INAUGURATION LECTURE

FREE- FORM LIGHTWEIGHT STRUCTURES IN ARCHITECTURE

NEKONVENČNÉ FORMY ĽAHKÝCH KONŠTRUKCIÍ V ARCHITEKTÚRE

doc. Ing. SABAH SHAWKAT, Ph.D.

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

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FACULTY OF CIVIL ENGINEERING

INAUGURATION LECTURE

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PREDSLOV

Dynamický vedecko-technický pokrok posúva hranice technicky nemožného. Konštrukčné a technologické metódy dnes často určujú architektúru budov. Nové technológie nám umožňujú realizovať konštrukcie, ktoré majú väčšie rozpätia a sú čoraz ľahšie. Tieto ľahké konštrukcie predstavujú vysoko estetické formy, založené na rovnováhe síl, ktoré na ne pôsobia. Patria medzi obľúbené architektonické formy dnešného staviteľstva a dizajnu - oslovujú najmä netradičným riešením a výnimočným tvarom. Strácajú sa rozdiely medzi dizajnom, konštrukciou a jej charakteristickou formou.

Ľahké konštrukcie možno vidieť v rôznych podobách v širokom spektre využitia v architektúre, strojárstve aj stavebníctve. Sú vysoko cenené pre svoj jemný estetický vzhľad a inovatívny charakter. Ľahké konštrukcie môžu byť vnútorné, vonkajšie, trvalé, dočasné, veľké, malé, podopreté, atď. Ich jedinečné formy hrajú dôležitú úlohu v súčasnej architektúre a dizajne od doby, kedy sa prvýkrát objavili ako súčasť tvorby svetoznámeho nemeckého architekta a inžiniera Otta Freia (za počiatočné dielo sa zvykne považovať pavilón na svetovej výstave v Montreale postavený v roku 1967).

Navrhovanie ľahkých konštrukcií je zložitá úloha. Splnenie všetkých technických kritérií a zároveň vnesenie krásy a elegancie do priestoru si vyžaduje úzku spoluprácu architekta a inžiniera. Každá časť je viditeľná a konštruktívna, pričom dôležité je správne fungovanie všetkých častí.

V súčasnosti sú ľahké konštrukcie neoddeliteľnou súčasťou architektonickej tvorby. Pretvárajú priestor svojim netradičným riešením, výnimočným tvarom, ale aj jemnou a elegantnou kvalitou. Koncept ľahkých konštrukcií zahájil aj novú diskusiu vo vzdelávaní. Jej cieľom je zvýšiť záujem o túto tému medzi študentmi architektúry a iných príbuzných odborov. Fyzické modely a ich transformácia do reálnych konštrukcií slúžia ako nástroj pre študentov na rozvoj kritického myslenia a tvorivého prístupu k modelovaniu. V prezentácii nových možností pri navrhovaní vidíme prínos pre študentov architektúry, ale aj architektov, statikov a interiérových dizajnérov, pretože inovatívne formy a postupy môžu poslúžiť ako inšpirácia pre kreatívny dizajn a koncepciu diela. Koncept ľahkých konštrukcií a nekonvenčných stavieb často nie je zahrnutý v osnovách architektonických škôl.

Ľahké konštrukcie sú zaujímavé najmä pre potreby architektov alebo dizajnérov v oblasti „Free-Form Finding“. Toto anglické slovné spojenie používané v architektúre by sme mohli preložiť ako "nájdenie voľnej formy". Ide o proces, ktorý sa využíva pri navrhovaní diel, budov a stavieb, kedy pracujeme s neštandardnými a organickými tvarmi, ktoré sa nezakladajú na klasických geometrických obrazcoch. Týmto spôsobom vznikajú jedinečné a nezvyčajné architektonické konštrukcie, typické napríklad pre moderné budovy a mestské oblasti.

Koncept "Free-Form Finding" v architektúre teda chápeme ako vytváranie organických tvarov a foriem, ktoré nie sú obmedzené striktnými pravidlami a predpismi geometrie. Tieto organické tvary sú vytvárané tak, aby rešpektovali kontext a potreby stavby, ako aj prírodné prostredie, v ktorom sa dielo alebo stavba nachádza.

Prezentované diela v prednáške, vytvorené v rámci konceptu "Free-Form Finding", sú výsledkom mojej vedeckej a umeleckej činnosti za posledných 15 rokov. Vychádzajú z podstaty tvorby ľahkých konštrukcií, ktorej základom je približovanie sa k prírode, prírodným javom a fyzikálnym zákonom. Tieto konštrukcie a formy sa v priebehu rokov vyvíjali a neustále napredujú vďaka pokrokom v oblasti materiálov a technológii. Typickým znakom dnešnej architektúry je jednota funkcie, štruktúry a formy. Konštrukcia alebo stavba navrhnutá logicky, v súlade so zásadami pozemného staviteľstva, je zároveň stavbou estetickou, ktorú zvykneme nazývať „pekná architektúra“.

Ďakujem za spoluprácu pri kreatívnej tvorbe mojim milým kolegom z VŠVU a Fakulty architektúry STU v Bratislave. Rovnako chcem poďakovať za podporu a pomoc svojej rodine a priateľom.

PREFACE

Dynamic scientific and technical progress pushes the boundaries of the technically impossible. Construction and technological methods often determine the architecture of nowadays buildings. New technologies allow us to realize structures that have larger spans and are more and more light. Lightweight structures represent highly aesthetic forms, based on the balance of forces acting on them. They belong to the popular architectural forms of today's construction and design - they appeal especially with their non-traditional solution and exceptional shape. The differences between design, construction, and its characteristic form are disappearing.

Lightweight structures can be seen in various forms and variations in a broad spectrum of use in architecture, engineering as well as building construction. They are highly appreciated for their subtle aesthetic appearance and innovative character. Lightweight structures can be internal, external, permanent, temporary, large, small, supported, etc. Their unique forms have played an important role in contemporary architecture and design since they first appeared as part of the work of the world-famous German architect and engineer Otto Frei (the pavilion at the World's Fair in Montreal built in 1967 is usually considered the initial work).

Designing lightweight structures is a complex task. Fulfilling all technical criteria and at the same time bringing beauty and elegance to the space requires close cooperation between the architect and the engineer. Each part is visible and constructive, while the proper functioning of all parts is important.

Nowadays, light constructions are an integral part of architectural creation. They transform the space with their unconventional solution, and exceptional shape, but also with their fine and elegant quality. The concept of light construction also started a new discussion in education. Its goal is to increase interest in this topic among students of architecture and other related fields. Physical models and their transformation into real constructions serve as a tool for students to develop critical thinking and a creative approach to modeling. In the presentation of new design possibilities, we see a benefit for students of architecture, but also architects, structural engineers, and interior designers, because innovative forms and procedures can serve as inspiration for creative design and conception. The concept of lightweight structures and unconventional buildings is often not included in the curriculum of architecture schools.

Lightweight constructions are especially interesting for the needs of architects or designers in the field of "Free-Form Finding". It is a process that is used in the design of works, buildings, and constructions when we work with non-standard and organic shapes that are not based on classic geometric shapes. In this way, unique and unusual architectural constructions are created, typical, for example, of modern buildings and urban areas.

We, therefore, understand the concept of "Free-form Finding" in architecture as the creation of organic shapes and forms that are not limited by the strict rules and regulations of geometry. These organic shapes are created to respect the context and needs of the building, as well as the natural environment in which the work or building is located.

The presented work created within the concept of "Free-form Finding" is the result of my scientific and designing activity over the past 15 years. It is based on the essence of creating light constructions, the basis of which is getting closer to nature, natural phenomena, and physical laws. These designs and forms have evolved over the years and continue to advance thanks to advances in materials and technology. Contemporary buildings are a synthesis of two concepts: Art and structure. A construction designed logically, in conformity with the principles of structural engineering, is at the same time an aesthetic construction, one that we tend to call "nice architecture".

