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Nature and Kinetic Architecture: The Development of a New Type of Transformable Structure for Temporary Applications

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Abstract: The contemplation of contemporary architectural designs shows an increasing demand for the development of more adaptable, flexible and transformable structures. This type of structures can adapt with different environmental conditions and meet different functions. This can help in reducing environmental waste and pollution associated with many buildings and above all can save on cost and time. Natural systems have inspired human being, since they began to build and design. Architects and designers have utilized nature as one of the main resources of information for the creation of innovative architectural spaces. One of the unique features of natural structures is the way that their components open and close in order to respond to a particular requirement or the environmental changes. This aspect has inspired many designers for the development of transformable architectural structures that can change their shape and geometry to be able to adapt with specific conditions. To make a way toward the design of transformable structure for temporary applications, the authors have developed a new type of adaptable structures according to natural forms. The proposed design applies the transformation principles that exist in potato's flower and the movement mechanisms used in a spider's leg. The design is able to fit to different topographies and have a potential to be folded to a very compact state in a very short period of time. The detailed design and the different configurations of the system applications will be presented in this paper. The result of the study shows that using modular triangular plates can create a changeable module that is not only able to respond to different functions and environmental changes but it is also able to shape different configuration to be able to respond to different user's ambitions. The compactability of this structure into 1/3 of its base dimensions; makes its transportation fast and with minimum costs. These capabilities make this structure suitable for temporary buildings such as exhibitions, temporary settlements or hospital in damaged areas.

Key words: Flexible, changeable, transformable, temporary structure, natural lessons.

1. Introduction

The interest in the design and construction of light and transformable buildings goes back to initial human civilization. Yurts with opening and closing elements and transformable components are one of such designs [1]. Leonardo Davinchi is one of the first designers in recent decades that made activities in this area and studied the design methods of transformable buildings such as movable bridges [2]. He applied the movement mechanism existing in the birds' wings to flight tools and also for the first movable roof. His works indicated the importance of natural world, as one of the best teacher, in human inventions and creations.

In recent years, due to urgent need for multi-functional buildings and also the necessity to maintain and respect to the environment in front of building's wastes, the demands for transformable and changeable structures has increased rapidly [3]. The main potential of transformable structures is that they can accommodate with different climates, topographies and can take many desired forms on the basis of the user's requirements.

This paper by classification of the main design criteria and the evaluation of major transformable structures inspired by nature proposes a new type of

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transformable structures that has been developed by mimicking from natural forms and mechanisms.

2. Main Criteria for the Design of Flexible Temporary Buildings

The idea of transformability in building design can respond to many architectural requirements and expectations, however if it does not comply with the design criteria (classified in Diagram 1), it may have negative impact into architecture and environment. Therefore, before describing our proposed design, the main design criteria for the design of temporary transformable structures classified by the authors will be explained and evaluated. The main criteria presented here are based on the general characteristics required from a transformable system in order that it could function as efficient and effective as possible. A comprehensive discussion on the selection of the evaluation criteria can be found in the book entitled "Transformable and Kinetic Architectural Structures" published by one of the authors [3].

2.1 Ease of Execution

A transformable temporary structure is expected to be built, erected and removed easily by workers even with a little experience. The ease of execution here means the reduction of costs in the excavation, foundation work and connections and tendency to simplicity, by avoiding complex details. Moreover, the simplicity of detailing and erection mechanism makes it possible for the structure to be erected in different places in a very short period of time with minimal wastes. This in turn reduces the cost of labour which is one of the significant expenses in the building industry [3].

2.2 Reuse and Cost Reduction

In the lifetime of a temporary building, there are four levels: production and execution, use and after use (recycling). Nowadays, the time which is required for the production and execution of a building has been reduced due to advanced technologies and new and innovative equipments. However, it is not the same for returning or recycling stage, as every building consists of a lot of non-recyclable components which increases costs and environmental pollutions if the building is supposed to be reused or demolished. Therefore one of the main design considerations for temporary transformable structures must be the use of recyclable and non-polluted materials and also the proposed folding and closing mechanism should be devised in such a way that it could reduce wear and tear during transformation process. This is also very important as a temporary structure is supposed to take various functions and be adaptable with different environmental conditions [4].

2.3 Beauty and Functionality

Details should be efficient and simple (the simplest

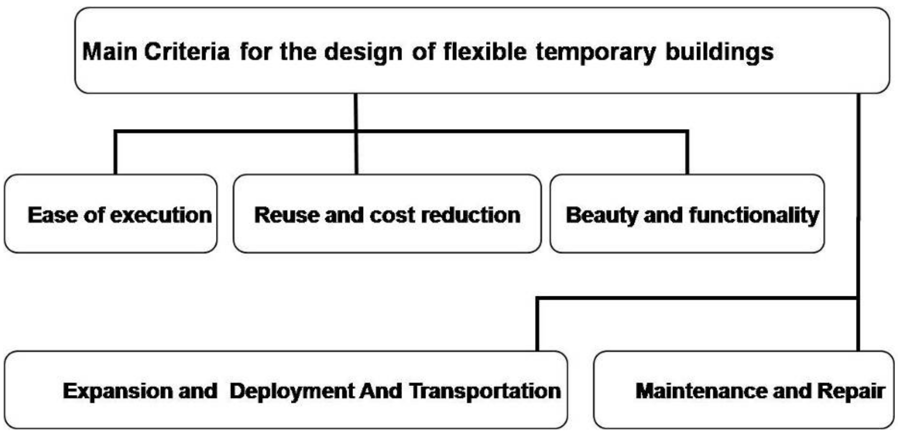


Diagram 1 Main criteria for the design of flexible temporary buildings (authors).

is the best). For creating beauty, there is no need to make up. A temporary structure should be elegantly designed so that when it is erected it is considered as a good piece of architecture, structure and art. A good design in this area should integrate art, architecture, science and functionality together.

One of the key characteristics that can be found in the transformable structures is the dual functionality of the structural elements. They may have both mechanical and structural functions that provide shelter and supports loads, and at the same time the mechanical components transfers loads to create movements (such as patented transformable structures designed by Chuck Hoberman). This feature makes reconfigurable more than just a piece of structure or architecture, but shows that great beauty of this type of structure in an effective marriage among art, science, architecture and engineering that rarely can be found in ordinary structures [3].

2.4 Expansion and Deployment and Transportation

A reconfigurable structure may be designed in such a way that it reaches stable configurations during the folding or deployment process, or just as a deployable portable structure that is stable when fully deployed (usually for temporary applications). Transformable structures may also be used in permanent buildings in which the whole, or part of the structure, is pre-manufactured and shipped to the final location for erection. Structures, when used in temporary situations, have the potential to be used in disparate environmental conditions and varied locations. Furthermore, they should be able to be folded into very small bundles that make them easy to transport and store. The innate property of reconfiguration in architectural transformable structures can create spaces that meet user requirements in an ever-changing world and are therefore an evolution towards dynamic architecture. They should be adjustable to our needs and can change continuously according to owner's needs and styles [3].

