - 2a_3(a_2+b_2+a_6)\cos(\pi-\alpha)$$
$$\Rightarrow \cos\alpha = \frac{a_7^2 - a_3^2 - (a_2+b_2+a_6)^2}{2a_3(a_2+b_2+a_6)} \quad (4.10)$$

Combining (4.9) and (4.10):

$$\frac{a_2^2 + b_3^2 - (a_4+a_5)^2}{a_2b_3} = \frac{a_7^2 - a_3^2 - (a_2+b_2+a_6)^2}{a_3(a_2+b_2+a_6)} \quad (4.11)$$

The formula (4.11) shall be called the simultaneous reconfiguration condition. The formula (4.11) imposes another restriction on the design parameters. In total there are two equality and three inequality constraints on the 11 design parameters. Due to the equality constraints, 8 of the 11 parameters can be selected freely. Below is a description of the design procedure:

The dimension a_1 is the height of the reconfigurable shelter and can be selected freely according to the design requirements.

There are five relationships among the link length a_2, b_2, a_3, b_3, a_4, a_5, a_6 and a_7 of the two four-bar loops: deployability conditions (4.3) and (4.4), reconfigurability conditions (4.5) and (4.6), and the simultaneous reconfiguration condition (4.11). Due to the three equality constraints, among the 8 parameters defined above 5 of them can be selected independently. It is rational that a_2, a_3, a_4, a_6 are independent parameters to satisfy the inequality constraints (4.7) and (4.8). The remaining independent parameter can be selected among b_2, b_3, a_5 or a_7. For instance, let b_2 be selected as an independent parameter. From the deployability conditions two out of b_3, a_5 or a_7 are dependent on the others. Let b_3 and a_7 be dependent. So from (4.3) and (4.4)

$$b_3 = a_2 + a_5 - a_4 \tag{4.12}$$

$$a_7 = (a_2 + b_2) + a_3 - a_6 \tag{4.13}$$

a_5 should be solved from the simultaneous reconfiguration condition (4.11). Manipulating (4.11):

$$a_3(a_2 + b_2 + a_6)\left[a_2{}^2 + b_3{}^2 - \left(a_4 + a_5\right)^2\right] = a_2 b_3\left[a_7{}^2 - a_3{}^2 - \left(a_2 + b_2 + a_6\right)^2\right] \tag{4.14}$$

Substituting (4.12) and (4.13) in (4.14):

$$\begin{aligned} &a_3\left(a_2 + b_2 + a_6\right)\left[a_2^2 + (a_2 + a_5 - a_4)^2 - (a_4 + a_5)^2\right] \\ &= a_2\left(a_2 + a_5 - a_4\right)\left[(a_2 + b_2 + a_3 - a_6)^2 - a_3^2 - (a_2 + b_2 + a_6)^2\right] \end{aligned} \tag{4.15}$$

Expanding and simplifying (4.15):

$$\begin{aligned} &a_3\left(a_2 + b_2 + a_6\right)\left[a_2\left(a_2 - a_4\right) + \left(a_2 - 2a_4\right)a_5\right] \\ &= a_2\left(a_2 - a_4 + a_5\right)\left[\left(a_2 + b_2\right)\left(a_3 - 2a_6\right) - a_3 a_6\right] \end{aligned} \tag{4.16}$$

Solving for a_5 from (4.16):

$$a_5 = \frac{a_2 a_6\left(a_2 - a_4\right)\left(a_2 + b_2 + a_3\right)}{a_3 a_4\left(a_2 + b_2 + a_6\right) - a_2 a_6\left(a_2 + b_2 + a_3\right)} \tag{4.17}$$

The remaining link lengths b_4 and b_6 are subject to 2 conditions: In fully closed configuration, the points G and H must be in line with D_0 and the distance between G and H should be equal to the required clear span width. These requirements are satisfied by changing the parameters b_4 and b_6 in Excel using the associated spin buttons.

In conclusion, among the 11 design parameters, 8 of them can be selected freely in order to satisfy the design requirements. Besides the design requirements mentioned so far, there may be some other design requirements, which are considered in the following case studies.

The design requirements considered in the case studies are the height a_1 and clear span width w = |GH| when G and H are on the ground. For case 1, the design requirements are such that a_1 = 3.5 m, and the clear span with is approximately 15 m. The free link lengths are chosen as: a_2 = 1 m, b_2 = 4.5 m, a_3 = 1 m, a_4 = 0.98 m, b_4 = 2.5 m, a_6 = 0.973 m and b_6 = 1.25 m as illustrated in Figure 4.11. Then, using formulas (4.12) – (4.17), b_3 = 6.663 m a_5 = 6.643 m and a_7 = 5.527 m.

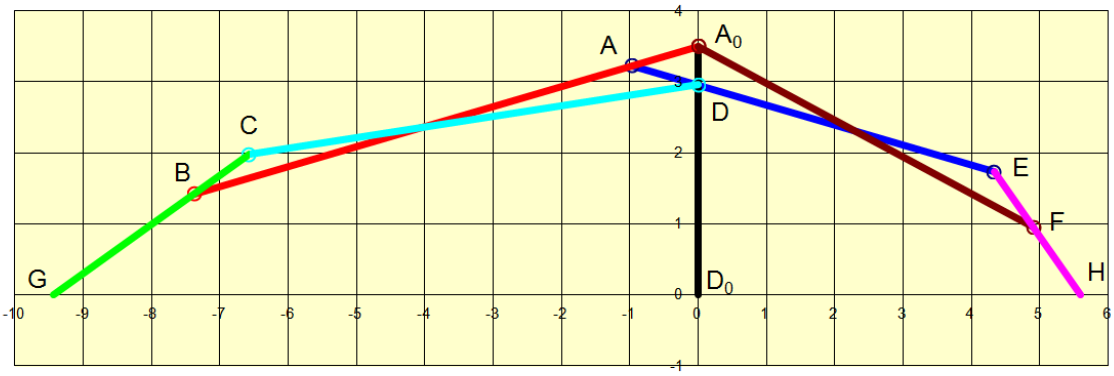


Figure 4.11. Case study 1 - closed form.

Figure 4.12 illustrates open form of case study 1. In this case, the width is approximately 16.8 m. A problem about this designed mechanism is that the folded form is not so compact (about 7.7 m long).

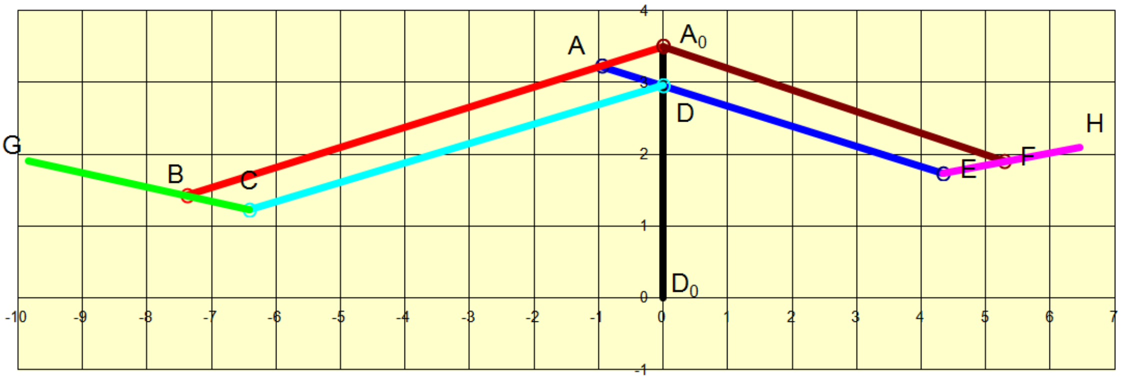


Figure 4.12. Case study 1 - open form.

For case study 2, a_1 = 3 m, the clear span with is approximately 4 m. The free link lengths are chosen as: a_2 = 0.25 m, b_2 = 1.5 m, a_3 = 0.25 m, a_4 = 0.23 m, b_4 = 2.75 m, a_6 = 0.223 m and b_6 = 1.75m as shown in Figure 4.13. Then, using formulas (4.12) – (4.17), b_3 = 1.165 m, a_5 = 1.145 m and a_7 = 1.777 m.

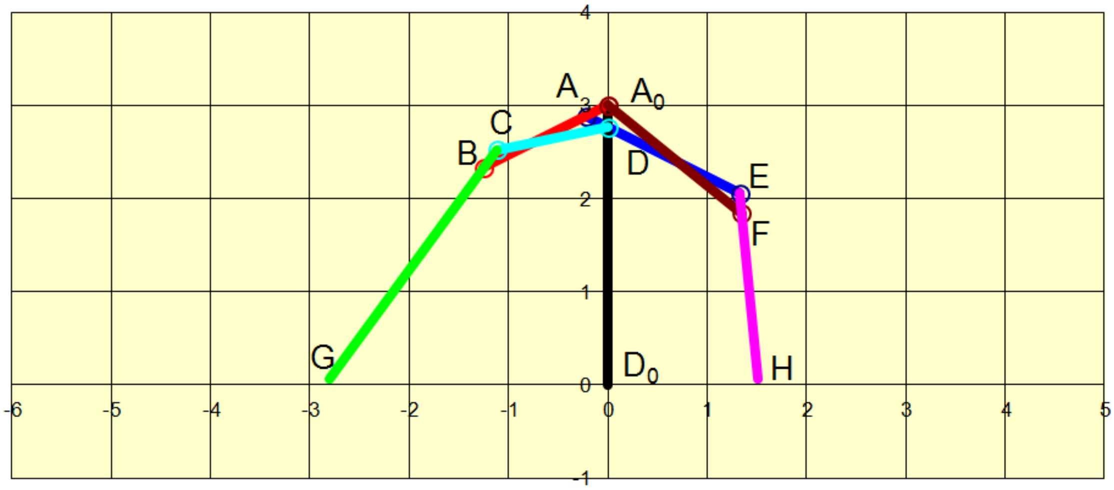


Figure 4.13. Case study 2 - closed form.

Figure 4.14 illustrates open form of case study 2. In this case, the width is approximately 7.45 m.

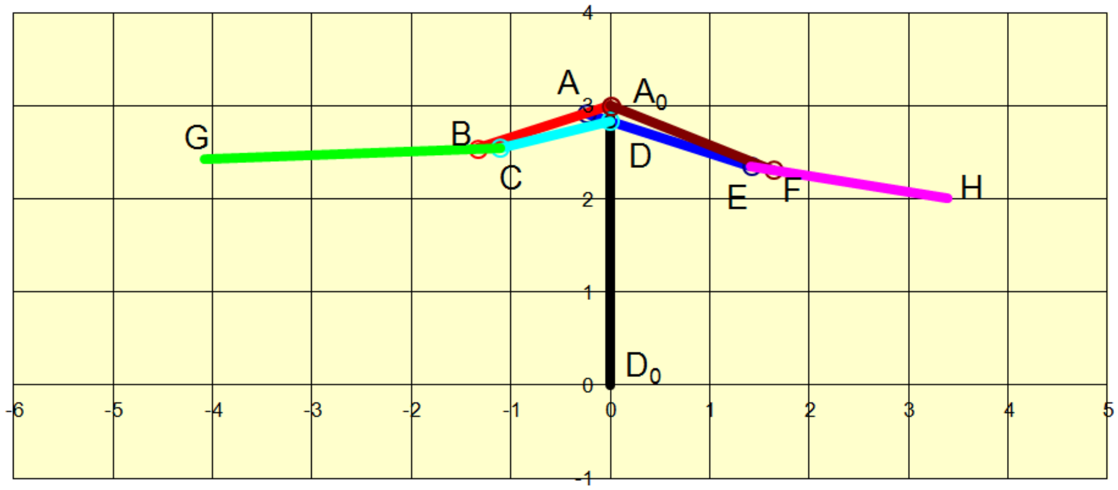


Figure 4.14. Case study 2 - open form.

When choosing the values of the free parameters, the values of a_2, a_3, a_4, and a_6 should be chosen as close values, because otherwise the mechanism is not assembled. In all case studies, b_2 is responsible of the symmetry of the mechanism. That is, if b_2 increases or decreases, the relative size of the two loops is affected.

For case study 3, let a_1 = 3 m, the clear span with is approximately 6 m. The free link lengths are chosen as: a_2 = 0.4 m, b_2 = 2.45 m, a_3 = 0.4 m, a_4 = 0.38 m, b_4 = 2.5 m, a_6 = 0.373 m and b_6 = 1.25 m as shown in Figure 4.15. Using formulas (4.12) – (4.17), b_3 = 1.961 m, a_5 = 1.941 m and a_7 = 2.877 m.

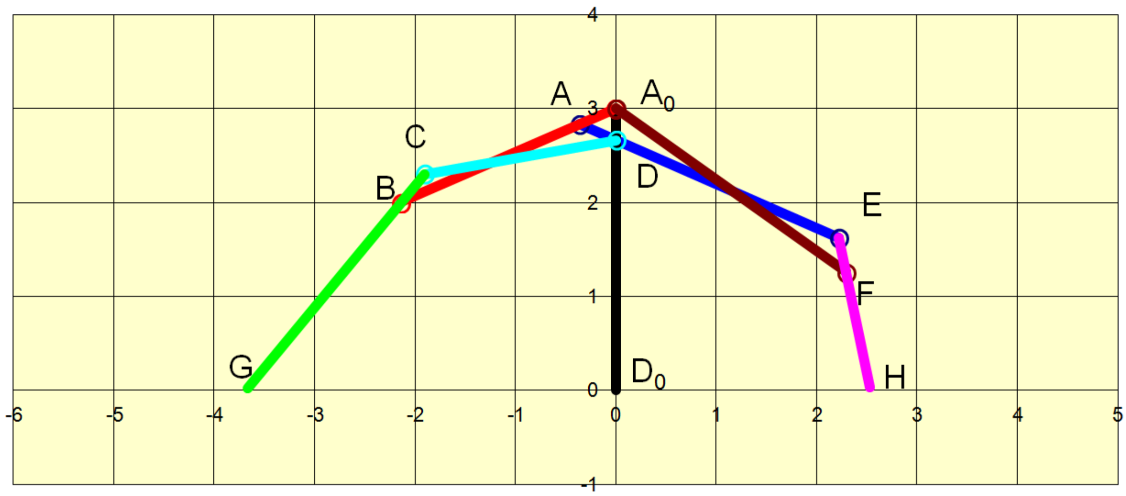


Figure 4.15. Case study 3 - closed form.