Keywords:

Anti-gravity; Biomimicry; Free-Form; Form-Finding; Grid Shells; Lightweight Structures; Membrane Structures; Parametric Design; Tensile Integrity Structures; Tessellation; Topology; Voronoi Design

All the models shown in this work have been made by the author

INTRODUCTION

By observing nature and the surrounding world, the spectator may discover that the only straight lines that surround him are those established by a man. The perfection of the time of straight lines and straightforward geometric shapes or Euclidean geometry in design was the period of cubism, constructivism, and functionalism. An attempt to free objects from shapes that are based on straight lines followed. One of the main representatives of this concept was in the second half of the 20th century the famous architect Le Corbusier with his celebrated quote “Form follows function”, saying that the form is subordinated to the function.

Later, Le Corbusier's "Form follows function" was changed to Frei Otto's "Form follows force", which means the form is subject to the course of forces. Otto's postulate "Form follows force" suggests that a structure's shape should be determined by the forces it needs to resist, rather than just aesthetic considerations. In other words, the structure should dictate the form of the architecture, rather than the other way around. This idea was further developed in Otto's concept of "natural architecture", which emphasized the use of lightweight materials and organic forms inspired by nature. He believed that by studying natural forms and processes, architects and engineers could create more efficient and sustainable structures that harmonize with their environment.

Most of us became familiar with Euclidean geometry during our studies, but we never learned non-Euclidean geometry unless we started studying math or science. The freedom that architects have gained after liberating themselves from linear conventions is now leading to "geometric anarchy", which is manifested in the design of so-called "free-form" geometry, which presents in contemporary architecture the modern mathematics of curved surfaces. Free-form shapes have no analogy in nature, and they can’t be exactly described mathematically. Complex object geometries require a new approach in the engineering part of their design. Form improvement provides a very interesting approach between artistic expression and structural engineering. A particular task of construction form of non-conventional structures is form-finding. Physical modeling of structures was used in their work by builders such as António Gaudi, Heinz Isler, and Frei Otto.

With the development of computer technology, numerical methods based on finding the shape and modeling of the equilibrium state have also begun to develop geometrically nonlinear problems. Physical models (form models) are used to describe the power of the variability and beauty of these structures to achieve the fine art of non-traditional structures. Working with physical modeling is a very powerful tool for the exploration of three-dimensional structural forms. It opens a new space and makes the relationship between structure and form easily comprehensive.

Structural designers together with architects analyse, discuss, and improve to create new forms, whether traditional or parametric to invent progressive construction processes as well as production technologies and thus enrich our society with new designs.

GOAL

The aim of non-conventional free-form geometry in architecture is to explore new and innovative ways to create structures that are not limited by traditional geometric shapes. By incorporating the principles of tensegrity, tensile structures, grid shells, biomimicry, topology, tessellation, and Voronoi design, architects can create buildings that are not only visually striking but also highly functional and sustainable.

Tensegrity structures, for example, use a system of compression and tension to create stable and flexible forms that can be adapted to a variety of architectural applications. Tensile structures, on the other hand, use tensioned membranes to create lightweight and flexible forms that can be used to create everything from shade structures to large-scale canopies.

Grid shells, which are made up of a series of interconnected geometric shapes, can be used to create complex and intricate forms that are both structurally sound and visually stunning. Biomimicry, which draws inspiration from the natural world, can be used to create structures that are not only beautiful but also sustainable and efficient. Topology, tessellation, and Voronoi design, meanwhile, offer a range of geometric principles that can be used to create complex and intricate forms that are both visually striking and highly functional. By incorporating these principles into their designs, architects can create buildings that push the boundaries of conventional architecture and offer new and innovative solutions to the challenges of the built environment.

The major goals of our work can be summarized in the following points:

- Show how to create physical models of non-conventional structures such as tensegrity systems, tensile membrane structures, and nonconventional free-form geometry simply in a stylish way (suitable as components for interior design as well as for public spaces).
- Find a feasible form-finding geometry process in architecture.
- Analyse the process of thinking using parametric programming, and parameterization of free-form geometry.
- Emphasize the importance of integrating structural considerations into architectural design, and viewing architecture and structure together as one integrated concept.

1. LIGHTWEIGHT STRUCTURES

Lightweight structures can bring beauty and elegance to the space. They are seen in various forms, shapes, sizes, and variations in a wide range of applications. They transform the space through their unconventional solutions, unique shape, as well as subtle and elegant quality. The smaller the ratio between a structure's dead load and the supported live loads, the "lighter" the structure [1].
Designing and forming lightweight structures is not an easy task due to the small ratio of the structure's self-weight to the live load compared to traditional structures where the ratio is much higher. Lightweight structures, in place of the stiffness of the material, derive their resistance from their shape and may therefore be denoted as shape active. One of the main design steps of lightweight constructions is therefore the design of a shape that is controlled by the required stress state.

The advantage of lightweight structures is that all forces are nicely visible [3]. Forces are a mechanical concept useful for engineers who want to size their structures and they are by nature visible.

From an ecological, social, and cultural perspective, lightweight structures have never been more contemporary and necessary than today. Physical models of pedestrian bridges shown in Fig. 1.1 and Fig. 1.2 are an example showing the relationship between art and structural engineering [2]. By differentiating cables and struts, the model of the footbridge provides information on whether tension and compression are present. Therefore, the dimensions of the components such as tubes size, and the arrangement of cables depend upon the material properties as well as on the level of tension, resp. compression state. Steel and prestressed concrete enabled us to embody the lightweight ideal in structural design. This type of parametric bridge is a wonderful example of this. The structural system of the cable-stayed bridge or suspension bridge is well suited to this desire: by decreasing the distance between the cable supports, the deck can be made slenderer as the bending moments are reduced. As seen in the figures, lightweight tensegrity structures are fascinating as gravity seems to be absent and the structure looks as if floating in the air. Cable-supported bridges, which can be built in a great variety of forms and with considerable elegance, have undisputed potential.