2.5 Maintenance and Repair

Transformable architecture, similar to static architecture, requires a carefully planned management and maintenance system in order to guarantee the safety of users and ensure the desired operation of the building, both architecturally and structurally. However, in transformable architecture, due to the nature of transformation which bears repeated opening and closing of the structure, special arrangements should be made to ensure the smooth and reliable movement and articulation of the structural components. Therefore the detailing and the maintenance management strategies chosen must consider the effective and efficient operation of the structure in both open and closed states and during the transformation process. This system should also carefully consider the construction, running costs and maintenance costs of the project [4].

3. Evaluation of Major Transformable Structures Inspired by Nature

Before introducing our proposed model, in this part, some proposals and transformable buildings inspired by natural structures and mechanisms will be evaluated in order to consider the potentials of nature in the development of transformable structures benefited from ease of erection, assembly and repair in a short period of time.

There are developing stacked assemblies formed from rigidly interconnecting expandable plate structure by inspiring from flower constructions in nature (Fig. 1). The connections between individual plates can themselves be volume filling, and therefore the stacked structure can also become an expandable three-dimensional object. As the plate structures from which one starts can have any planar shape, and only simple kinematics constraints have to be satisfied in order for them to maintain their internal mobility in the stack configuration, nearly any shape can be generated, including so-called free-forms or *blobs* [5] (Figs. 2 and 3).

Fig. 4 shows a spherical model shaped by expanding elements which are represented in Figs. 2 and 3. It was constructed using identical plastic plate structures of which four were trimmed so that their outer boundaries form circles of different radius. To rigidly connect two expandable plate structures the motion of the individual plates being connected must be identical. Earlier, the motion of each plate was described as the combination of a radial motion, i.e., a translation and a rotation. Because the rotations in the two layers are equal and opposite, imposing an additional rigid body rotation to the whole structure, equal to the rotation undergone by one of the layers, the motions of the two layers become a pure rotation and a pure translation,

Fig. 1 Rafflesia arnoldii flower as a natural inspired model [6].

Fig. 2 A model of non-circular structure with scissors joint. [5].

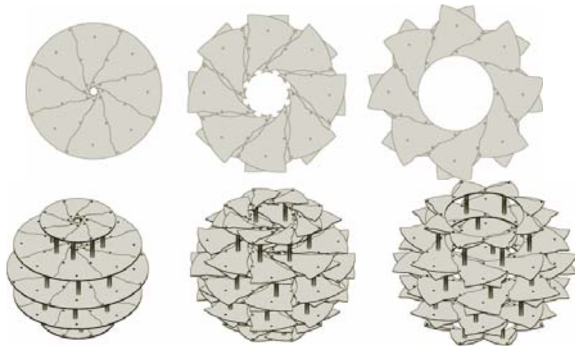


Fig. 3 An expandable circular plate structure. [5].

respectively. [5] According to the main criteria, presented in part 1, this mechanism allows the structure to compact easily and also the modular construction makes the repair process easy and fast.

One of the interesting structures made from foldable plate is the roof system of the Qizhong Stadium (Fig. 5) which is made of 3 parts: (1) A huge spatial steel ring-truss of 123 m diameter; 24 m wide, and 7 m high located on the main reinforced concrete structure. (2) Eight retractable roof systems on the 123 m-diameter spatial ring truss, each having 1 fixed shaft and 3 concentric rail systems. (3) Eight petal-shaped steel pipe roof trusses on the corresponding eight rail systems, and each petal-shaped roof truss is 72 m long, 48 m wide, and has a 61.5 cantilever length [7]. Its opening and closing resembles the blooming of a Flower. The building illustrates the current development in transformable plate structure design that goes beyond converting an indoor space to an outdoor one. It is an example of the potential of spatial frame structures to integrate technology, science and art.

Other type of foldable plate structure, which is inspired from natural constructions such as *hornbeam*'s leaves structure (Fig. 6a), is the leaves develop within a bud where they are protected by several layers of bud scales. In spring the folded leaves emerge, revealing their regular folding pattern [8], this building consists of foldable plastic, glass and other kind of materials. The glass folded plate structure is a new combination of these construction methods, almost without visible steel components. The surfaces are linked by hinges in order to follow the principle of the paper model and to simultaneously reduce the bending stress that lies on the plates [9]. Figs. 7-10 show examples of such structures in this field.

The butterfly's wings and poppy's flower also have similar construction, too (Figs. 6b and 6c).

These compactable geometries make the transportation process easy and fast.

Fig. 4 Expandable sphere. [5].

Fig. 5 Qizhong Stadium in Shanghai, China. [7].

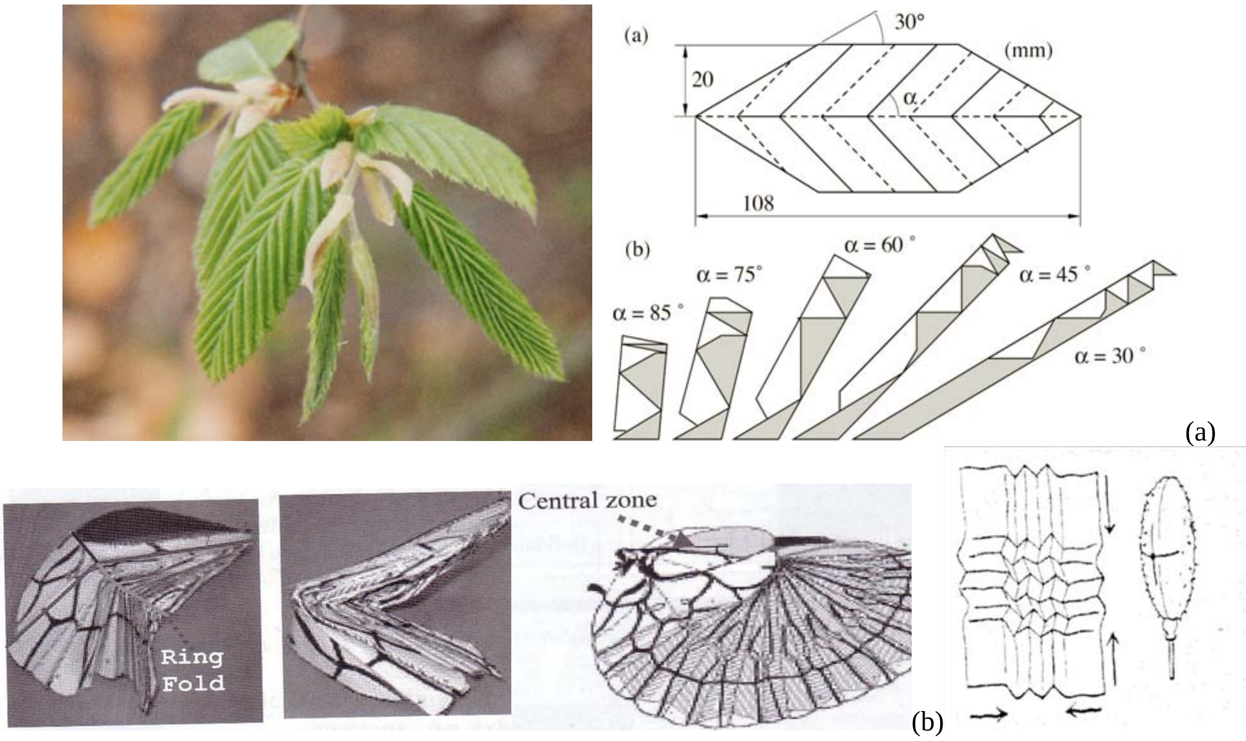


Fig. 6 Natural inspiration for foldable structures: (a) horn beam leaves [8]; (b) butterfly's wings [10]; (c) the poppy petal flower [11].