Figure 4.14 illustrates open form of the case study 3. In this case, the width is approximately 8.75 m.

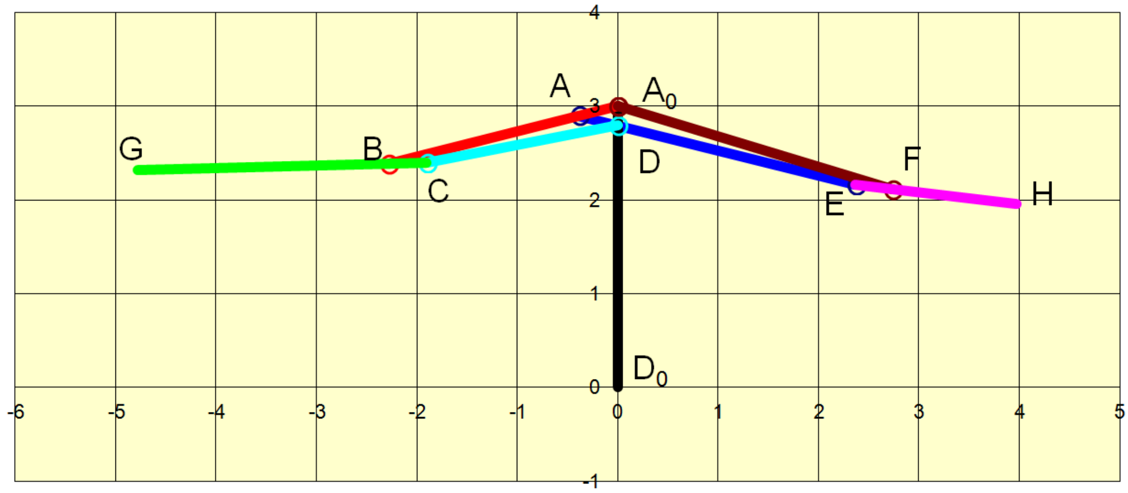


Figure 4.16. Case Study 3 - open form.

The special case is the parallelogram version. For a parallelogram all reciprocal links have equal length. Owing to this property, all links are collinear when the mechanism fully deploys. If the mechanism comprises parallelogram loops, the following equalities are valid:

$$b_3 = b_2 = a_5 \quad (4.18)$$

$$a_4 = a_2 = a_6 = a_3 \quad (4.19)$$

$$a_7 = a_2 + b_2 \quad (4.20)$$

Consider the following case: a_1 = 3 m, the clear span with is approximately 6.5 m and the free link lengths are chosen as a_2 = 0.4 m, b_2 = 2.5 m, a_3 = 0.4 m, b_4 = 2.45 m and b_6 = 1.55 m as shown in Figure 4.17. In the open configuration all links become collinear and the width is 9.8 m (Figure 4.18).

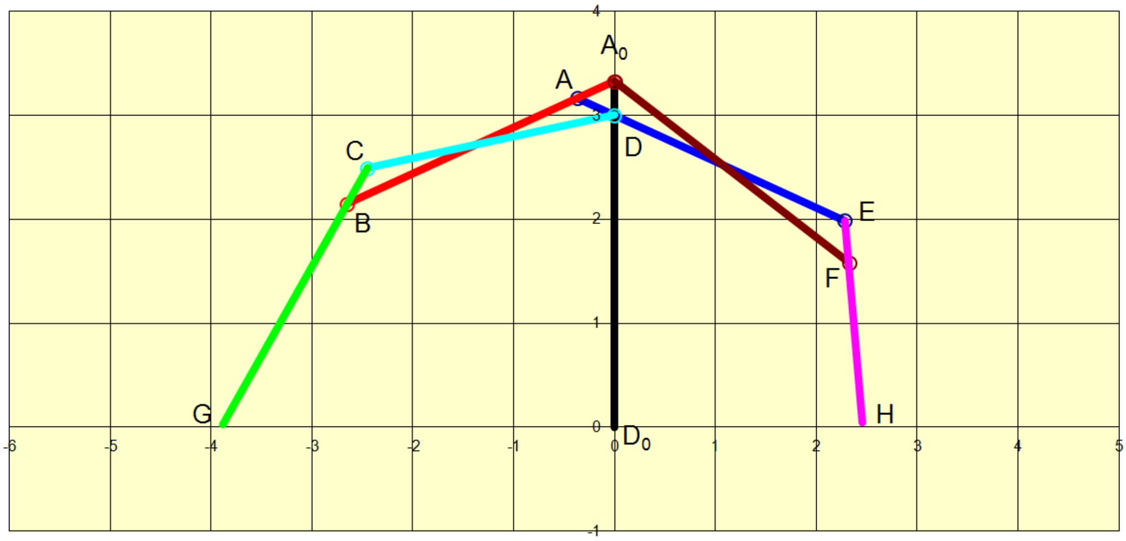


Figure 4.17. Parallelogram case – closed form

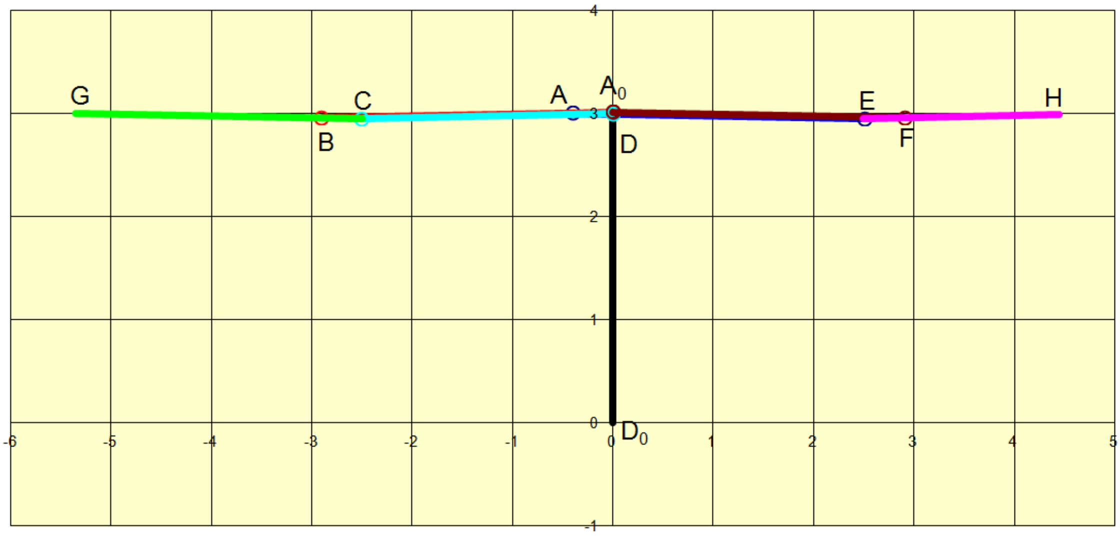


Figure 4.18. Parallelogram case – open form

In order to see how the length-to-width ratio changes while the link lengths of the loops are kept constant, a_1 and b_4 and/or b_6 values for case study 3 are varied. Minimum length of a_1 is selected as 2.5 m. When the height is minimum the clear span with is approximately 7.55 m, while b_6 = 1.25 m is kept and b_4 is modified as 2.76 m. If the mechanism fully deploys in this case, the width is approximately 9.0 m. a_1 shall not be less than 2.5 m because in fully open configuration, points C and E go below 2 m. Figures 4.19 and 4.20 illustrate closed and open forms of the mechanism.

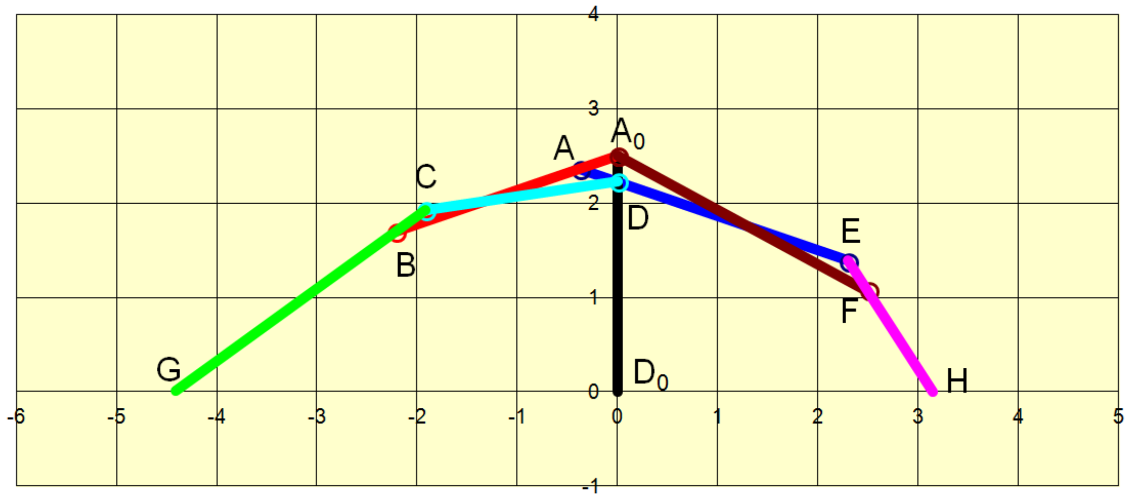


Figure 4.19. a_1 = 2.5 m – closed form

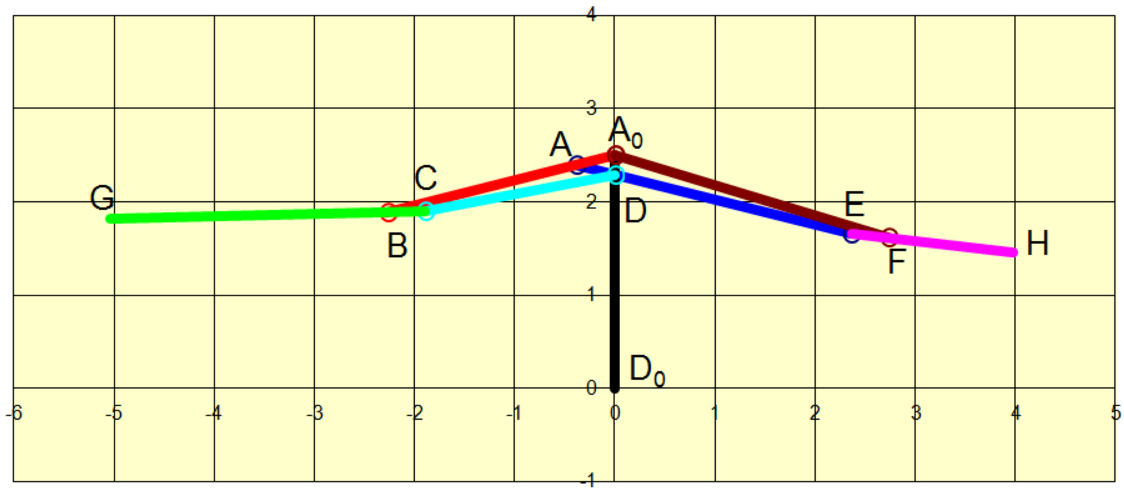


Figure 4.20. a_1 = 2.5 m – open form

Maximum value of a_1 length should not be more than 3.5 m because above this value clear span width narrows down and link FH tends inwards. When a_1 = 3.5 m in closed form, b_4 = 2.76 m and b_6 = 1.44 m, the clear span width is approximately 5.84 m. If the mechanism fully deploys, the width is approximately 9.37 m. So, changing a_1 does not have a significant effect on the width of the open configuration. Figures 4.21 and 4.22 illustrate the case for a_1 = 3.5 m.