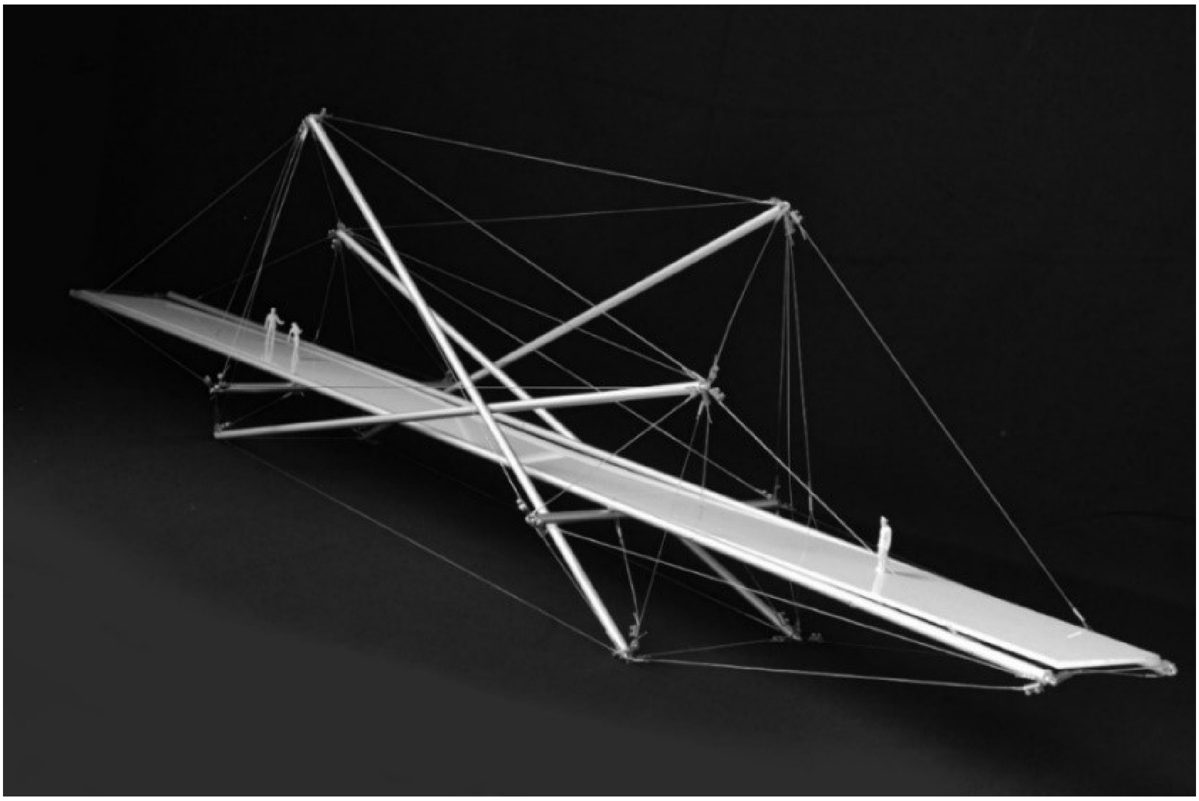


Fig. 1.1. Pedestrian Tensegrity Bridge I. (model created by the author)

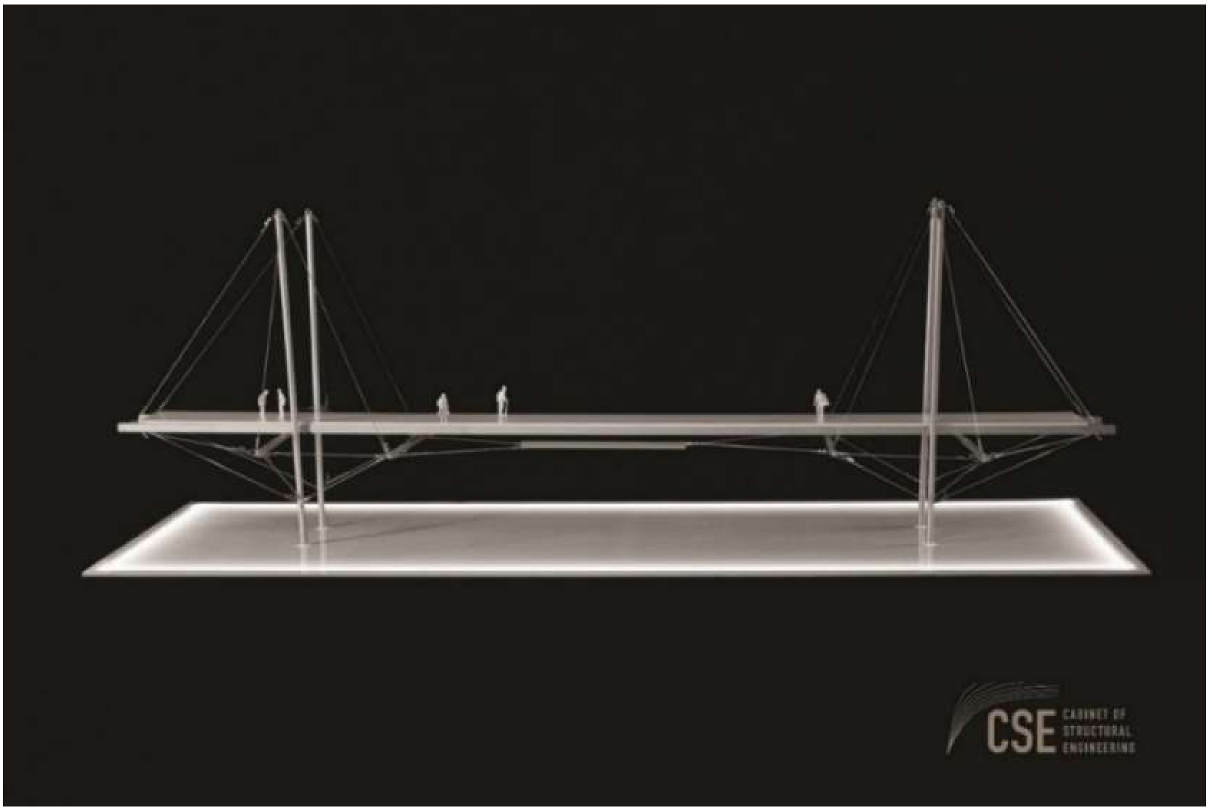


Fig. 1.2. Pedestrian Tensegrity Cable-Stayed Bridge II. (model created by the author)

1.1 TENSEGRITY STRUCTURES

According to their characteristics, lightweight structures can be divided into several subgroups, one of them being tensegrity structures. Tensegrity is a design principle that applies when a discontinuous set of compression elements is opposed and balanced by a continuous tensile force, thereby creating an internal prestress that stabilizes the entire structure. Tensegrity is based on the use of isolated components in compression inside a net of continuous tension, in such a way that the compressed members (usually bars or struts) do not touch each other, and the prestressed tensioned members (usually cables or tendons) delineate the system spatially. The tensegrity concept offers a high level of geometrical and structural efficiency when the external load acting on construction is transmitted to all elements of the structure in the same way. Once the external force is removed the elements will return to their original shape.

The mechanical stability of structures does not depend on the strength of individual parts but on the whole structure distributing and balancing mechanical strain. Vibration in one part of the structure causes vibration in all other parts [5].

As already mentioned tensegrity structures are a particular class of lightweight structural systems. Tensegrity systems were introduced approximately in the middle of the 20th century through the work of Fuller and Snelson [4,7]. The word tensegrity was coined by Fuller in the 1960s, by combining the words tension and integrity [6,7]. Richard Buckminster Fuller (1895 - 1983) was an American engineer, architect, inventor, and futurist. He developed the famous Geodesic dome, a spherical form in which lightweight triangular or polygonal facets consisting of either skeletal struts or flat planes, largely in tension, replace the arch principle and distribute stresses within the structure itself. Kenneth Duane Snelson (1927 – 2016) was an American sculptor and photographer. He was one of the first to build tensegrity sculptures and he defined tensegrity as a closed structural system composed of compression struts within a network of tension tendons. He liked to describe his tensegrity sculptures as floating compression. Snelson considered tensegrity as a connection between architecture and art. Fuller's basic model of tensegrity patent has quotes of element length, but no indication of how lengths would be proposed. Probably the lengths were then calculated and parameterized, as measured by the length of the elements of the finished structure.

The main shortcomings and problems of the practical application of tensegrity technology for the practice these artists have identified are:

1. Low load response - relatively high deformation and low material efficiency compared to conventional, geometrically rigid structures.

2. The complexity of the production of details - spherical and domical structures are complicated to produce details of joints as well as the selection of suitable material for their realization, which can lead to production difficulties.

In other words, in a tensegrity structure, the two types of forces in nature, tension, and compression are completely separated and you can see them in their pure state. Where there is a strut, there is pure compression; and where there is a cable, there is pure tension.