Fig. 7 Church building with foldable plate [12].

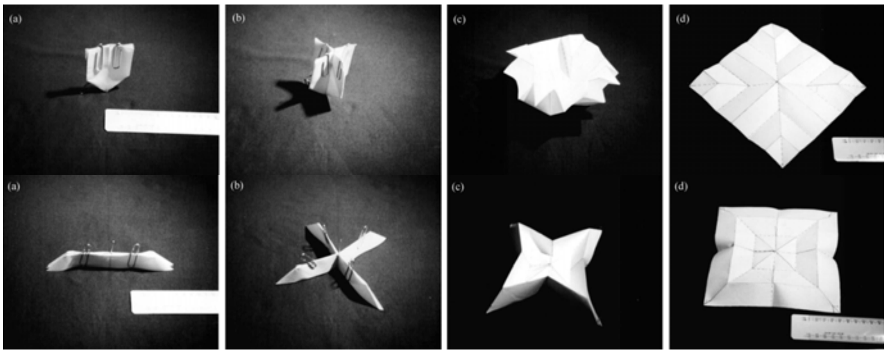


Fig. 8 models of foldable plates [13].

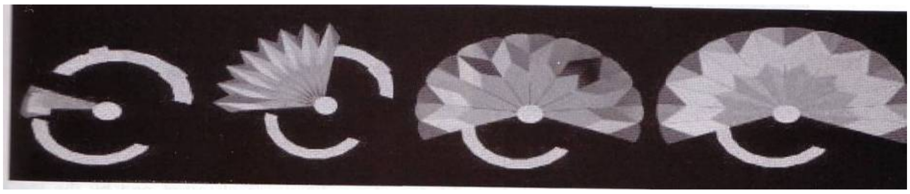


Fig. 9 models of foldable plates [14].

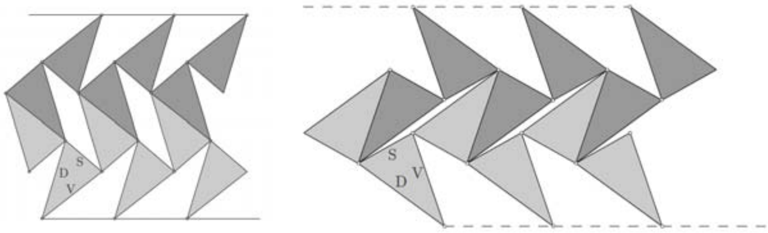


Fig. 10 Models of foldable plates inspired from butterfly wings [15].

Other example in this field is the transformable roof for Starlight Theatre in America (Fig. 12) which is realized that it has been inspired from potato's flower structure. It has usually five or six petals and foldable gussets are between individual petals, as shown in Fig. 11 [16], or other foldable flowers with fixed mid point. Fig. 13 shows other structures for antennas that are inspired from mentioned model.

The structure of bones and muscles of animals and humans can be used in the design of transformable structures. Many architects have used the principles behind these structures in their building designs for example Renzo Piano used spider's leg's form and structure of bird's wings in the Ladybird Travelling Pavilion (Fig. 14) and Santiago Calatrava used nearly the same mechanisms in his design for Kuwait Pavilion (Fig. 15).

The contemplation of the above examples shows the great potential of natural structures, patterns and mechanisms for the design and construction of transformable structures. What is important here is that by direct or abstract use of natural principles, it is not always possible to create a workable transformable structure from an engineering and mechanical point of view, but also nature can direct us to come up with more innovative, artistic, sustainable and functional architectural solutions. The following part of this paper will describe and evaluate a solution proposed by the authors for a transformable, multifunctional and portable structure inspired by nature.

4. Proposed Structure

4.1 Main Concept

The proposed system by the employment of natural principles can meet the main design criteria for transformable temporary structures (as explained earlier) including transformability, rapid instalment, adaptability and to various functions, developability, ease of repair and maintenance. Table 1 shows the new structures capacities in responding to maintained criteria.

The proposed base structure is inspired from potato's flower with triangle parts, as a stable known form. This structure is realised by mixing and arranging triangle models so that a stable and developable structure is created. Fig. 16 shows a wide plan view of the proposed system with its transformation process. As it shows, the structure consists of a central core (4 triangles) and 4 triangle wings (like a general follower structure). This combination of triangular forms makes the creation of various forms with different scales and in different conditions possible. Also these modular constructions facilitate repair process by just changing damaged part.

4.2 Possibilities of Changing the Scale

Every frame shown in Fig. 16 can contain smaller modules (Fig. 17), so it can develop or change its scale. For maintaining the stability of triangle plates, while increasing the module dimension to more than 2 m (base module). They should be built from different base modules, so it is possible to make a structure with bigger dimensions.

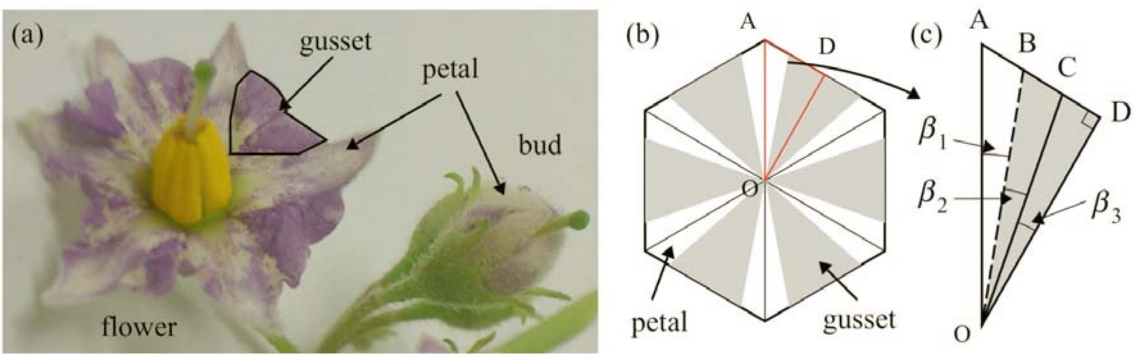


Fig. 11 The structure of a Potato's flower [16].