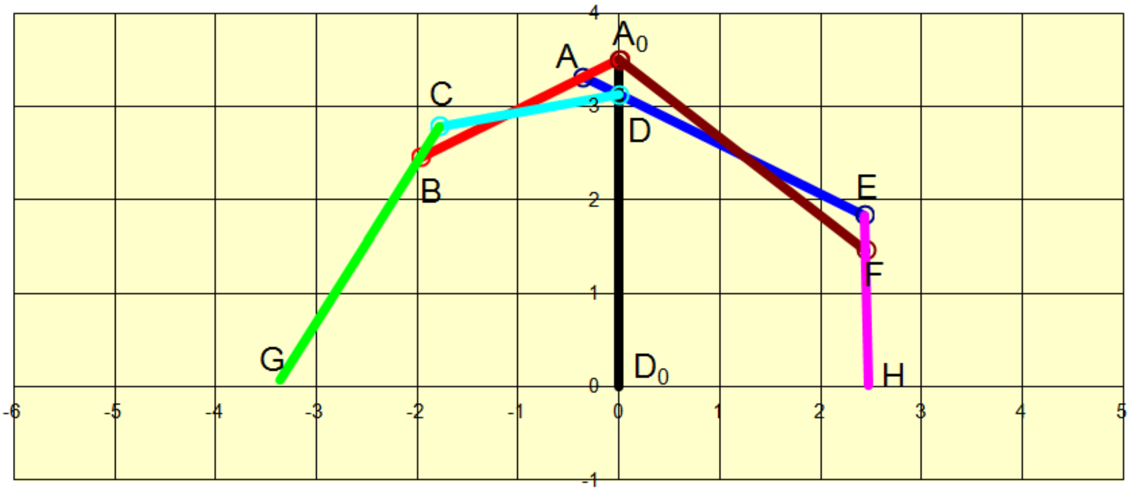


Figure 4.21. a_1 = 3.5 m – closed form

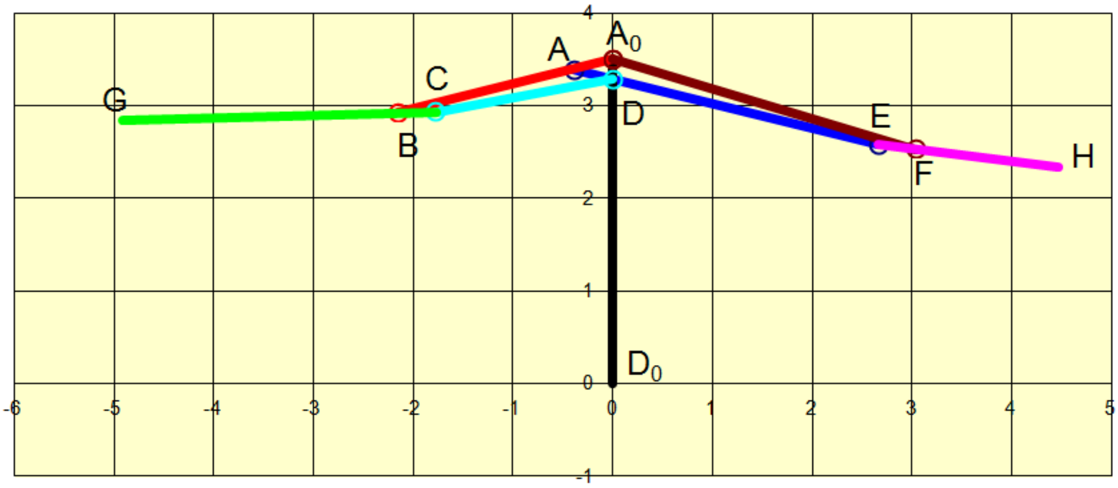


Figure 4.22. a_1 = 3.5 m – open form

CHAPTER 5

APPLICATION OF RECONFIGURABLE DEPLOYABLE STRUCTURE

5.1. Installation of the RDS to a Shelter or a Canopy

The reconfigurable deployable structure (RDS) concept is multi–functional to create closed, semi open and open spaces with reconfigurable parallelogram mechanisms The RDS can be used for different purposes. The parallelogram mechanism is a special case four bar linkage. The special case is the parallelogram version. For a parallelogram all reciprocal links have equal length. Owing to this property, all links are collinear when the mechanism fully deploys. When the RDS is used to create a closed space, it becomes a shelter. On the other hand, the RDM becomes a canopy if it is used to create semi open and open space.

Figure 5.1. Folded configuration during the storage.

Figure 5.1 shows folded configuration of the RDS. Dimensions of the folded configuration are 45x55x309 cm. During storage, its membrane is stored separately.

Figure 5.2 shows installation steps to create closed space under the shelter. Firstly, the RDS is fully deployed on ground by pulling from both sides. Each two planar parallelogram mechanisms take the form of anti-parallelogram on the ground. In this phase, the structure is covered with a membrane. By holding the structure from beneath, it is lifted up. Two end links are assembled to the ground. Thus, the fully deployed reconfigurable shelter covers an area of 2.65x9.80 m with 3.15 m high and its mass is approximately 45 kg, so four people are sufficient to install the shelter (Figure 5.3).

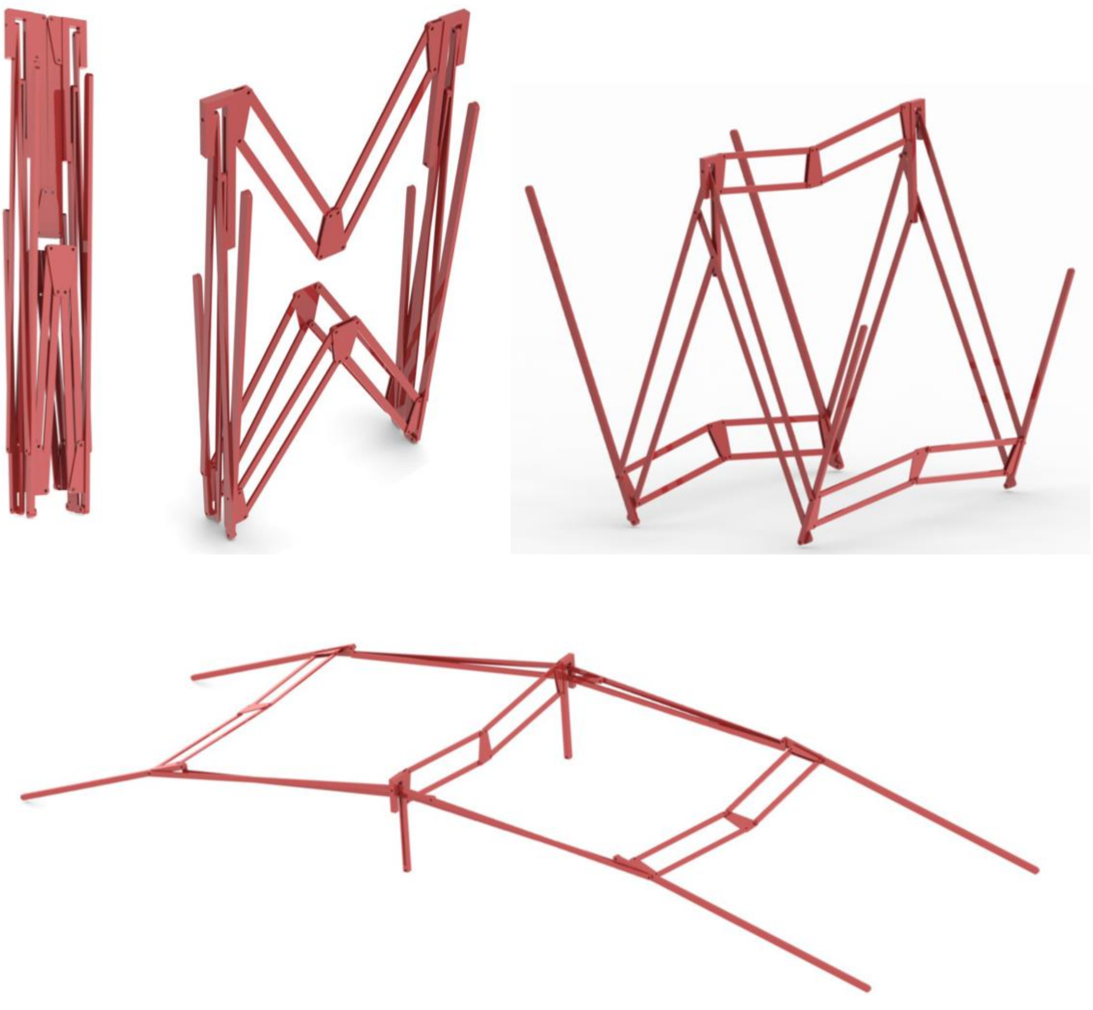


Figure 5.2. Fully deployed configuration of the RDS on the ground.

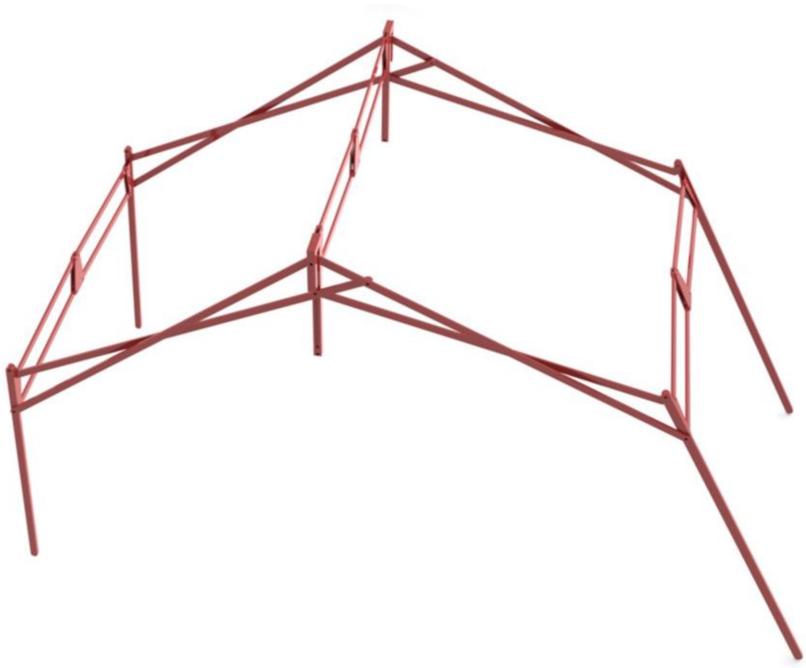


Figure 5.3. Fully deployed configuration of the RDS.

Figure 5.4 illustrates installation chart of the RDS to create open space under the canopy. Each two planar parallelogram mechanisms must be deployed in the form of parallelogram on the ground. In this phase, the structure is covered with a membrane again. The canopy is lifted up and attached to two fixed pylons like an umbrella which protect people from the rain and the sun. Screwed pile foundation must be already placed on the floor to connect with the pylon. Thanks to feature of singularity, when two loops are parallelogram, the reconfigurable shelter provides to create open spaces. In addition to, while one loop is parallelogram, other loop can be anti-parallelogram. This configuration can be preferred to create semi-opened spaces (Figure 5.5).

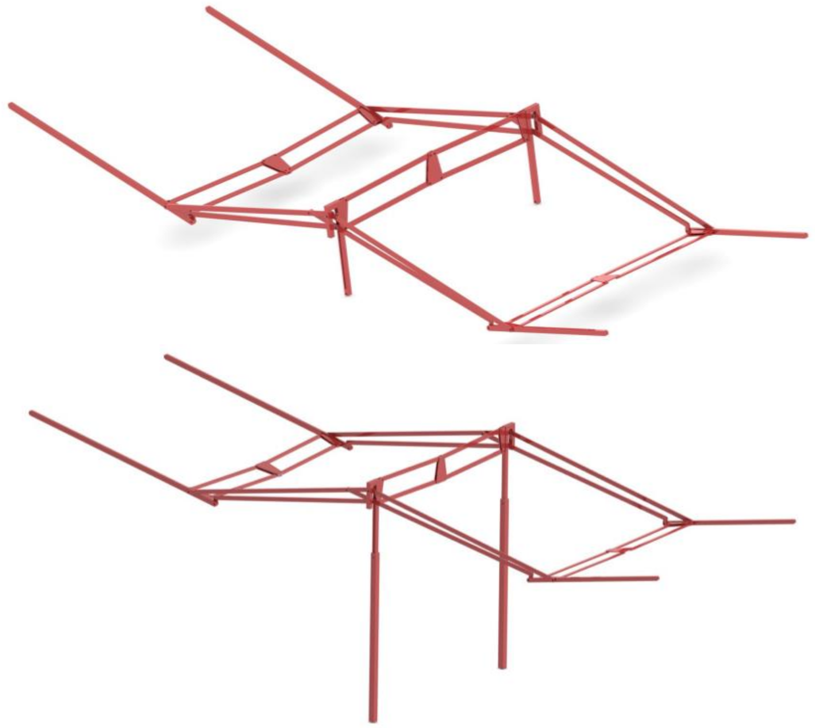


Figure 5.4. Fully deployed configuration of the RDS to create open space under it.

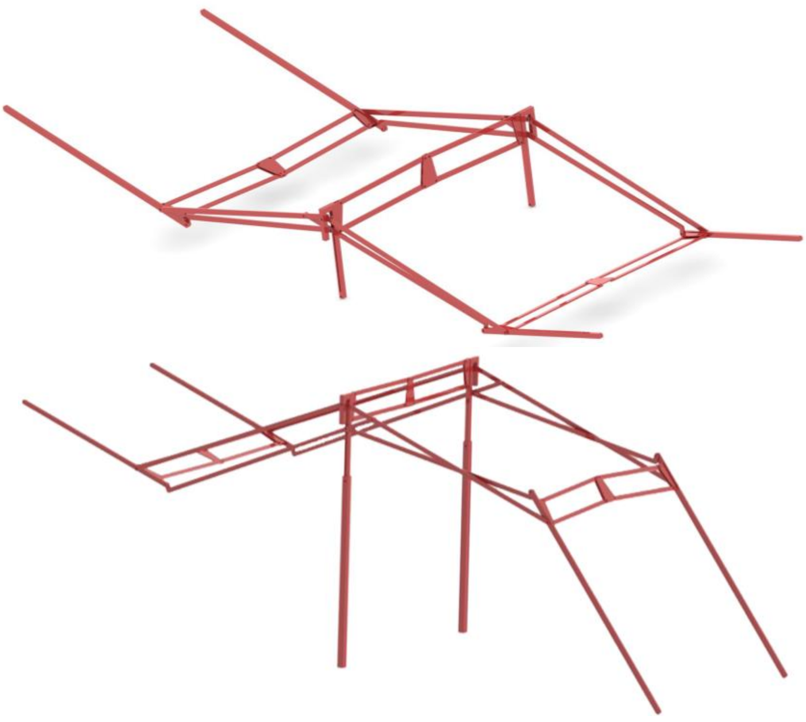


Figure 5.5. Fully deployed configuration and semi open configuration of the RDS.