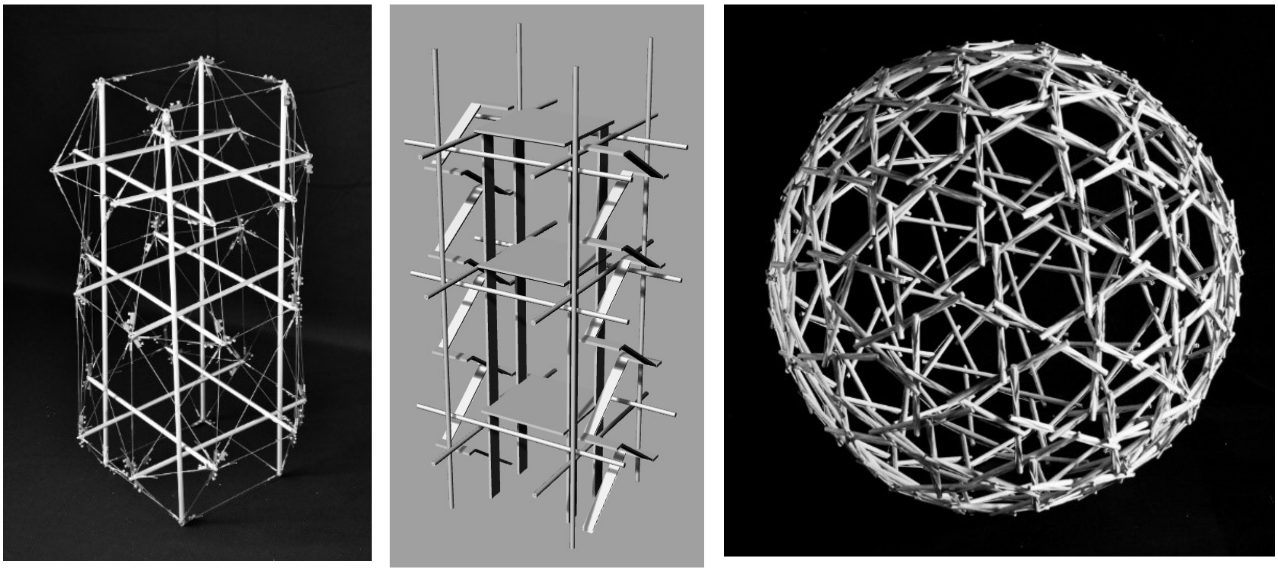
We can describe the characteristics of a tensegrity structure as follows:

- The structure is free-standing, without any support.
- The structural members are straight.
- The struts do not contact each other at their ends.
- The response to the loads is nonlinear.

French architect and engineer David George Emmerich (1925 – 1996) added the condition of a self-stress state: Tensegrity structures consist of rods mounted in such a way that the struts remain physically isolated in a continuous set of cables [8]. Fig. 1.1.1a, b shows physical models of two tensegrity structures with no direct contact between the compression elements: a high-rise building of rectangular shape and a shell geodesic dome based on the idea of Fuller [9].

The term “geodesic” describes in geometry a curve representing the shortest path between two points on a surface. A geodesic structure consists of as many struts of the same length as possible as well as congruent surfaces. It is a network of equal triangles whereby the cross points are always situated on the surface. This triangulation guarantees the strength and rigidity of the ball-shaped structure. The struts can be combined into triangles, pentagons, or hexagons, whereby each strut is aligned in a way that each connection point is held in a firm position. This guarantees the stability of the whole structure. Tension is distributed equally to all parts of the whole construction. Increased tension in one part provides increased tension in all parts. A global increase in tension is balanced by an increase in tension in various parts. Whilst tension is thus distributed evenly in the whole system, only individual parts are balanced by compression.

Both types of structures depicted in Fig. 1.1.1.a, b use separate elements for tension and compression. In our models, struts are made of aluminium or wood and tendons represent nylon or steel cables.



1.1.1a 1.1.1b

Fig. 1.1.1.a, b Tensegrity Tower and Geodesic Tensegrity Dome (models created by the author)

There are several problems associated with tensegrity systems, and the primary one is the geometry of the structure. The self-stressed equilibrium of the structure is determined by the form-finding method. Since much of the ideas on tensegrity structures have been developed based on existing identification with nonlinear geometrical behaviour, it also follows that the challenges identified are also on the same track.

Firstly, analytical form-finding methods need to be developed. Without the proper analytical form findings methods, it would be impossible to understand high-order tensegrity structures. Secondly, form-finding for arbitrary tensegrity structures is seen to involve only a little knowledge of structure. This is especially the case with structures such as spheres, cylinders, and others. There are challenges in simultaneous form-finding, also there are constraints in understanding the member length and axial stiffness parameters. Sometimes, the advancement in the context of parameter identification poses a challenge as well. In form-finding of assemblies, there are difficulties in identifying the known tensegrity units and the unknown tensegrity grids. Contrary to developing and optimizing structures using intuition and experimentation, form-finding is the determination of the design of the tensegrity geometrical configuration analytically. The configuration found should also keep the tensegrity structure in a state of equilibrium. Form-finding studies have been carried out on tensegrity structures from the early research studies of Fuller and Snelson [4,7]. The tensegrity structures that they formed were mostly convex polyhedron based. They used this geometric research to understand the existing structure and understand how to formulate newer configurations if possible.

Tensegrity structures can be seen as “internally pre-stressed, free-standing pin-jointed networks, in which the cables or tendons are tensioned against a system of bars or struts.” This description introduces the fact that the system is pre-stressed and pin jointed. This implies that there are only axial forces present in the system and there is no bending or torsion. The tensegrity concept offers a high level of geometrical and structural efficiency and results in modular and lightweight structures. When the external load acting on construction is passed on from one element or place to another element of the structure finds a new form.

Fig. 1.1.2. shows some of the author´s physical models of the series called "Tensegrity Land" which were presented at an exhibition at the Faculty of Civil Engineering of the Czech Technical University in Prague in 2019 [10]. These tensegrity structures can serve as table lamps.

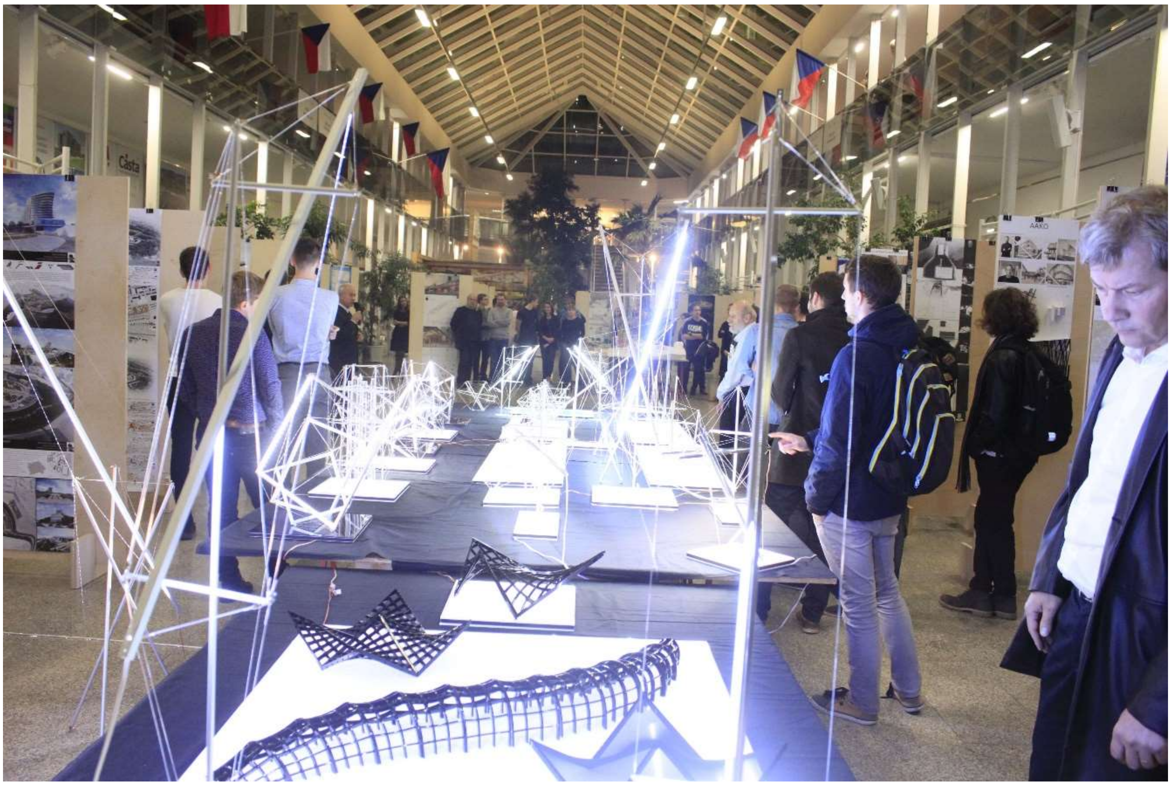


Fig. 1.1.2. Tensegrity Land (models created by the author)

One of the most elegant tensegrity forms is a three-struts T-prism. The tension of the cable is applied to each strut (compression) element. As it is a three-dimensional system, at each end of the strut we should have at least three cables in tension attached to the node to ensure the stability of the entire structure. Based on this principle, we created a triangular tensegrity prism that can serve as a nice hammock for public space which is depicted in Fig. 1.1.3. [9].