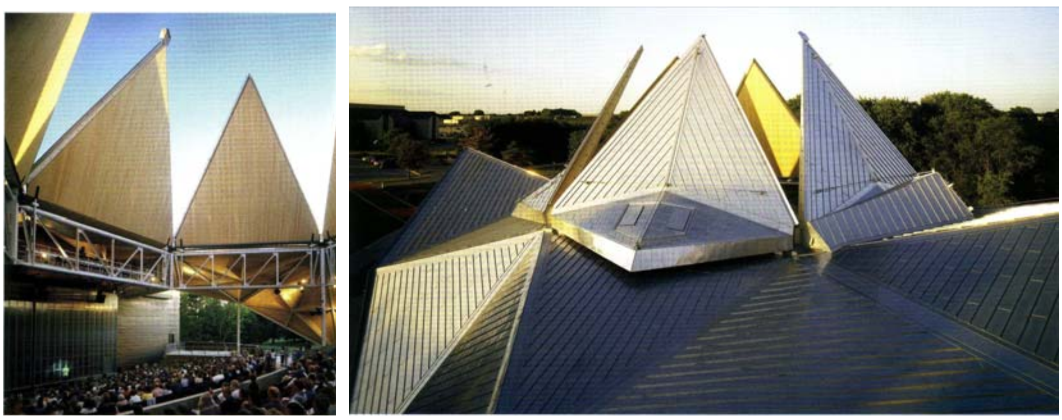


Fig. 12 Starlight theatre USA 2003 [1].

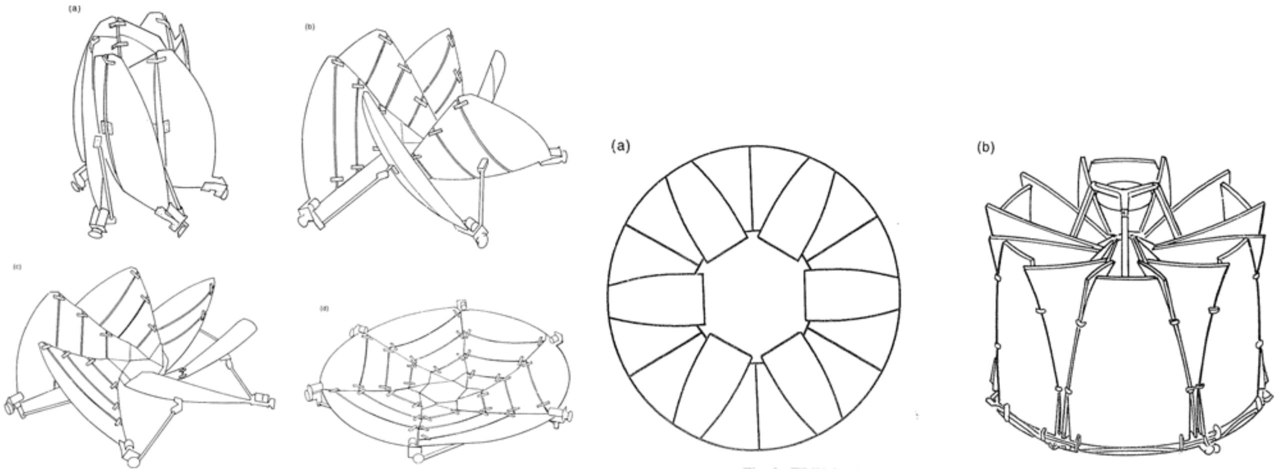


Fig. 13 Models of foldable plates used for antennas [17].

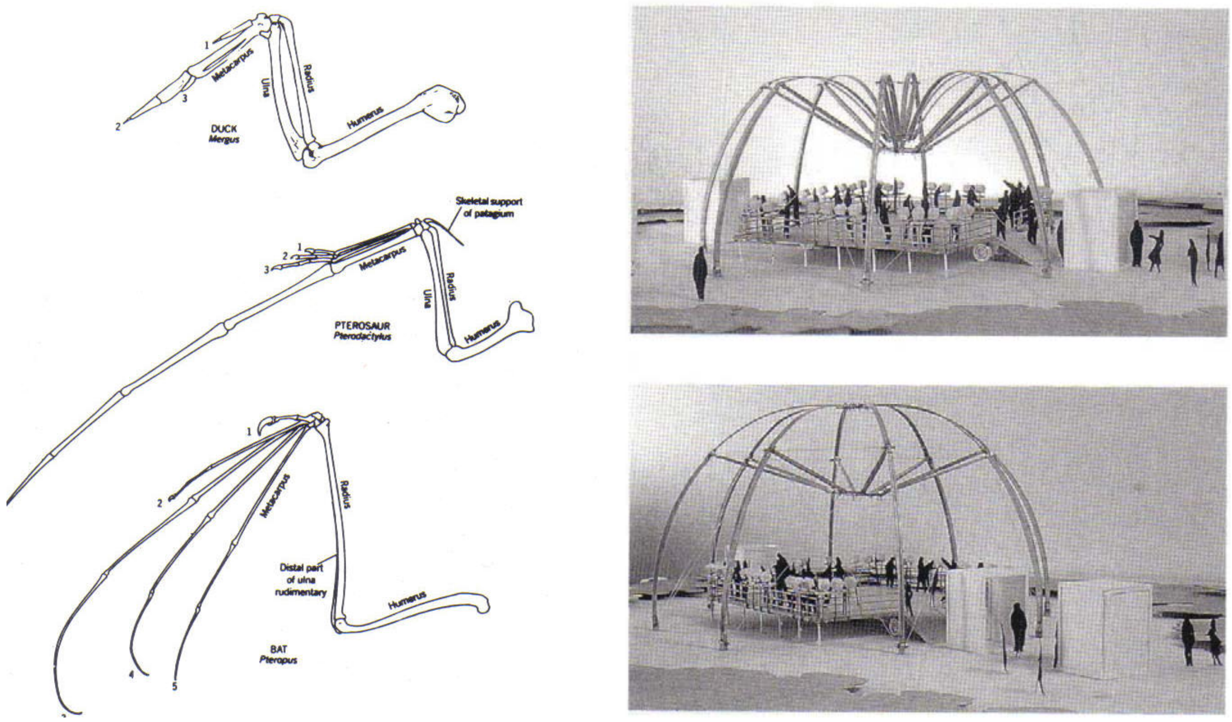


Fig. 14 Renzo Piano pavilion [11].