5.2. Links and Connection Details of the RDS

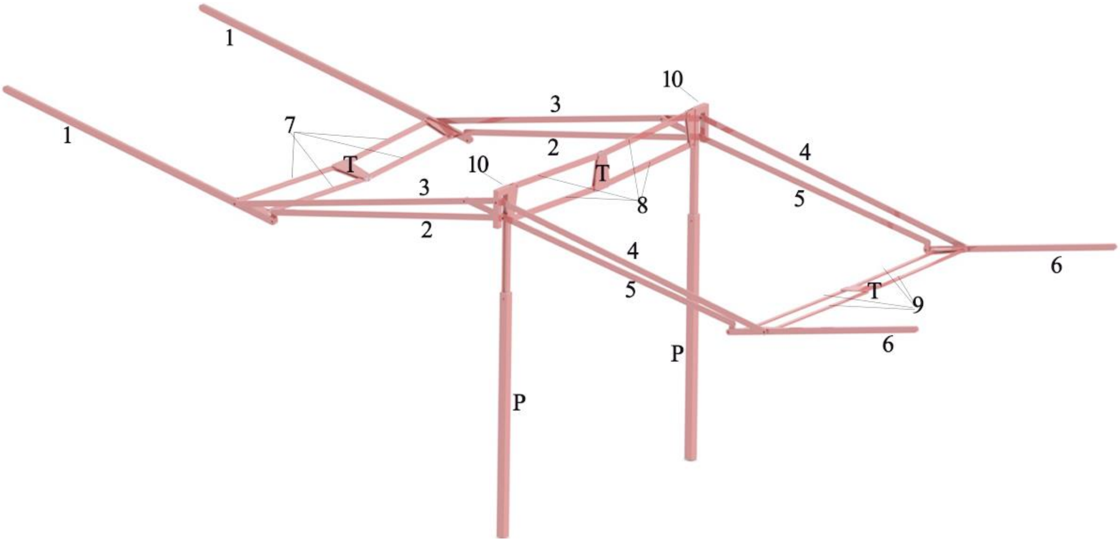


Figure 5.6. Numbered links of the reconfigurable deployable structure.

Figure 5.6 shows link number of the reconfigurable deployable mechanism. This mechanism has two links 1, 2, 3, 4, 5, 6, 10 and P, three links T and four links 7, 8 and 9. While Figures 5.7-19 20 show link detail, Figure 5.20-26 show connections of links details. The technical drawings given in Figures 5.7-26 are just representative drawings. More details should be included for technical drawings for manufacturing.

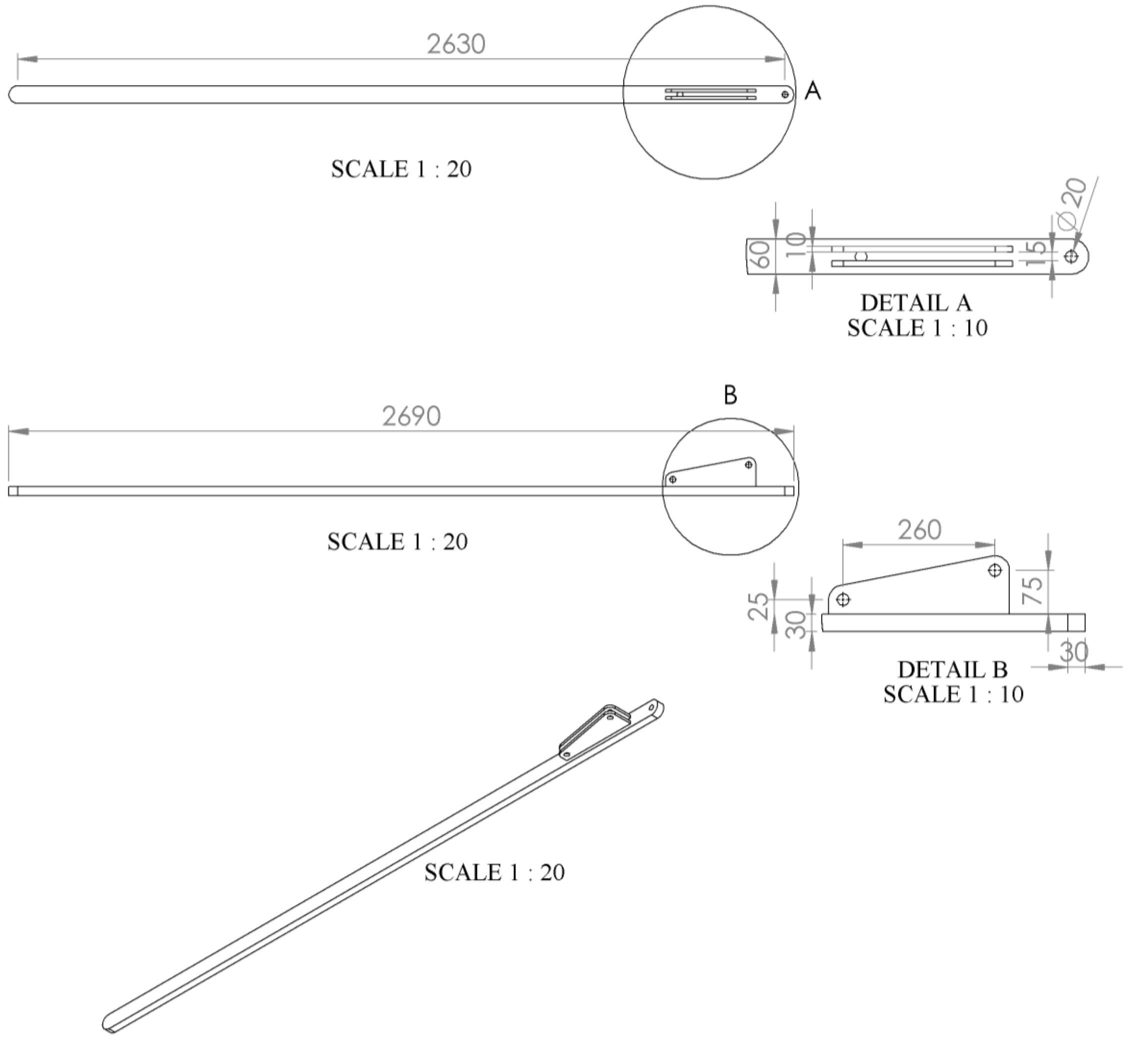


Figure 5.7. Link number 1.

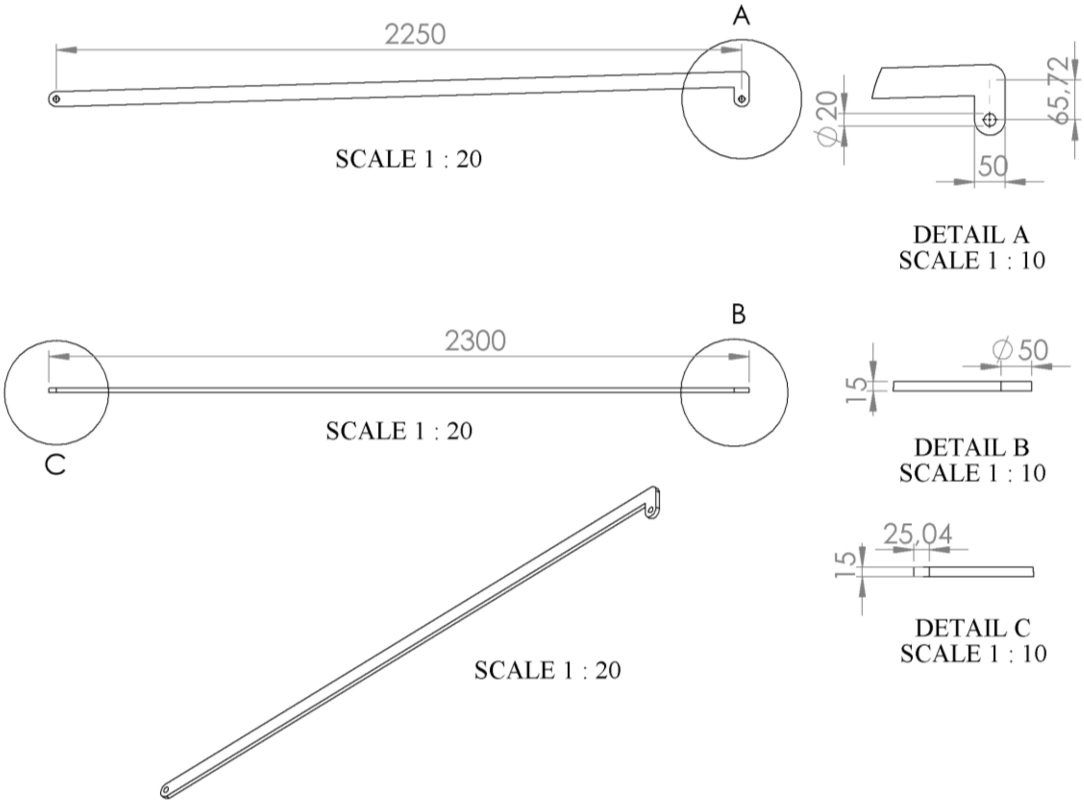


Figure 5.8. Link number 2.

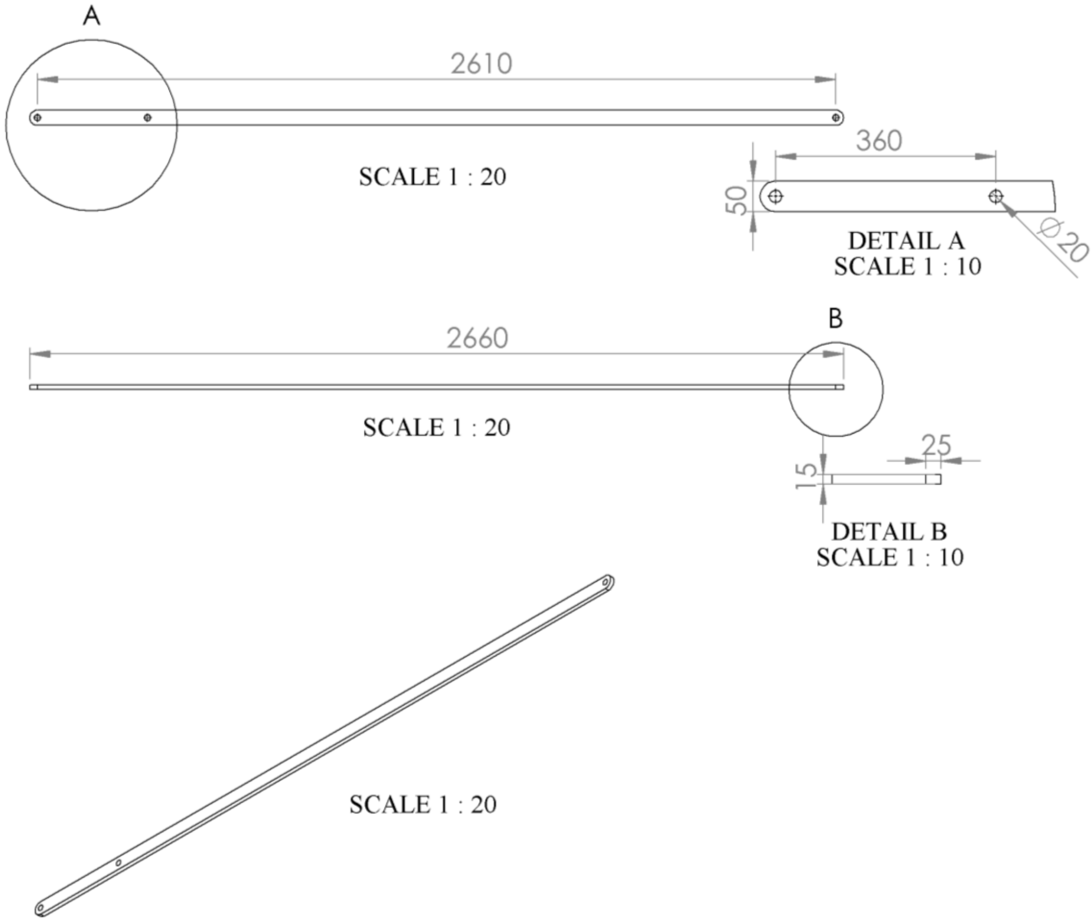


Figure 5.9. Link number 3.