Fig. 1.1.3. Orthogonal Triangular Tensegrity Prism (models created by the author)

All members of a tensegrity structure are axially loaded. Generally, members that experience deformation in two or three dimensions are much harder to model than members that experience deformation in only one dimension. Hence, increased use of tensile members is expected to yield more efficient structures.

According to literature, the 3-strut T prism was probably first made either by a Lithuanian artist Karl Ioganson around 1920 or by Fuller´s student named Ted Pope at the University of North Carolina in the early 1950s [7,8]. As it is a three-dimensional system, at each end of the strut we should have at least three cables in tension attached to the node. This is also observed by Snelson: “I know I need a minimum of three cables on any end of any stick” [7]. The resultant of each triad of forces at each node, added to the relatively small weight of each component, must be in line with the axis of the strut because otherwise the rod would be affected by a bending moment and would not be in equilibrium, i.e. there is a three-dimensional equilibrium of tensions and compressions at each node. From this analysis, we can understand the definition of tensegrity structures as internally pre-stressed, free-standing pin-jointed networks, in which the cables or tendons are tensioned against a system of bars or struts.

In order to make a parametric design for a tensile integrity structure, we created algorithmic editors that ordinarily consolidate visual programming dialects using Grasshopper inside Rhino as depicted in Fig. 1.1.4. and Fig. 1.1.5.

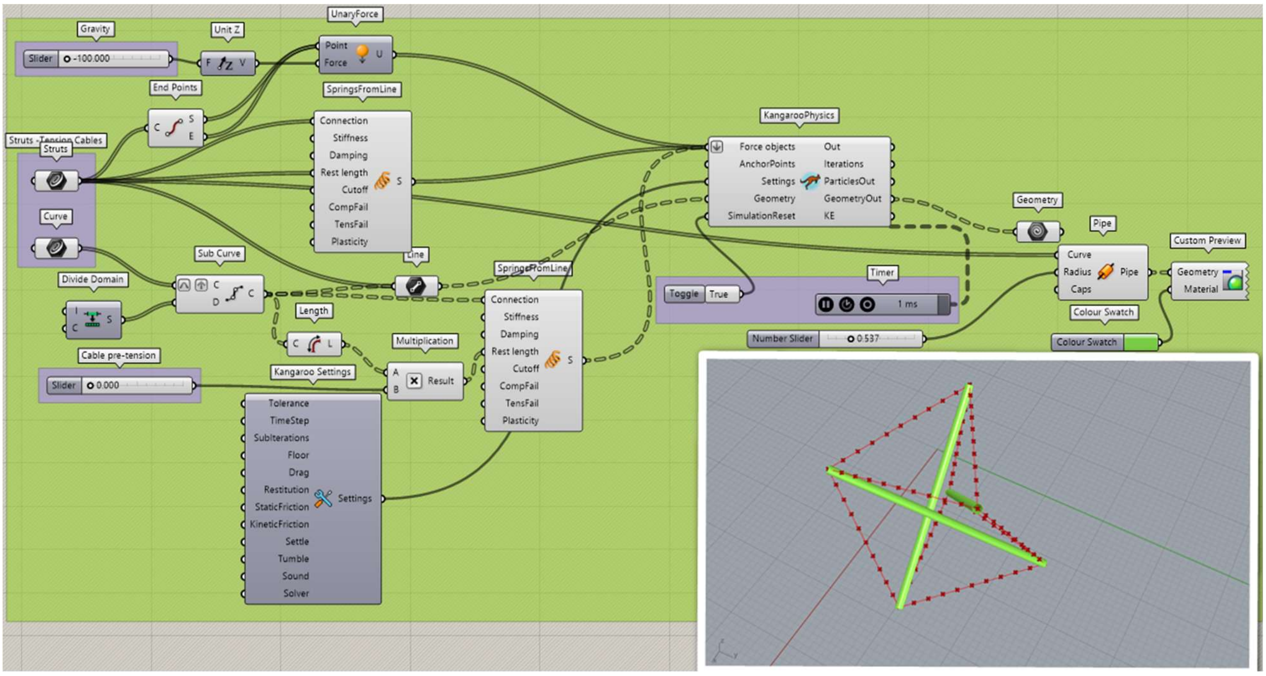


Fig. 1.1.4. Parametric Tensegrity Design I. (script created by the author)

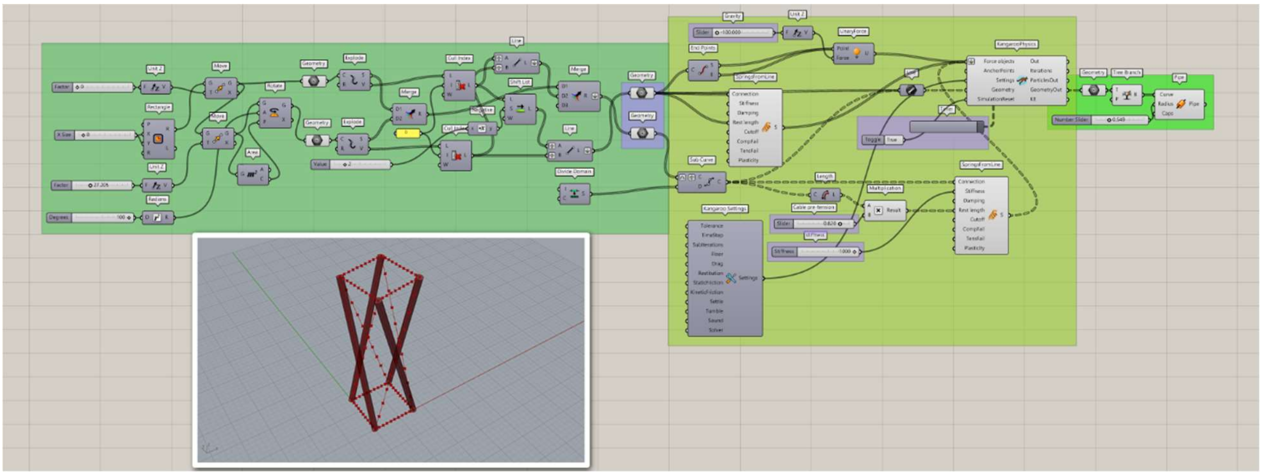


Fig. 1.1.5. Parametric Tensegrity Design II. (script created by the author)

Tensegrity icosahedron is a construction made of one tensegrity spatial 3D element consisting of six X-shaped modules (six strut elements of equal length and shape) as shown in Fig. 1.1.6.a The strut elements are oriented in three mutually perpendicular axes (each having the same length) and eighteen cable elements. Three cables pass through each node. The assembly of triple-X shapes provides structural morphology of tensegrity systems and adding tension cables to the components gives a stable state to the structure, therefore, preventing a motion of the triple X-shapes out of their plane. The creative process is started with a simple system and next, more and more struts and cables are added step by step, however, the strut elements must not touch together. The upper edge of the struts must be connected to the lower edge of the other elements. The properties such as weight, the thickness of the elements, and the use of the same material in all directions have an influence on the stability and equilibrium of the structure [5,7].

Figures 1.1.6a and b present our physical models of triple-X shape tensegrity showing their structural beauty. We have transformed them into exterior, respectively interior components, namely table lamps or lamps for public spaces, to show some of the other possible functions of this creative tensegrity design [9].