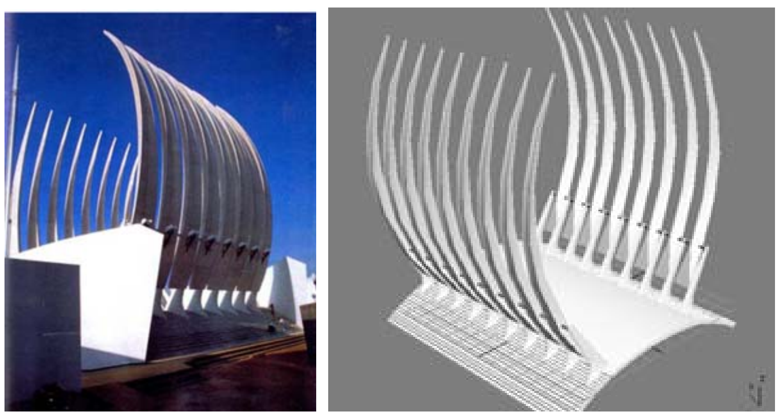


Fig. 15 Kuweit Pavilion by Calatrava [12].

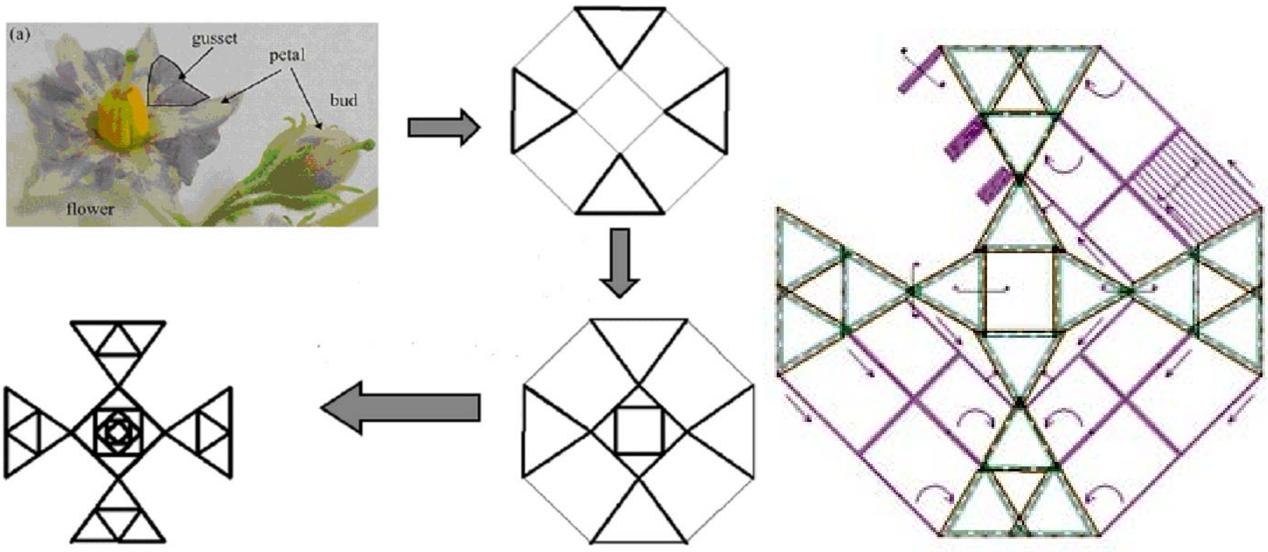


Fig. 16 The shaping process of the proposed structure.

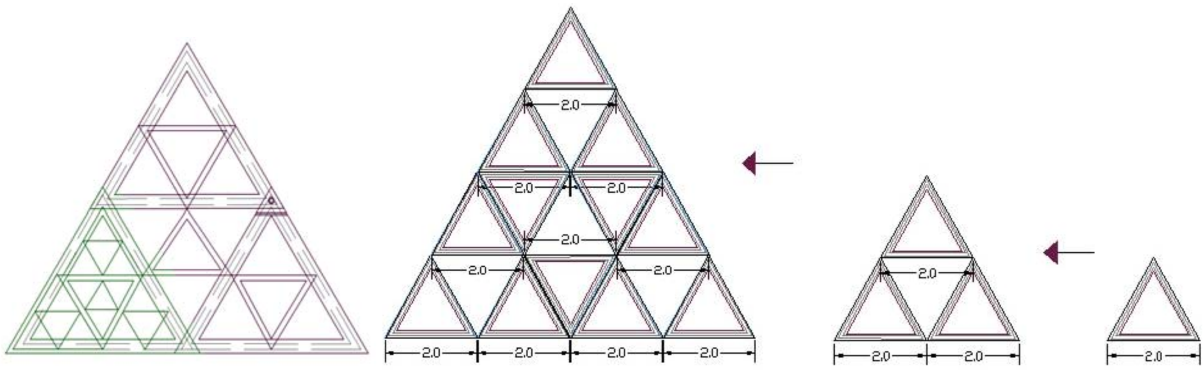


Fig. 17 The process of joining modules to develop the structure's dimensions.

Table 1 Evaluation and analysis of the proposed structure.

Purpose	Methods
Ease of execution	Using modular components and simple connections made the assembly of the structure easy even without the use of experienced workers. Various connection methods and techniques can be applied according to the existing facilities and equipment in destination.
Reuse and cost reduction	1. Transforability and the ability of the structure to take different shapes and configurations make the structure reusable and this in turn reduces the costs of future uses. 2. It is possible to use the structure in various climatic conditions and different layout configuration due to the flexibility and adaptability of structural components and connections. 3. Modular design reduces made costs.
Beauty and functionality	1. The structure incorporates both beauty and functionality with use of modular, transformable elements and also it can adapt with various forms according to user's requirement and expectations.
Expansion and deployment and transportation	1. Modular components and adjustable connections makes it possible to realize different shapes, configuration and scales.
Maintenance and repair	2. The damaged and defective parts can be easily repaired or replaced due to ease of connections and modularity of the structure.

4.3 Proposed Materials

For small dimensions the structure can be made of composite triangular plates, MDF or rollable intelligent skins. It is also possible to make each triangle as a hollow wooden or metallic frame filled with different materials ranging from glass to wood, steel and polymeric fabrics (Fig. 18). In current design, the second method was used due to better influence in the performance of the structure, ease of installation and the ability to accommodate with different climatic and formal conditions.

4.4 Detailing and Connections

To allow circulation, all the parts are connected by articular connections (Fig. 19).

In order to allow the movement in the third dimension (Z axis), hinge connections, which can be found on spiders legs or bird wings construction (Fig. 9), are used at the end of all triangular plates (Fig. 20).

In order to fix the corners depends on various existed technical conditions, two different connections are suggested:

(a) Using the former spring form with ability to set in height and slope in the center of upper plate (Fig. 20a).

(b) Using circular elements with different fixed point which is showed in Figs. 20b and 21.

The second method can be erected in various angles and it is more adaptable than the first one.

4.5 Transportation Methods

Two methods can be realized for the folding and compacting of the structures for easy transporting. In the first and the simplest one, all of the elements can be disconnected from the structure and then they can be stacked on top of each other for transportation and future uses. In the second technique, due to the specific connection and hinges that allows the triangular frames to rotate in three dimensions, it is possible to transform the structures into a very compact state as showed in Fig. 22. Therefore the structure can be easily transported or stacked for future uses and it minimize the cost and the time of packing and transportation. In these way triangular frames, connected to the main core, can two by two be circulated and folded on core so that the volume of the structure is minimized into one-third of its first dimension. While the second way is more efficient for small-scale structures, say 100 sqm space, for bigger structure due to more complexity, the first way, seems to be more workable. The transportation system depends on the projects scale it can be a car for small scales to air plane for large scales.