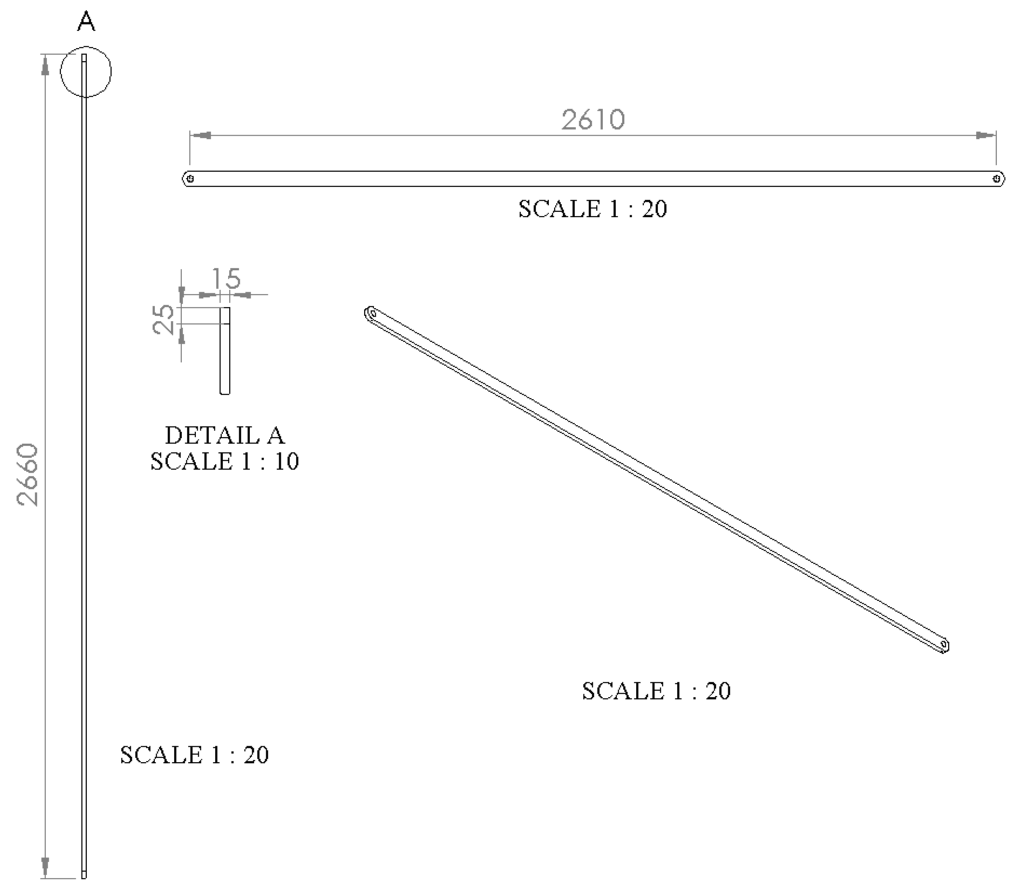


Figure 5.10. Link number 4.

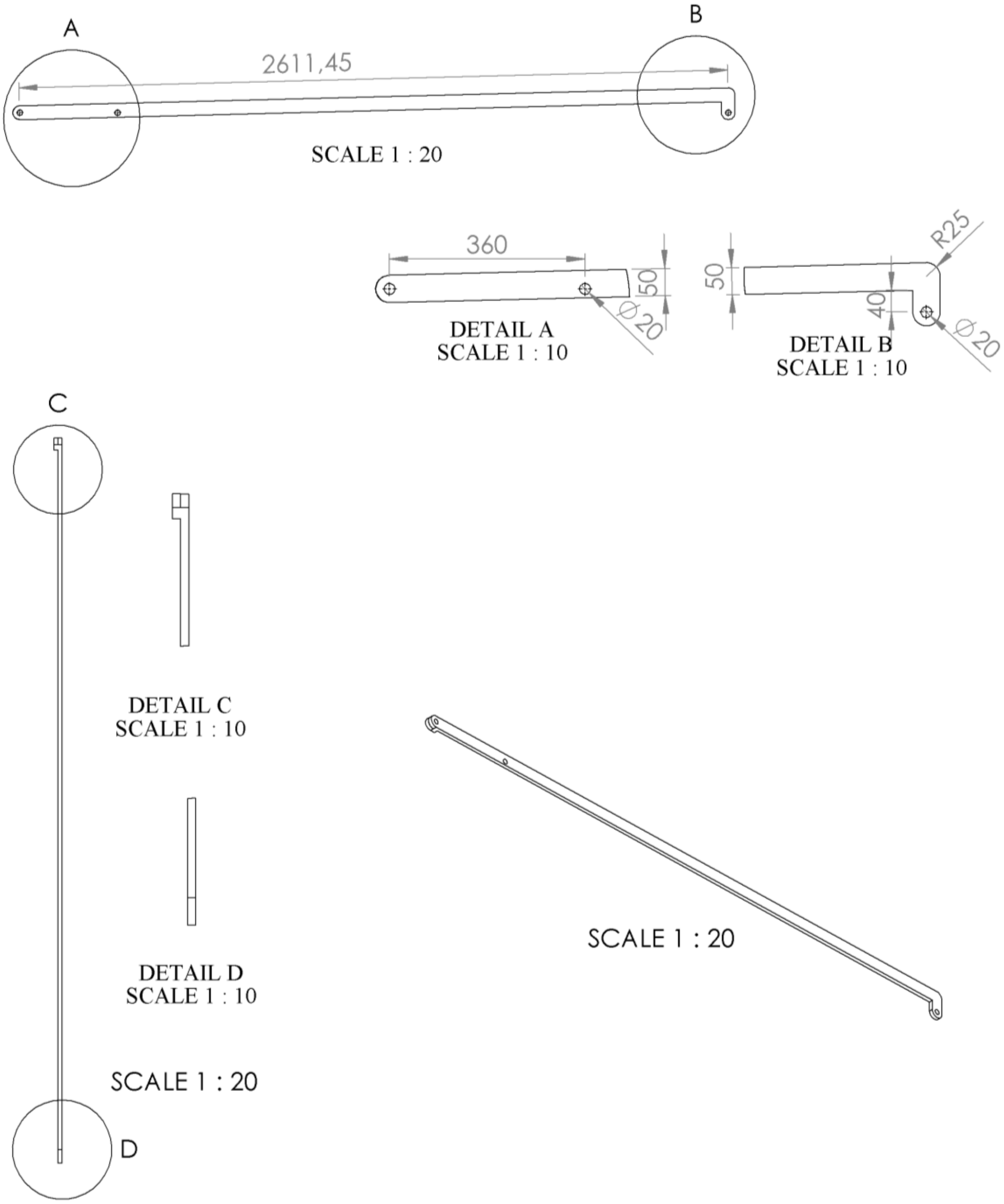


Figure 5.11. Link number 5.

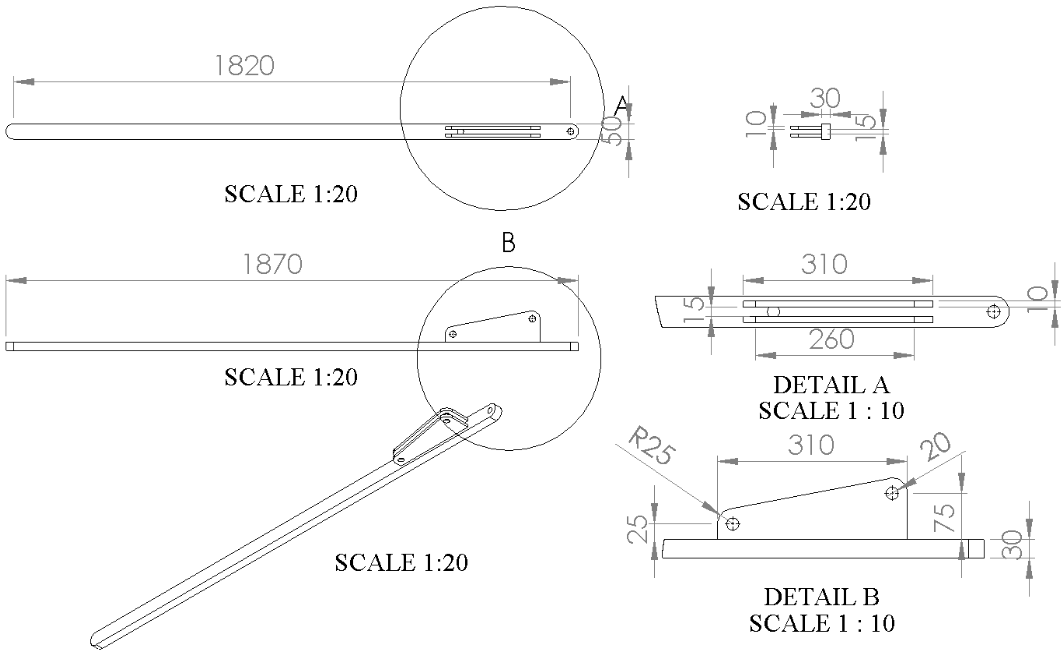


Figure 5.12. Link number 6.

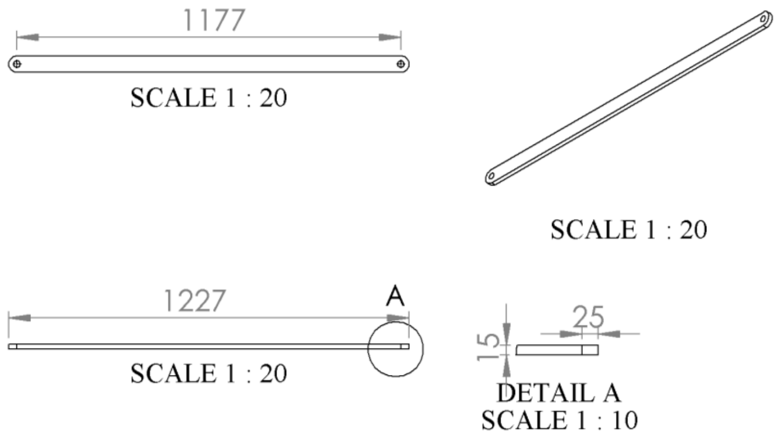


Figure 5.13. Link number 7.

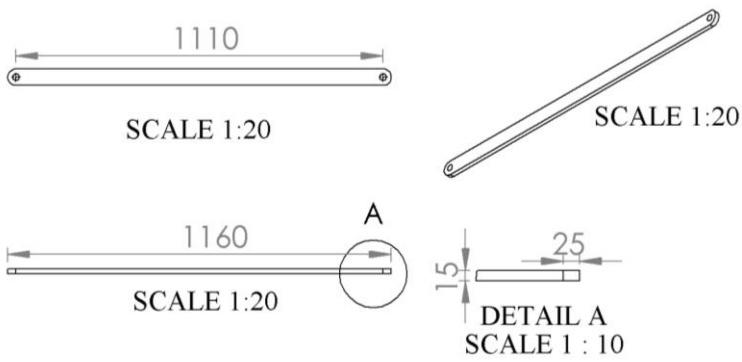


Figure 5.14. Link number 8.

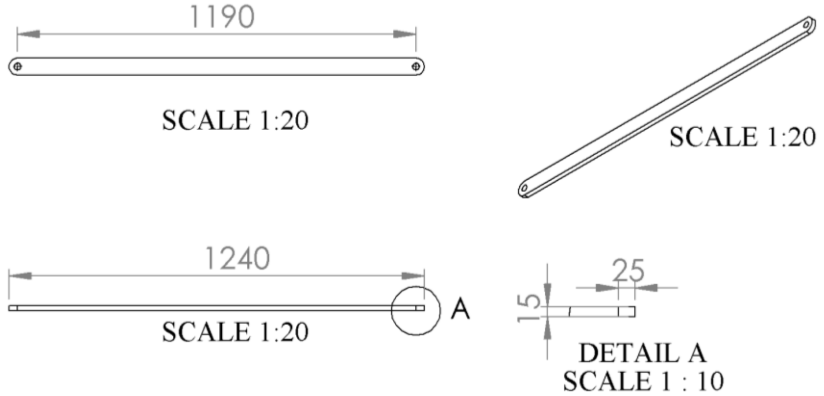


Figure 5.15. Link number 9.

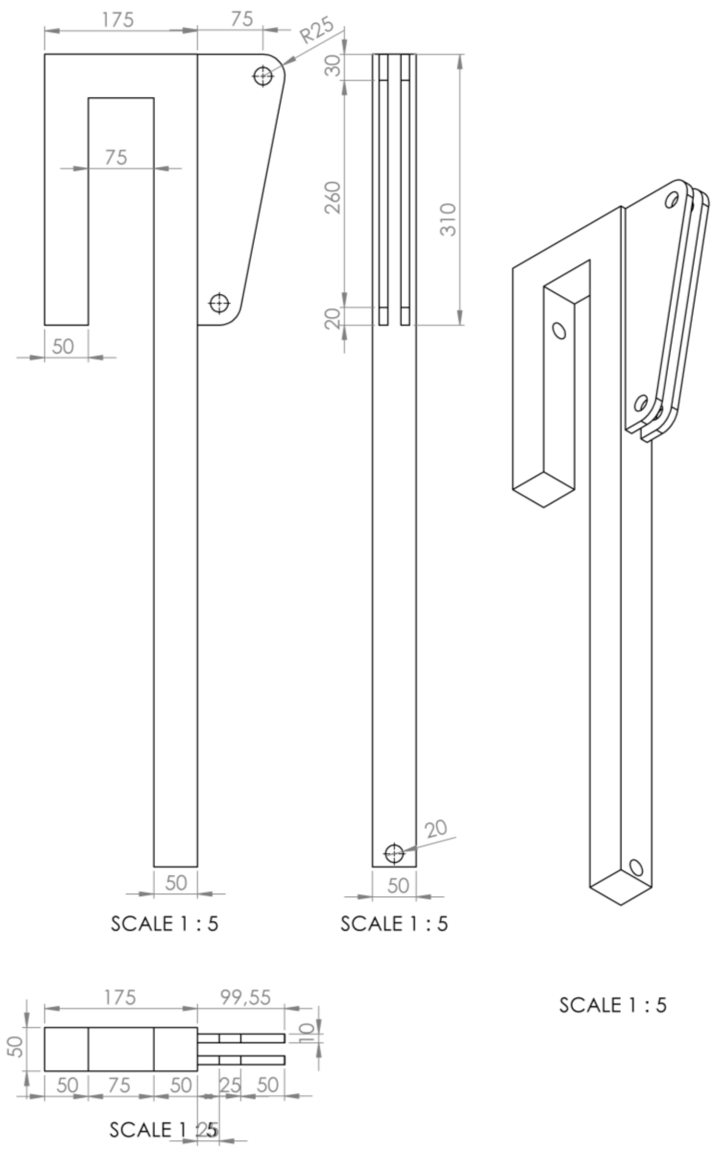


Figure 5.16. Link number 10.