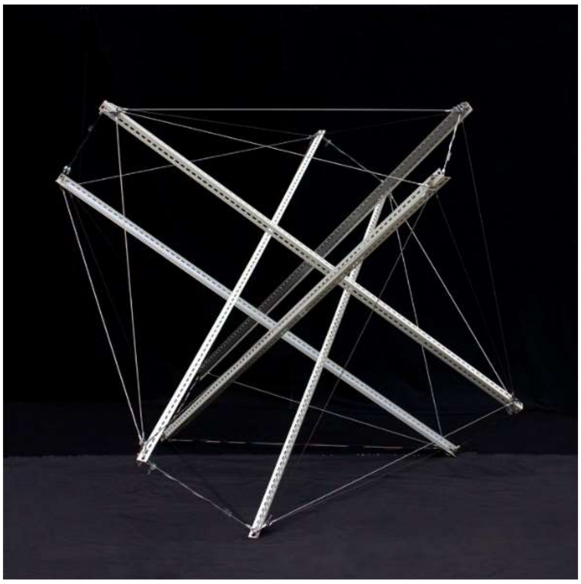


Fig. 1.1.6.a Tensegrity Icosahedron – Exterior Lamp (model created by the author)

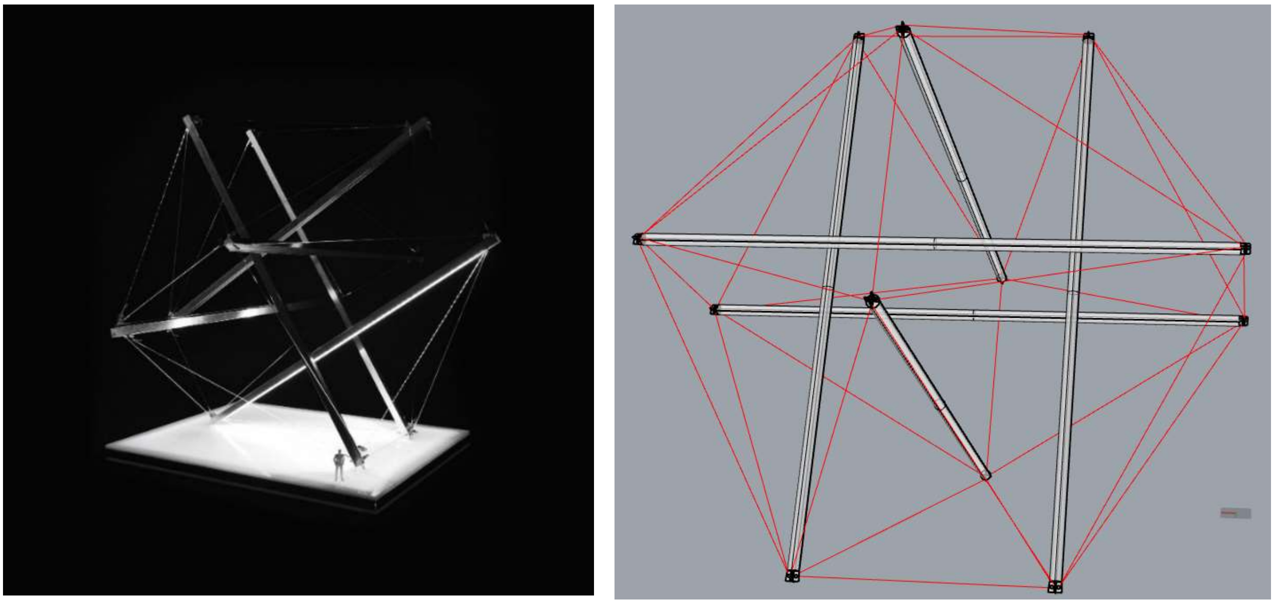


Fig. 1.1.6.b Tensegrity Icosahedron – Table Lamp (model created by the author)

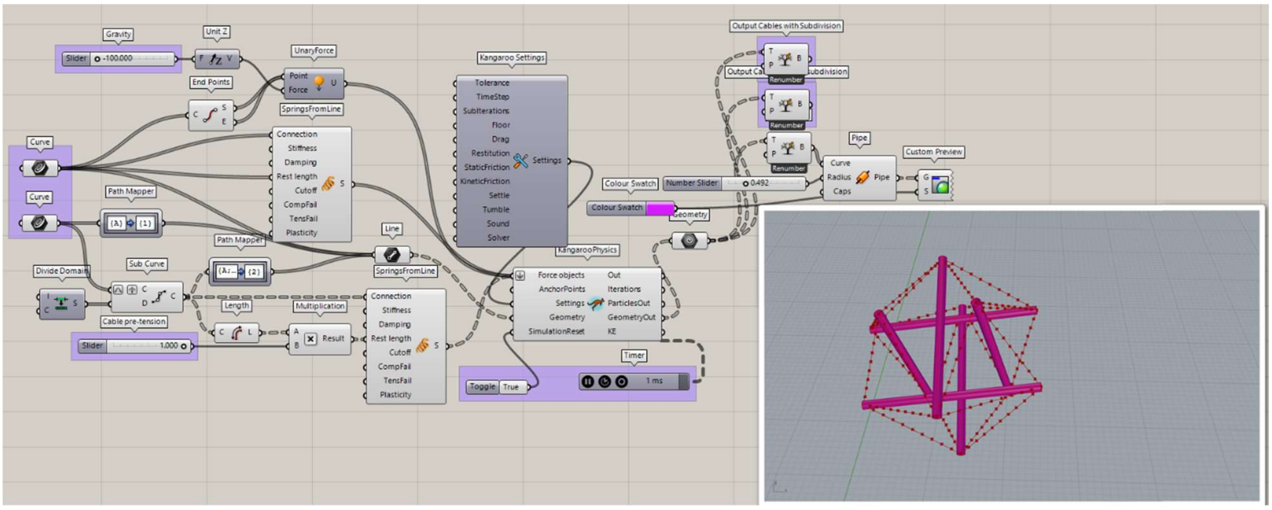


Fig. 1.1.6.c Parametric Tensegrity Design (script created by the author)

Fig. 1.1.6.c shows the process of parametrising a tensegrity icosahedron by visual programming. The plugins create codes that generate the form of the structure.

Tensional forces naturally transmit themselves over the shortest distance between two points, so the members of a tensegrity structure are precisely positioned to best withstand stress. For example, if the configuration of an "expanded octahedron" is changed and the cables are fixed following the zigzag pattern as depicted in Fig. 1.1.7. the result is a "truncated tetrahedron" [9]. As Motro (2003) remarked, it is not always possible to attain a balanced geometry and, therefore, sometimes the figures do not have a perfect definition of the polyhedron in question [5]. Due to the orientation of the struts that converge in each face, it can be appreciated that a certain distortion of the regular polygons can arise.