4.6 Methods and Materials for Filing the Gaps

After making the structure, there are gaps in between the plates that must be covered in order to create a fully closed structure. There are different methods for covering these spaces, including the use of flexible materials like fabric and membranes and some light and movable materials which are made of temperate insolate polymers with light-controlling capacity. For this structure, a polymeric membrane with 1 m wide

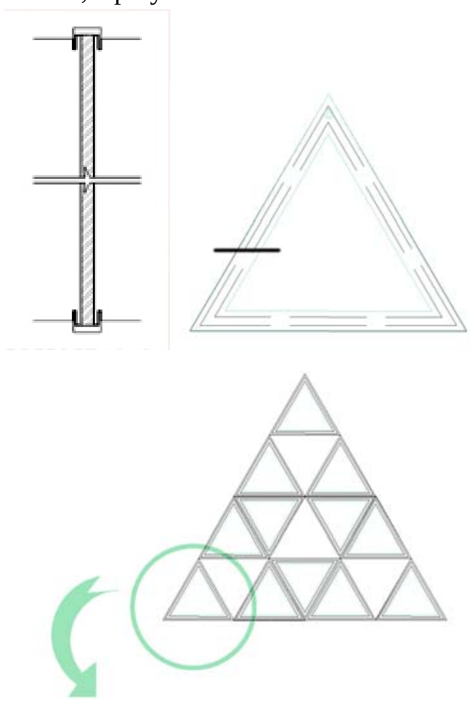


Fig. 18 Frames and methods of plate's installation.

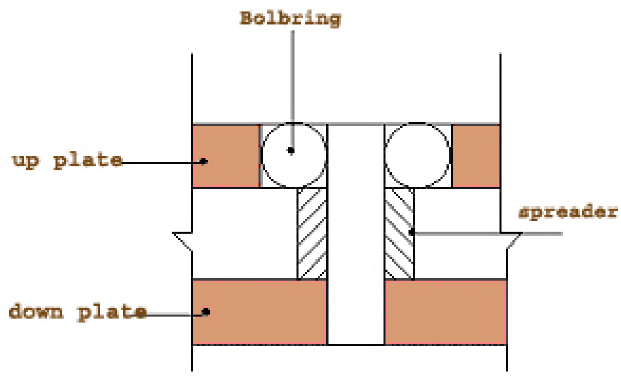
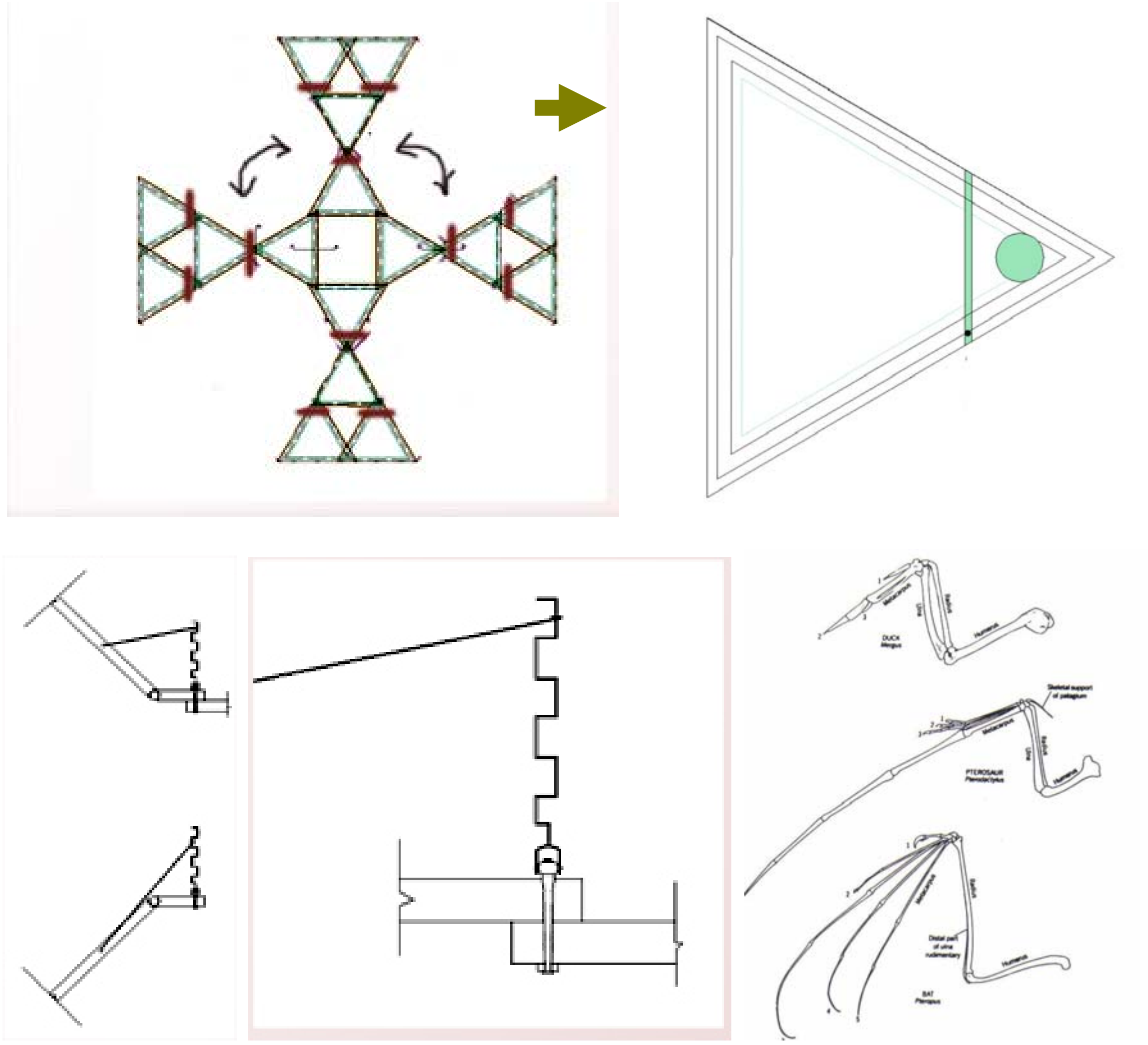
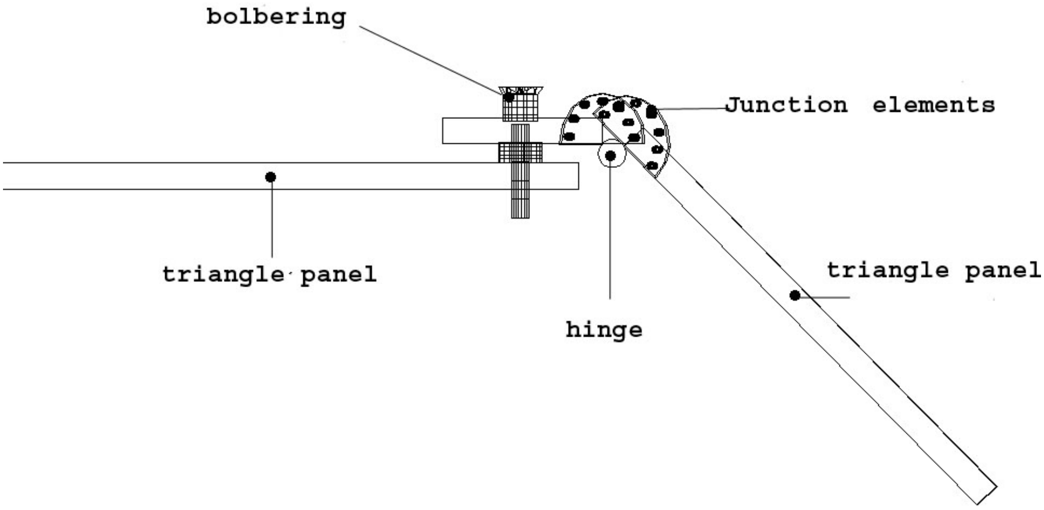