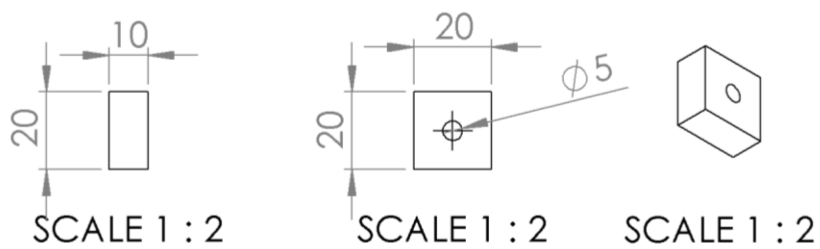


Figure 5.17. Sliding joint (Sj).

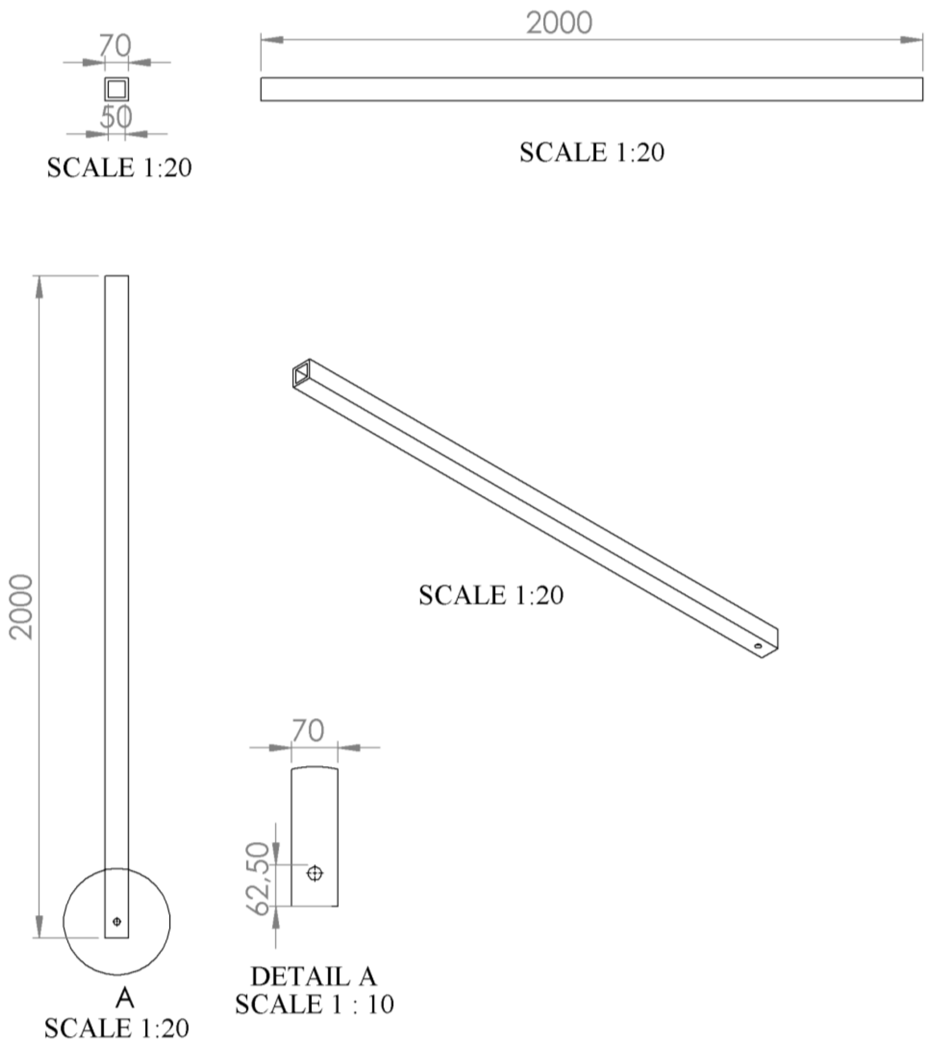


Figure 5.18. Pylon (P).

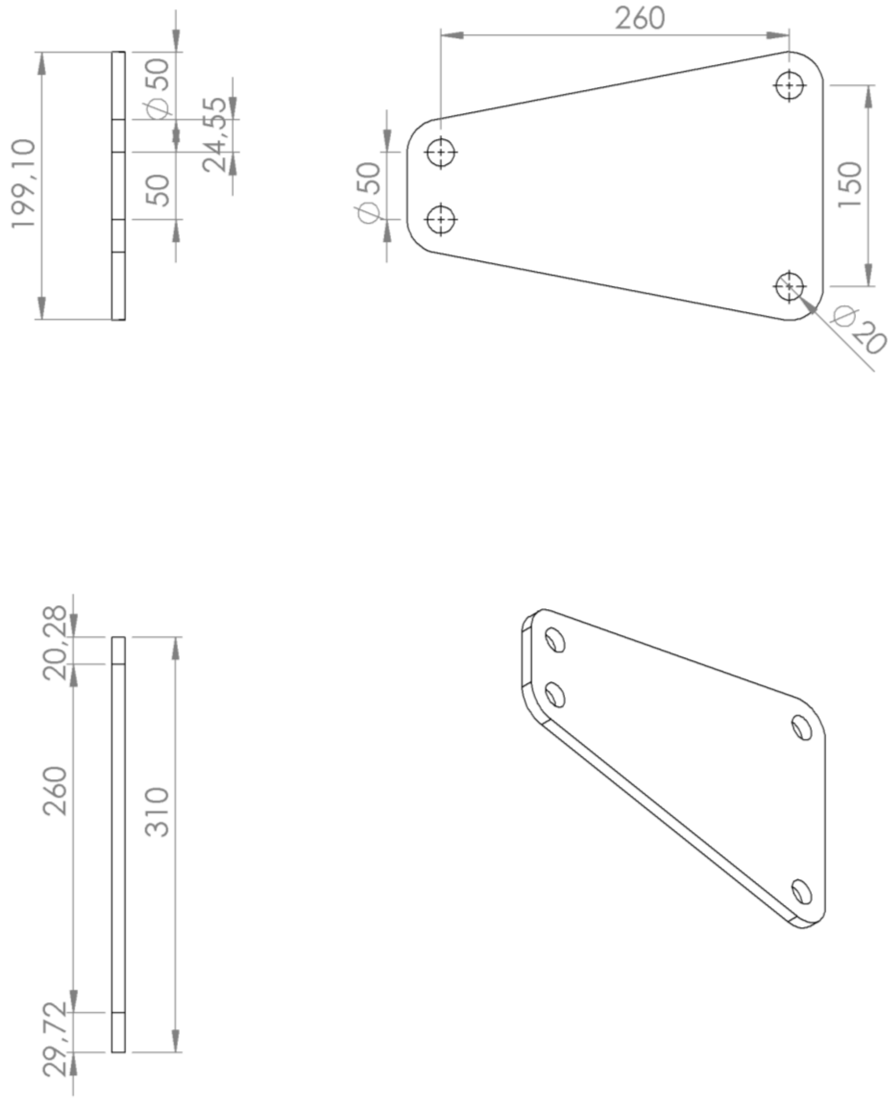


Figure 5.19. Trapezoid link (T).

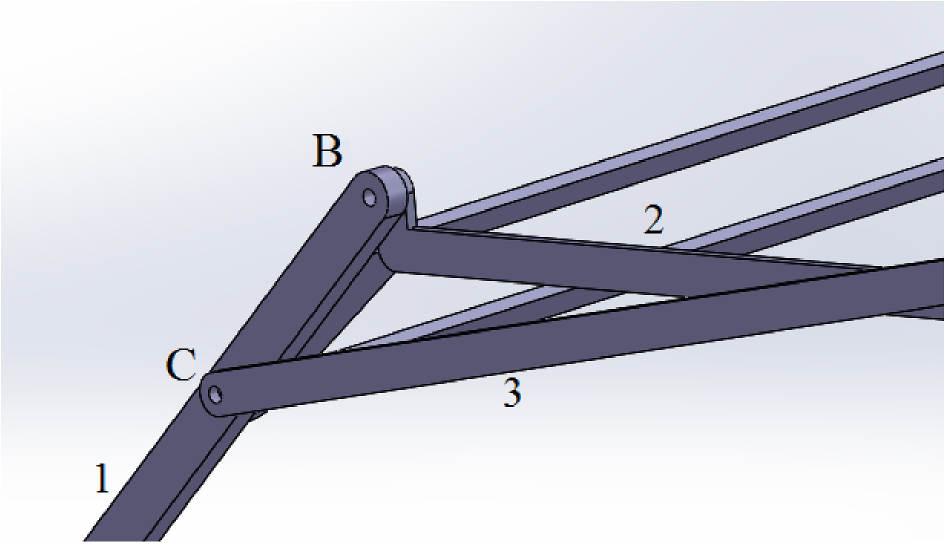


Figure 5.20. Connection detail of links 1-3 and 1-2.

Links 1 and 2 are connected at point B with a revolute joint and links 1 and 3 are connected at point C with a revolute joint (Figure 5.20). When these links are connected, link 1 must be paid attention to be between 2 and 3 because links 2 and 3 must not sweep.

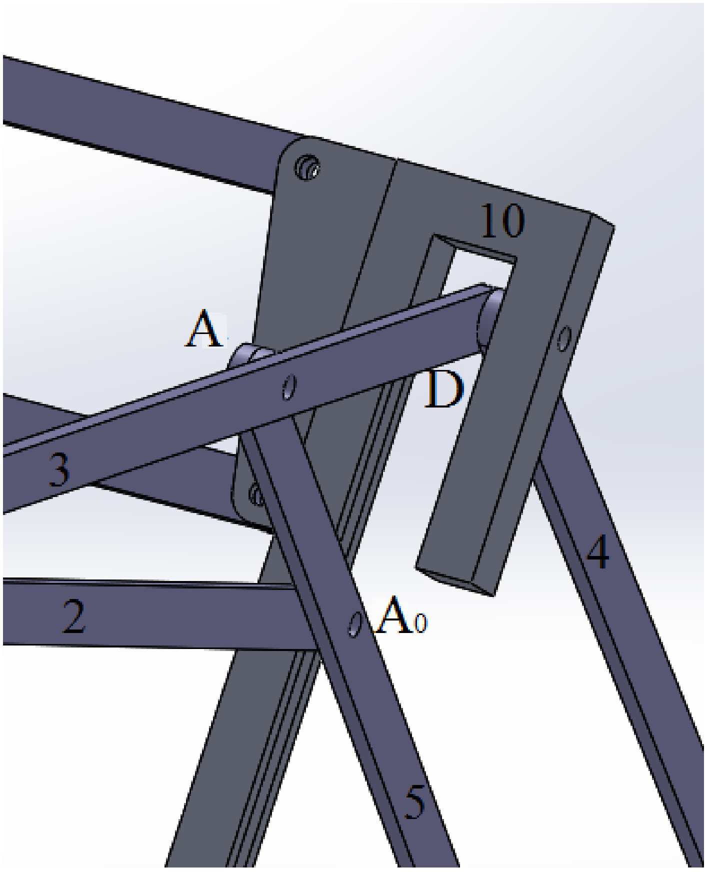


Figure 5.21. Connection detail of links 2-5, 3-5 and 3-4-10.

Links 3 and 5 are connected at point A with a revolute joint and links 3, 4 and 10 are connected at point D with a revolute joint. When links 2, 5 and 10 are connected at point A_0 with a prismatic joint and two revolute joints (Figure 5.21).

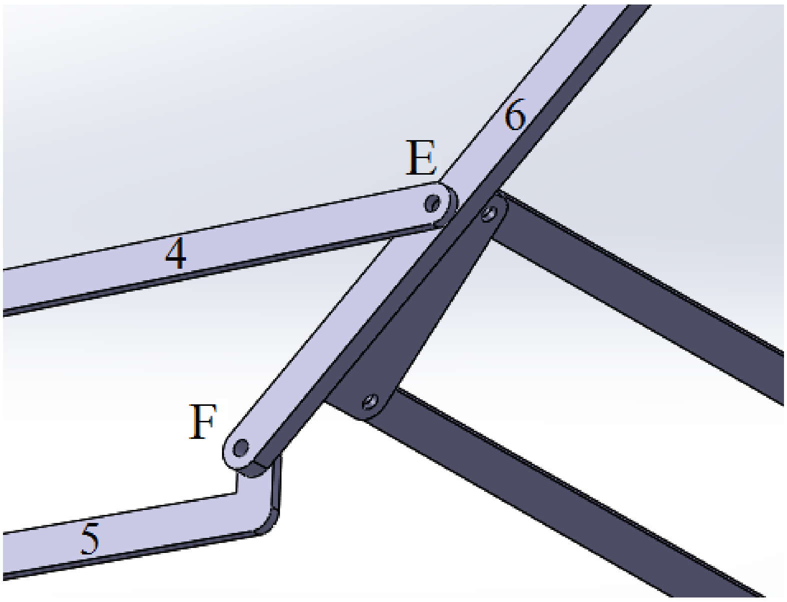


Figure 5.22. Connection detail of links 4-6 and 5-6.

Links 4 and 6 are connected at point E with a revolute joint and links 5 and 6 are connected at point F with a revolute joint (Figure 5.22). When these links are connected, link 6 should be between 4 and 5 because links 4 and 5 must not collide.