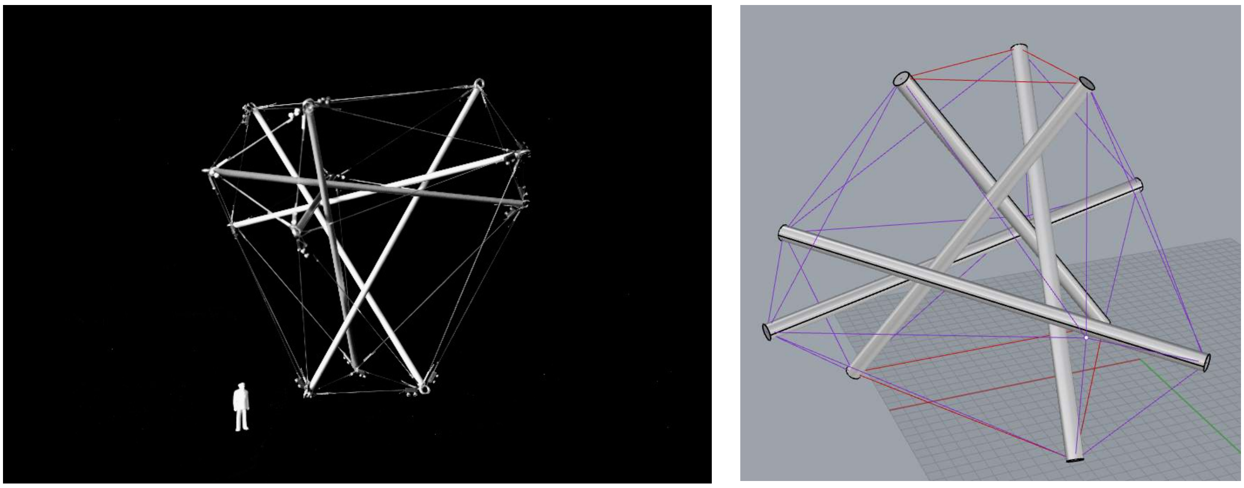


Fig. 1.1.7. Physical Model Diamond T- Tetrahedron (model created by the author)

Fig. 1.1.8. shows another interesting model a geodesic tensegrity dome that can be used as the roofing of different spaces [9]. It is constructed from aluminium tubes (struts) and nylon fibre (rods). The struts do not touch each other. The model consists of 15 basic modules that are mutually connectable and detachable. The base module has three struts bars with a diameter of 6 mm and a length of 166 mm. The upper base rods are 140 mm long, the bottom base rods are 80 mm long. The rods connecting the lower and upper bases are 115 mm long. The top base of the base module is 1.75 times larger than the bottom base, ensuring a dome-shaped curvature when bonded. The basic modules and the whole structure are removable thanks to the rods. The joint is a cut slit into the aluminium tube into which the rods are inserted. The rods are terminated at the end with a node that is larger than the slot to avoid the collapse of the structure. In practice, it is advisable to use solid joints.

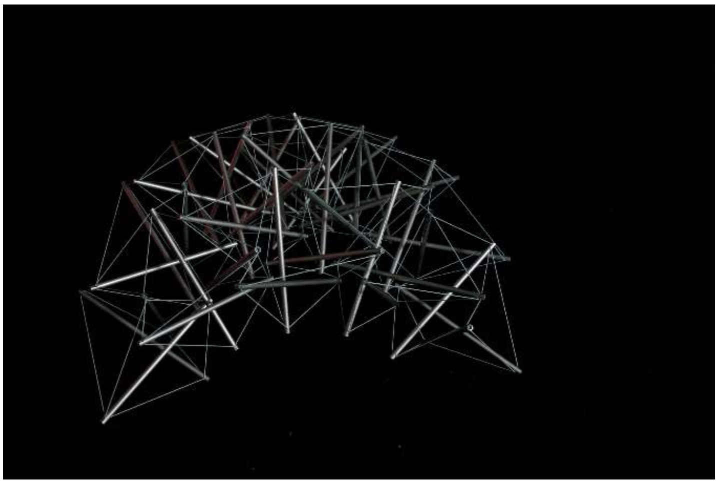
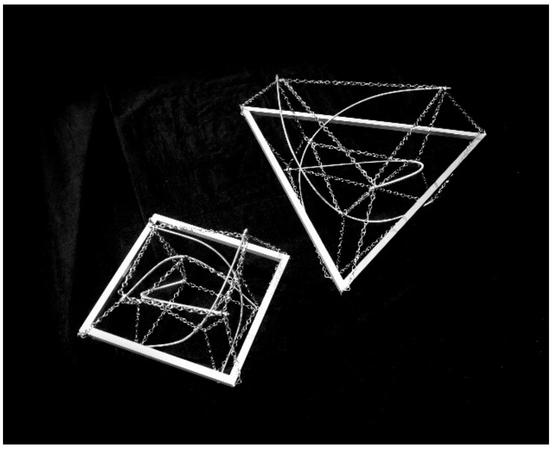


Fig. 1.1.8. Physical Model - Double-Layer Tensegrity Dome



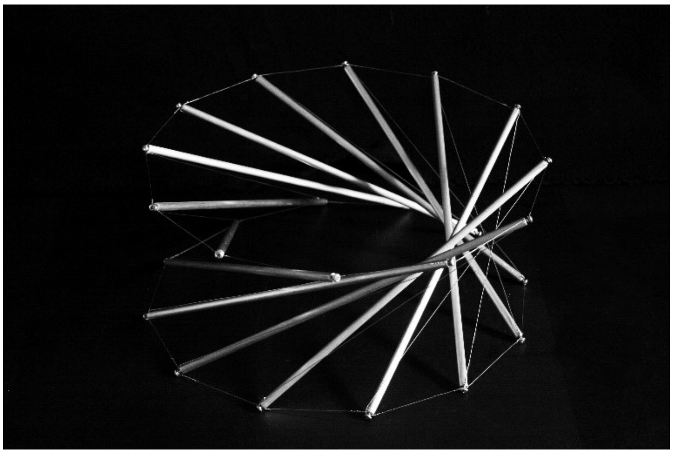
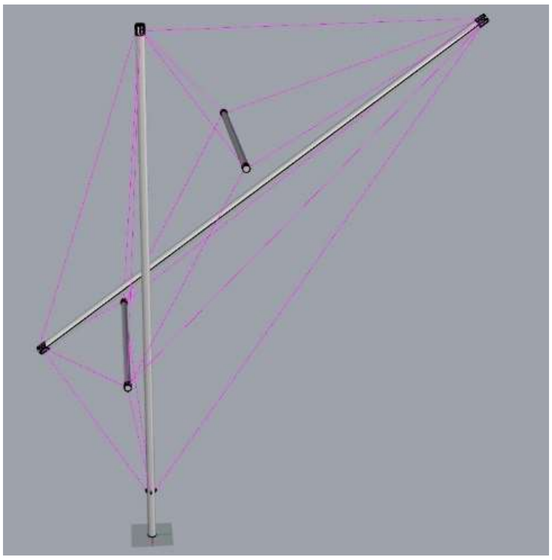


Fig. 1.1.9. Physical Models – Tensegrity (models created by the author)



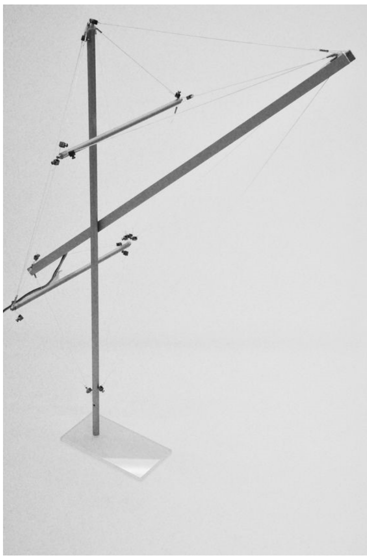


Fig. 1.1.10. Table Lamp (model created by the author)

We dealt also with fine art structures together with the students of Academy of Fine Art and Design in Bratislava, aiming to bring fresh ideas into the field and create various models based on tensegrity. Fig. 1.1.9. - 1.1.16. show physical models used for living and pleasure such as table lamps, chairs, sculptures, and toys. We payed attention not only to the structure itself, but also to details, aesthetics, and the elegance of the models.

To our physical tensegrity models belongs an amazing collection of chairs shown in Figures 1.1.11. - 1.1.13. created in collaboration with our colleague Miroslav Debnár and his students from the Department of Design. They were used to clarify the main ideas of tensegrity in the education process and at the same time, they can serve as unique chairs.