Fig. 19 Plate's connections.



(a)



(b)

Fig. 20 The types of proposed connections for installing plates.

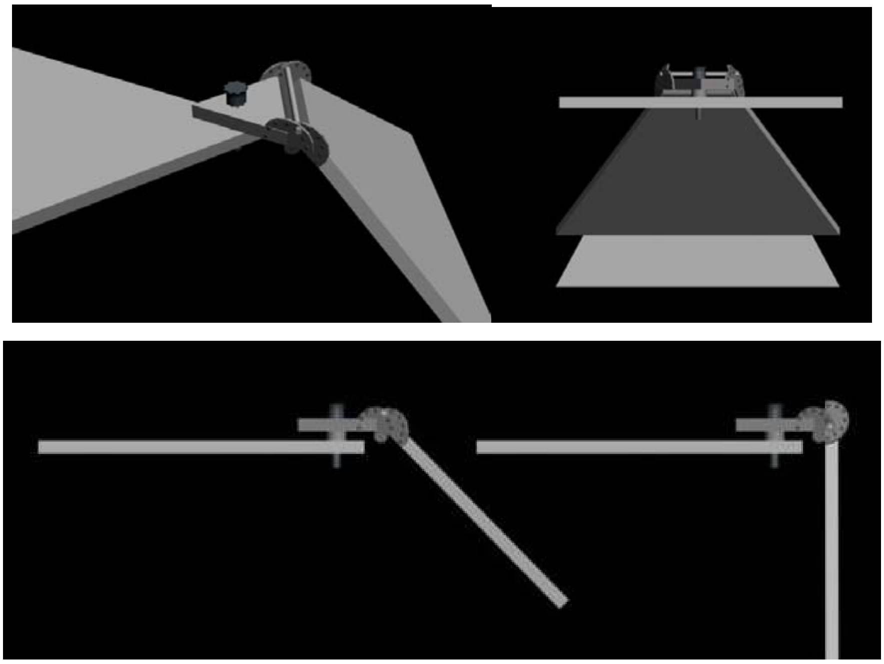


Fig. 21 The methods of connecting neighbor elements.

and changeable length according to the size of the structure as showed in Fig. 23, is used. This frame acts like a spool and regulate the membrane size according the gaps' size (Fig. 24). The frames as shown in Fig. 25, with the ability to being opened and closed, are applied between two covers to fix them.

4.7 Structural Form Variations

The proposed structure can make different forms according to their performance dimensions, grand slope, space's function and etc. Some possible realization can be seen in Figs. 26 and 27.

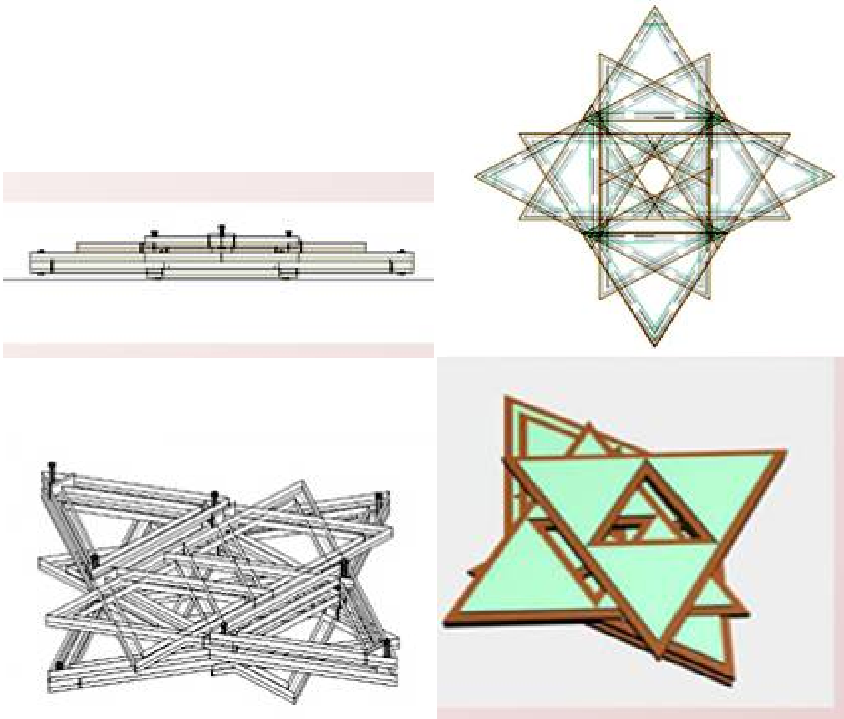


Fig. 22 Folding methods and configurations.

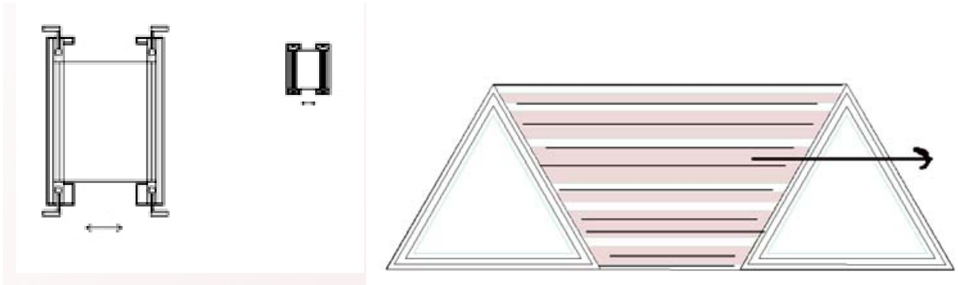


Fig. 23 Covering plates with the ability to open and close.