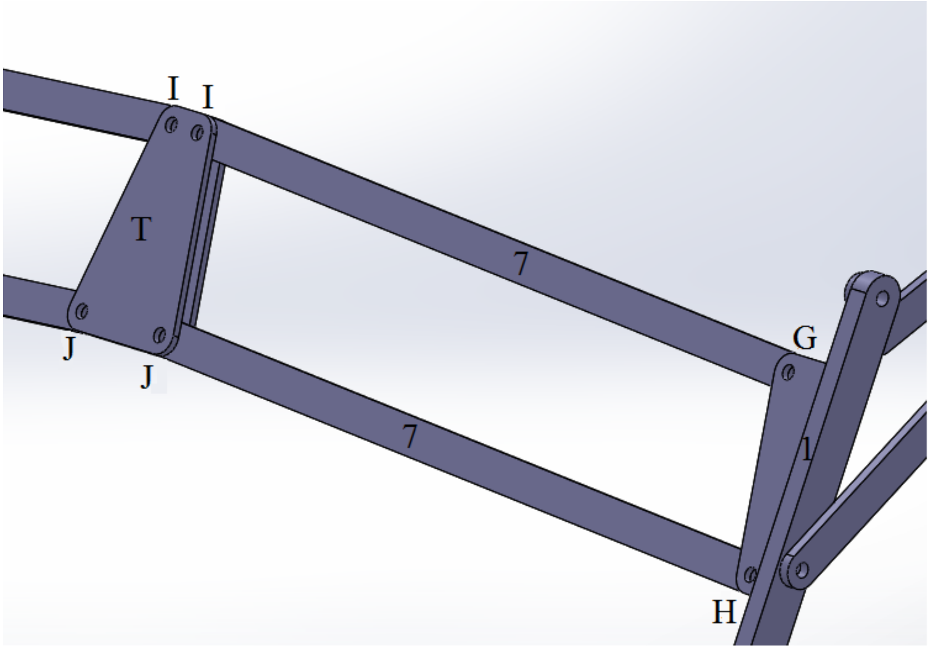


Figure 5.23. Connection detail of 1-7 and 7-T links.

To connect 2 number of links 7, 1 and link T there are revolute joints at points G, H, I, J (Figure 5.23).

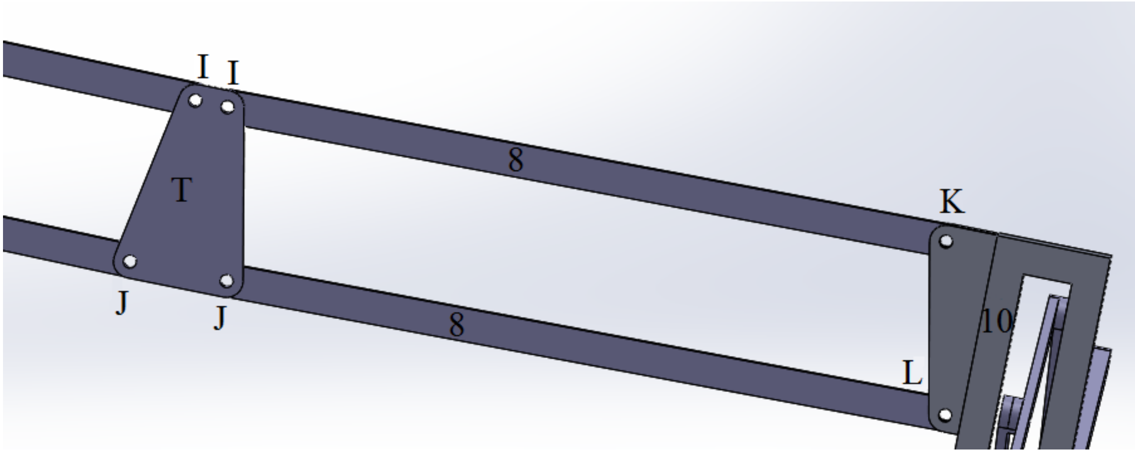


Figure 5.24. Connection detail of 8-10 and 8-T links.

To connect 2 number of links 8, 10 and link T there are revolute joints at points K, L, I, J. (Figure 5.24).

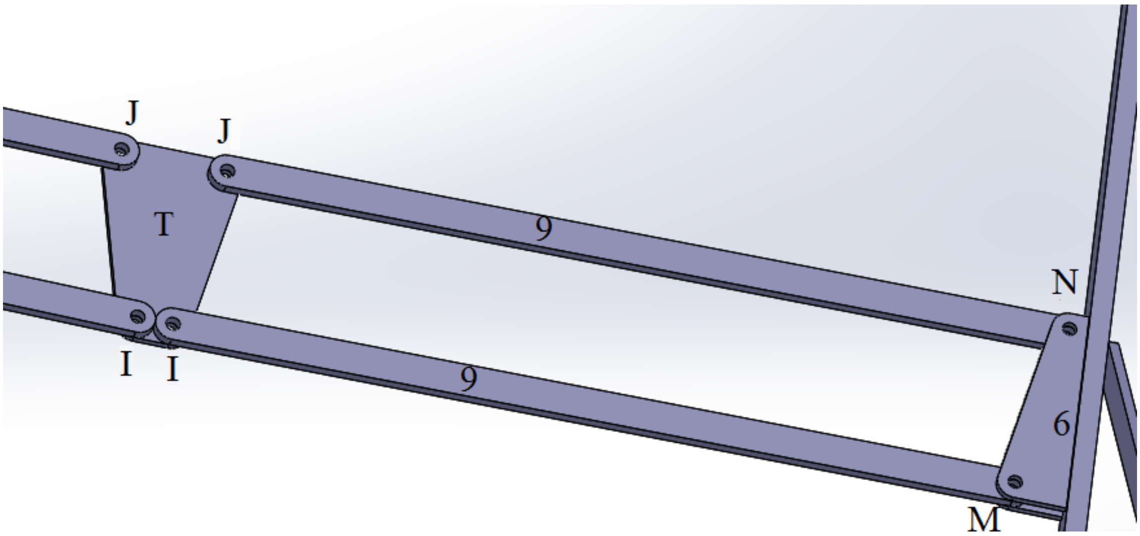


Figure 5.25. Connection detail of 9-6 and 9-T links.

To connect, links 9, 6 and link T there are revolute joints at points M, N, I, J (Figure 5.25).

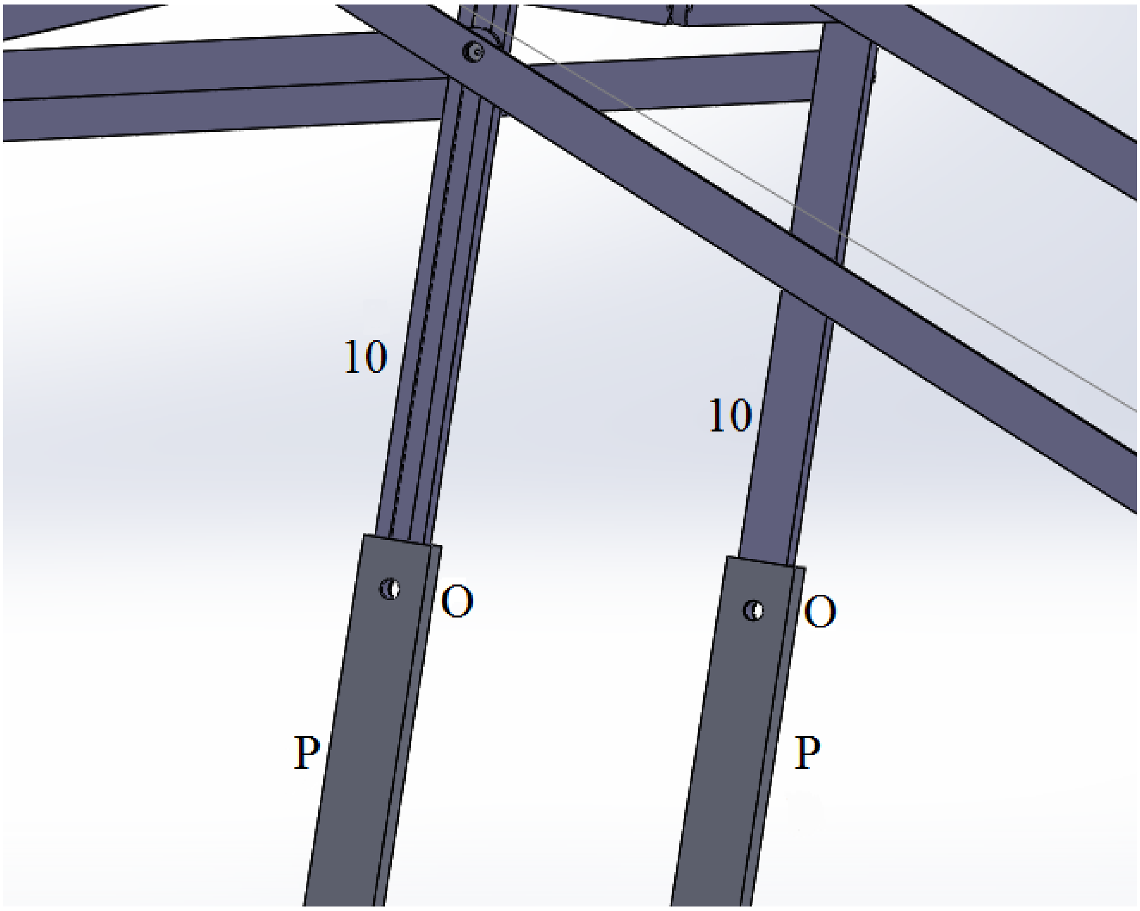


Figure 5.26. Connection detail of 10 and links P.

Links P and 10 are connected with prismatic joint. The hole at point O will be used as a stopper (Figure 5.26). Pylons will be attached to screwed pile foundations. Figure 5.27 shows a kind of screwed pile foundation.

Figure 5.27. Screwed pile foundation (SPF).

5.3. Cost Analysis of the Reconfigurable Shelter

Total estimated material price of the reconfigurable shelter is calculated in Table 5.1. This cost analysis is done using unit rate of Ministry of Environment and Urbanization.

Table 5.1. Material Cost Analysis of the Reconfigurable Shelter.

Link Name	**Item Number**	**Description**	**Dimensions**				**Number**	**Price** (TL/kg)	**Total** (TL)
			width (mm)	**height** (mm)	**length** (mm)	**weight** (kg)			
1	233.300	Aluminum box profile	15	50	2690	2,55	2	7,80	39,78
2	233.300	Aluminum box profile	15	50	2300	1,46	2	7,80	22,78
3	233.300	Aluminum box profile	15	50	2660	1,69	2	7,80	26,36
4	233.300	Aluminum box profile	15	50	2660	1,69	2	7,80	26,36
5	233.300	Aluminum box profile	15	50	2660	1,71	2	7,80	26,68
6	233.300	Aluminum box profile	15	50	1870	2,03	2	7,80	31,67
7	233.300	Aluminum box profile	15	50	1227	0,78	4	7,80	24,34
8	233.300	Aluminum box profile	15	50	1160	0,74	4	7,80	23,09
9	233.300	Aluminum box profile	15	50	1240	0,79	4	7,80	24,65
10	233.300	Aluminum box profile	50	50	1500	2,36	2	7,80	36,82
P	233.300	Aluminum box profile	70	70	2000	2,89	2	7,80	45,08
T	233.300	Aluminum sheet	10	100	310	0,84	3	7,80	19,66
Sj	233.300	Aluminum sheet	20	20	10	0,01	2	7,80	0,16
TOTAL WEIGHT AND PRICE OF MECHANISM						44,5			347,4
								Price (TL/n)	
SPF	-	Screwed pile foundation	3	76	1800	15	2	66	132
						Total weight	**Total m²**	**Price** (TL/m²)	
PPM	-	100 micron PVC polyester	265	315	980	52,63	87,71	15	1.315
TOTAL PRICE									**1.795**

*Exchange rate of dollar for SPF: 2.2TL (20.10.2014)

According to Ministry of Environment and Urbanization, unit rate of aluminum (TL/kg) is 7,8 TL. Links of the reconfigurable shelter are made from aluminum box profile and sheet. Aluminum is lighter than other metals although it is more expensive than others. This design is significant to be light because the reconfigurable shelter is designed for post disaster housing so lightness and also speed are remarkably important. Total weight of the mechanism is approximately 45kg. It is sufficient to be moved and installed by four people.

Foundation of the reconfigurable canopy is preferred to be SPF because SPF and disaster areas should be reutilized when these shelters are collected. The reconfigurable shelter is covered by 100 micron PVC polyester membrane.

This material cost analysis of the Reconfigurable Shelter is not included labor cost.

CHAPTER 6

CONLUSION

In this thesis, common temporary housing and especially deployable structures have been entirely investigated. During this investigation, usage areas of the deployable structures have been examined and their shortcomings with respect to form flexibility have been exposed. It is obvious that deployable structures do not have full form flexibility. A reconfigurable deployable structure overcomes the shortcomings. Deployable structures with various configurations are expressed as reconfigurable structures in this thesis. The possibilities of constructing a single degree of freedom reconfigurable deployable structure passing from one assembly mode to another built the objective of the thesis.

This thesis comprises the design of reconfigurable mechanism. The proposed single DoF mechanism has four assembly modes. The conditions for deployment and reconfiguration of the mechanism are derived. These conditions impose three equality and two inequality constraints on the 11 design parameters of the mechanism. A virtual model of the mechanism is constructed in Excel for design and simulation purposes. A computational case study is presented.

A temporary structure has been developed by utilizing the single DOF reconfigurable mechanism. The reconfigurable mechanism consists of two planar linkages with multiple assembly modes. The planar reconfigurable linkages are assembled parallel to each other to obtain spatial assemblies. Proposed reconfigurable deployable structure can achieve alternative forms although it has single DOF. Thanks to reconfiguration feature, it can be used for post disaster housing as a shelter or canopy. In this respect, the present study is a pioneering study on reconfigurable structures for architectural applications.

In the context of this thesis, the proposed reconfigurable deployable structure has been conceived primarily as a temporary building for post disaster housing. However, this reconfigurable deployable structure built with parallelogram mechanism can be used for different functions as well. For instance, it can be used as a shelter or canopy for military purpose and public needs.