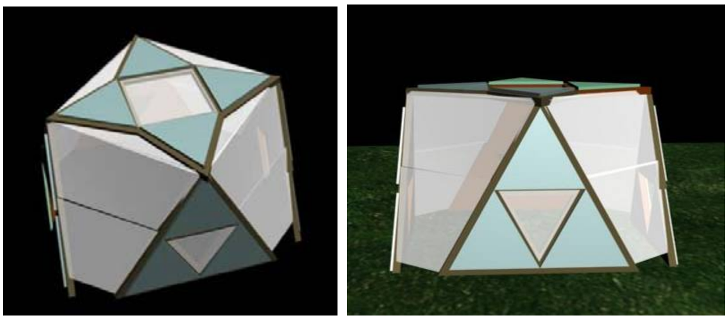


Fig. 24 A covered sample with membranous plates(shown in Fig. 18).

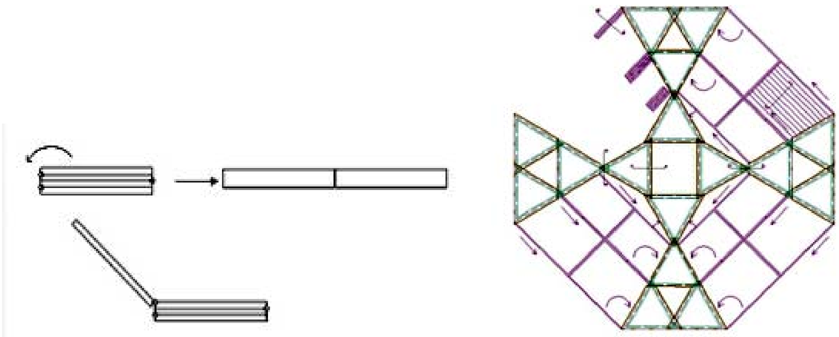


Fig. 25 Additional frames.

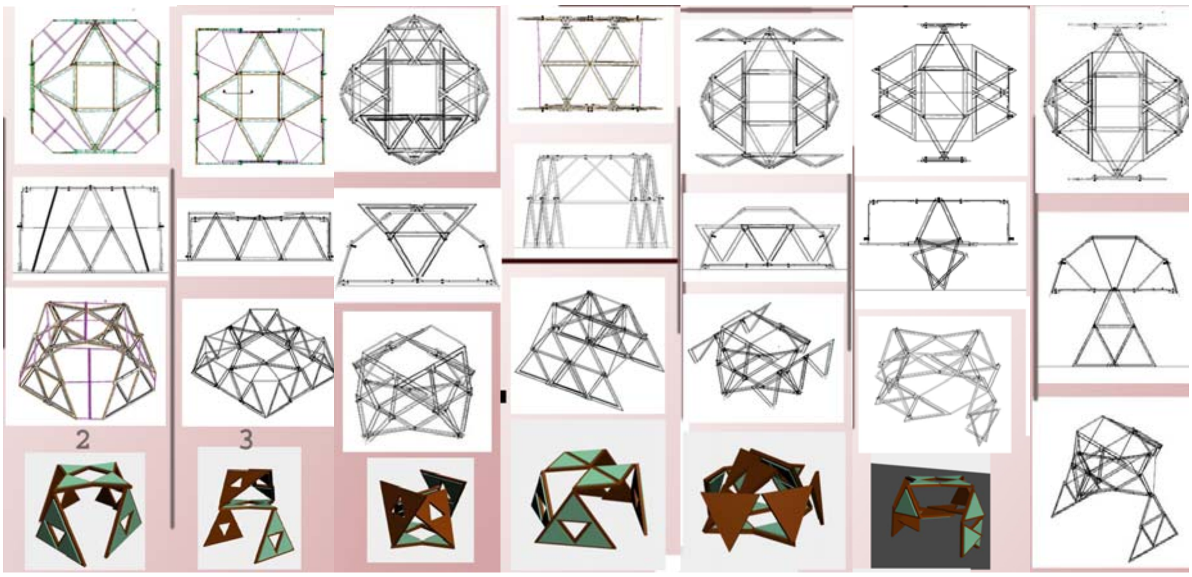


Fig. 26 Form variations of a single model.

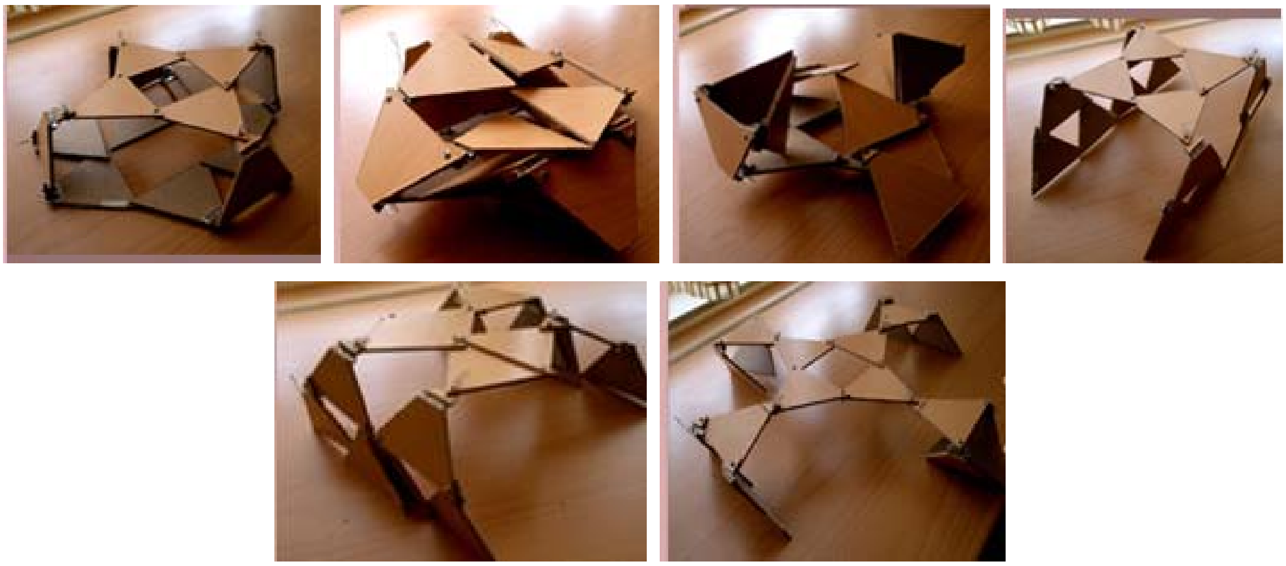


Fig. 27 Model images.

5. Conclusion

The proposed structure can take different shapes and configuration and is able to be quickly assembled and disassembled for temporary applications. This structure can be built up in different topographical conditions, and due to its re-configureablity and movement of its elements, it is able to meet different performances and functions. The main features and characteristics of this structure are concluded in Table 1.

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