In Chapter 4, mathematical model, analysis and design procedures were discussed. According to several case studies, limitation on link lengths and deployed span with were defined. The deployed width of Case study 1 is approximately 16.8 m. A problem about this designed mechanism is that the folded form is not so compact. It is about 7.7 m long. The deployed width of Case study 2 is approximately 7.45 m. It is the minimum narrowness for architectural applications. It is conceivable that these two case studies are minimum and maximum value of this mechanism. The values of Case study 3 are average values of Case study 1 and 2. The deployed width of Case study 3 is approximately 8.75 m. Parallelogram case is a special case for this study. If it is obtained parallelogram case, all reciprocal links must have equal length. These are: $b_3 = b_2 = a_5$, $a_4 = a_2 = a_6 = a_3$, $a_7 = a_2 + b_2$. When a_1 value of Case study 3 is changed, different case studies are obtained. Maximum value of a_1 length should not be more than 3.5 m because above this value clear span width narrows down and link FH tends inwards.

In Chapter 5, link and cover material were discussed. The technical drawing was given. And also, the material cost analysis was calculated. To conclude, Aluminum box profile for mechanism link and PVC polyester for covering material are found suitable to design the RDS. This design is significant to be light because the reconfigurable shelter is designed for post disaster housing so lightness and also speed are remarkably important. The estimated material cost analysis of the RDS is 1.795 TL.

Two international conferences full texts in Seville and Portugal have been written in the present study, and also there is a patent application from this study.

6.1. Recommendations for the Future Research

In this thesis, the structure of the reconfigurable mechanism is given, however how the reconfiguration is achieved in practice is not discussed. In the present form of the design, reconfiguration may be performed manually on site. However, it is also possible to design some extra mechanisms of tools for reconfiguration. Further research on the reconfiguration means of the proposed RDS will provide new research perspectives.

The thesis also includes selection of covering material and mechanism link materials and also a cost analysis. For manufacturing the RDS, further investigation should be carried out for material selection, assembly details considering end-user requirements and manufacturability.

Consequently, this thesis has showed that common temporary buildings for post disaster housing can be RDSs and exposed the potential of this structure to create an adaptive structure. In this respect, this dissertation is a pioneering study for the research field of reconfigurable deployable structures for architectural purposes. Further studies can concentrate on RDSs for different architectural applications.

REFERENCES

Abod House. (2013). Retrieved April 17, 2013 from http://www.abodshelters.com/ http://www.abodshelters.com.

Acerer, S. (1999). Afet Konutları Sorunu ve Deprem Örneğinde İncelenmesi, Master Thesis ITU, İstanbul.

Akgün, Y. (2010). A Novel Transformation Model for Deployable Scissor-Hinge Structures. A dissertation submitted for the degree of Doctor of Philosophy, Izmır Institute of Technology, Izmir, Turkey.

Akünal, S. (1986). Proposal for an Alternative Post-Earthquake Housing and Contribution of this Alternative Case to the Existing Condition. Unpublished master's thesis, METU, Ankara. Quoted in Dikmen, N. (2005), A Provision Model and Design Guidelines for Permanent Post-disaster Housing In Rural Areas of Turkey Based On an Analysis of Reconstruction Projects In Çankırı, Phd Thesis, METU, Ankara.

Ark Nova. (2013). Retrieved December 17, 2013 from http://www.huffingtonpost.com/2013/09/30/ark-nova_n_4016731.html.

Balkan, E. (1988). Yaşama Biçimi ve Konut Tasarımı Arasındaki İlişkiler, İDMMA, Department of Architecture, Proficiency Study, İstanbul.

Bolin, R. & Stanford, L. (1998). The Northridge Earthquake: Community-based Approaches to Unmet Recovery Needs, Disasters, 22(1), 21-38.

Chen, Y. (2003). Design of Structural Mechanisms. A dissertation submitted for the Degree of Doctor of Philosophy, University of Oxford, Oxford, UK.

Cole, P. M. S. (2003). An Empirical Examination of the Housing Recovery Process Following Disaster. Unpublished Ph.D. thesis, Texas A&M University.

Conestoga Wagon. (2012). Retrieved May 15, 2012 from http://en.wikipedia.org/wiki/File:Conestoga_wagon.jpg.

Deployable Umbrellas. (2013). Retrieved March 5, 2013 from http://www.freiotto.com/FreiOtto%20ordner/FreiOtto/FreiOttoSchirmeGross.

Deployable roof of Emergency Center. (2012). Retrieved November 24, 2012, from http://www.miestai.net/forumas/showthread.php?p=148824&langid=1.

Ergünay, O. (1996). Afet Yönetimi Nedir? Nasıl Olmalıdır, “Erzincan ve Dinar Deneyimleri Işığında Türkiye’nin Deprem Sorunlarına Çözüm Arayışları”, TUBITAK Earthquake Symposium, 15-16 February 1996, p: 263-273, Ankara.

Ervan, M.K. (1995), Acil Durumlarda Kullanılabilecek Demontabl Yapıların Tasarım Kriterlerinin Belirlenmesine Yönelik Kavramsal Bir Model, Gazi University Institute of Science, Ankara.

Escrig, F., Valcarcel, J. P. & Sanchez J. (1996). Deployable Cover on a Swimming Pool in Seville. *Journal of the International Association for Shell and Spatial Structure*: IASS, 37 (120), 39-70.

Escrig, F. (2013). Modular Light and Transformable Architecture. In F. Escrig & J. Sanchez (Eds.), New Proposals for Transformable architecture. Engineering and Design in the honor of Emilio Perez Pinero (pp.11-22). Seville: Starbooks.

Expandable mobile mini house. (2013). Retrieved February 7, 2013 from http://inhabitat.com/the-expandable-mobile-mini-house.

Friedman, N. & Farkas, G. (2011). Roof structures in motion – On retractable and deployable roof Structures enabling quick construction or adaption to external excitations. Concrete Structures 2011.

Foldable entrance for Ernsting store. (2013). Retrieved February 20, 2013 from http://designtheorykje.wordpress.com/2012/10/18/1983-1985-ernstings-warehouse-2.

Fuller, B. R. (1962). Tensile integrity structures, US Patent No 3063521.

Fuller, B.R. & Applewhite, E. J. (1975). Synergetics: Explorations in the Geometry of Thinking, Scribner.

Gantes, C. J., Connor J. J., & Logcher R. D. (1994). A Systematic Design Methodology for Deployable Structures. *International Journal of Space Structures.*

Glen Curtis’ Aerocar. (2009). Retrieved October 7, 2012 from http://blog.hemmings.com/index.php/2009/11/19/hemmings-find-of-the-day-1938-curtiss-aerocar.

Gürcü, F., Korkmaz, K. & Kiper, G. (2013). Design of a Reconfigurable Deployable Structure In F. Escrig & J. Sanchez (Eds.), *New Proposals for Transformable architecture. Engineering and Design in the honor of Emilio Perez Pinero* (pp.145-149). Seville: Starbooks.

Gürsu, H. (1986). Design Recommendations for Temporary Pneumatic Structures in Design Areas. Unpublished master’s thesis, METU, Ankara. Quoted in Dikmen, N. (2005), A Provision Model and Design Guidelines for Permanent Post-disaster Housing in Rural Areas of Turkey Based On an Analysis Of Reconstruction Projects in Çankırı, Phd Thesis, METU, Ankara.

Hanaor A. & Levy R. (2001). Evaluation of Deployable Structures for Space Enclosures. *International Journal of Space Structures*, 16(4), 211-229.

Herrmann J. (2007). Disaster Response Planning & Preparedness: Phases of Disaster, New York Disaster Interfaith Services.

Hoberman Arch. (2013). Retrieved May 30, 2013, from http://hoberman.com/portfolio/hobermanarch.php?myNum=22&mytext=Hoberman+Arch&myrollovertext=%3Cu%3EHoberman+Arch%3C%2Fu%3E&category=architecture&projectname=Hoberman+Arch.

Iris Dome. (2013). Retrieved May 30, 2013, from http://hoberman.com/portfolio/irisdomeworldsfair.php?myNum=26&mytext=Iris+Dome&myrollovertext=%3Cu%3EIris+Dome%3C%2Fu%3E&category=architecture&projectname=Iris+Dome.

Kiper G., Gürcü F., Korkmaz K. & Söylemez E. (2014). Kinematic Design of a Reconfigurable Canopy, *New Trends in Mechanism and Machine Science*, (pp.167-174), EUCOMES, Guimaraes, Portugal.

Kokawa, T. (1995) A Trial of Expandable Arch. Proc.of IASS Symposium in Milan, 1, 501-510.

Kronenburg, R. (2002). Houses in motion: The Genesis, History and Development of the Portable Building. Academy Editions, London. 144pp. ISBN1-85490-395-0.

Kronenburg, R. (2003). *Portable Architecture (3rd expanded edition), Architectural Press, Oxford. 274pp.* ISBN 0-7506-5653-0.

Kuo, C.-H., Dai, J. S. & Yan, H.S. (2009). Reconfiguration principles and strategies for reconfigurable mechanisms. In: Dai, J. S., Zoppi, M. and Kong, X. (Eds.): ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots REMAR 2009, pp. 1-7.

Langbecker, T. & Albermani, F. (2003). Kinematic and non-linear analysis of foldable barrel vaults. Engineering Structures, 23,158-171.

Longman Dictionary. (2012). Retrieved December 3, 2012 from http://www.ldoceonline.com/dictionary/temporary.

Maden, F., Korkmaz, K. & Akgün, Y. (2011). A review of planar scissor structural mechanisms: geometric principles and design methods, Architectural Science Review, 54:3, 246-257.

Mason, M. T. (2001). Mechanics of Robotic Manipulation (Series: Intelligent Robots and Autonomous Agents). MIT Press, p. 11.

Motro, R. (2003) Tensegrity: Structural Systems for the Future, London: Kogan Page Science.

Mele, T. V. (2008). Scissor-Hinged Retractable Membrane. A dissertation submitted for the degree of Doctor of Philosophy, Vrije Universiteit Brussel, Brussel, Belgiumç.

Miwa Takabayashi's Pavilion. (2013). Retrieved July 27, 2013, from http://www.miwaart.com/packaged.html.

Mush-balloon. (2013). Retrieved May 20, 2013, from http://www.tensinet.com/database/viewProject/3839.html.

Olympic Stadium in Montréal, Canada. (2013). Retrieved December 25, 2013, from http://www.stadeolympiquemontreal.ca/le-toit-taillibert.aspx.

Otto, F. & Bodo, R. (1995). Finding Form: Towards an Architecture of the Minima. Fellbach: Editions Axel Menges.

Porta-Kamp. (2014). Retrieved July 27, 2014, from http://www.sistersonthefly.com/photo-gallery/preview/524?page=38.

Rapidly Deployable Shelter. (2006). Retrieved July 27, 2013, from http://www.hoberman.com/portfolio/rapidlydeployableshelter.php?projectname=Rapidly+Deployable+Shelter.

Relaux, F. (1963). "The Kinematics of Machinery", Dover Publications Inc. New York. Quoted in Söylemez E. Mechanisms. Ankara: METU Press; 2009.

Renee Pearce, L. D. (2000). An Integrated Approach for Community Hazard, Impact, Risk and Vulnerability Analysis: HRV. Unpublished Ph.D. thesis, The University of British Colombia, Vancouver. Quoted in Dikmen, N. (2005), A Provision Model and Design Guidelines for Permanent Post-disaster Housing In Rural Areas of Turkey Based On an Analysis of Reconstruction Projects In Çankırı, Phd Thesis, METU, Ankara.

Rentaro Nishimura's Pavilion.(2009). Retrieved July 27, 2013, from http://madesignsuite.com/2009/12/01/rentaro-nishimura-cardboard-banquet-project.

Rippmann, M. (2007). Curtain Wall: Building Design Semesterarbeit. Stuttgart: Universität Stuttgart-ILEK.

Robbin, T. (1996). Engineering a New Architecture. Massachusetts: Quebecor- Eusey Press.

Rolling Bridge, (2014). Retrieved May 25, 2014 from http://www.heatherwick.com/rolling-bridge.

Rostock Tower. (2013). Retrieved May 25, 2013 from http://tensegrity.wikispaces.com/Warnow+Tower.

Sey, Y. & Tapan, M. (1987). Afet Sonrasında Barınma ve Geçici Konut Sorunu Raporu, İTU, İstanbul.

Street lamps (2014). Retrieved May 25, 2014 from http://www.west8.nl/projects/all/schouwburgplein.

Söylemez, E. (2009). Mechanisms. Ankara: METU Press.

Söylemez E. (2014). Retrieved December 25, 2013 from http://ocw.metu.edu.tr/pluginfile.php/3960/mod_resource/content/1/appendices/ek2/BASIC.bas

Temmerman, N. (2007). Design Analysis of Deployable Bar Structures for Mobile Architectural Applications, PhD Dissertation, Vrije Universiteit Brussel, Brussels.

The DH1 Disaster House. (2006). Retrieved May 7, 2013 from www.greggfleishman.com/structures.html.

The Prairie House. (2012). Retrieved October 25, 2012, from http://www.orambra.com/~prairieHouse.html.

Tibert, A.G. (2002). Deployable Tensegrity Structures for Space Applications. A dissertation submitted for the degree of Doctor of Philosophy, Royal Institute of Technology Department of Mechanics. Stockholm, Sweden.

Weaver, J. M., Wood, K. L. & Jensen, D. (2008). Transformation facilitators - a quantitative analysis of reconfigurable products and their characteristics. In: Proceedings of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2008, Brooklyn, NY, DETC2008-49891.

Zhang Y. & Peacock W.G. (2009). Planning for Housing Recovery? Lessons Learned From Hurricane Andrew. Journal of the American Planning Association, Vol. 76.