Fig. 1.1.11. Tensegrity as a Chair (Shawkat and co-authors, 2019)

Fig. 1.1.12. Tensegrity as Chairs (Shawkat and co-authors)

Fig. 1.1.13. Tensegrity as Chairs (Shawkat and co-authors)

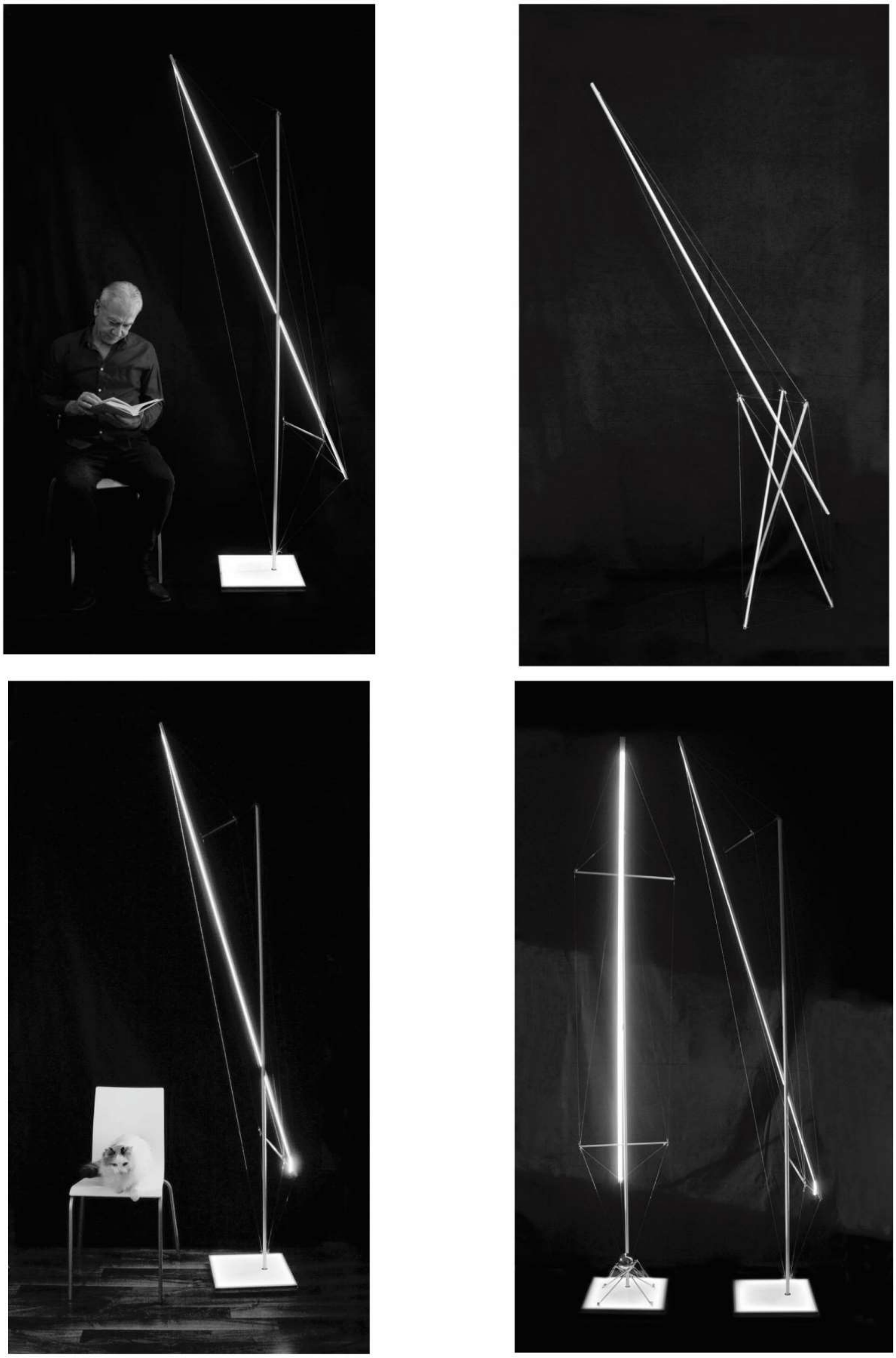


Fig. 1.1.14. Tensegrity Art-Parametric Modelling (models created by the author)

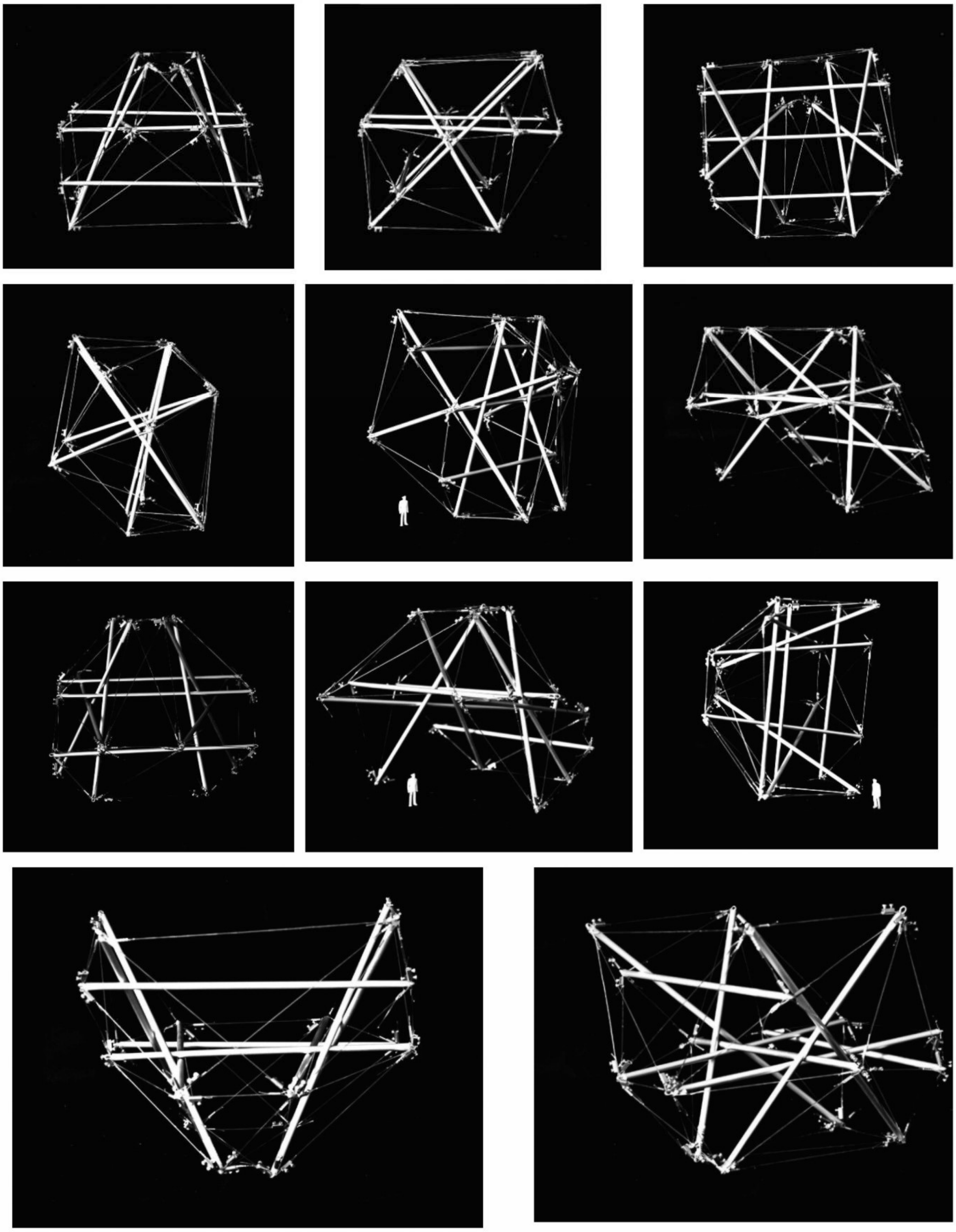


Fig. 1.1.15. Tensegrity Form Finding-Physical Models as Sculpture I (models created by the author)

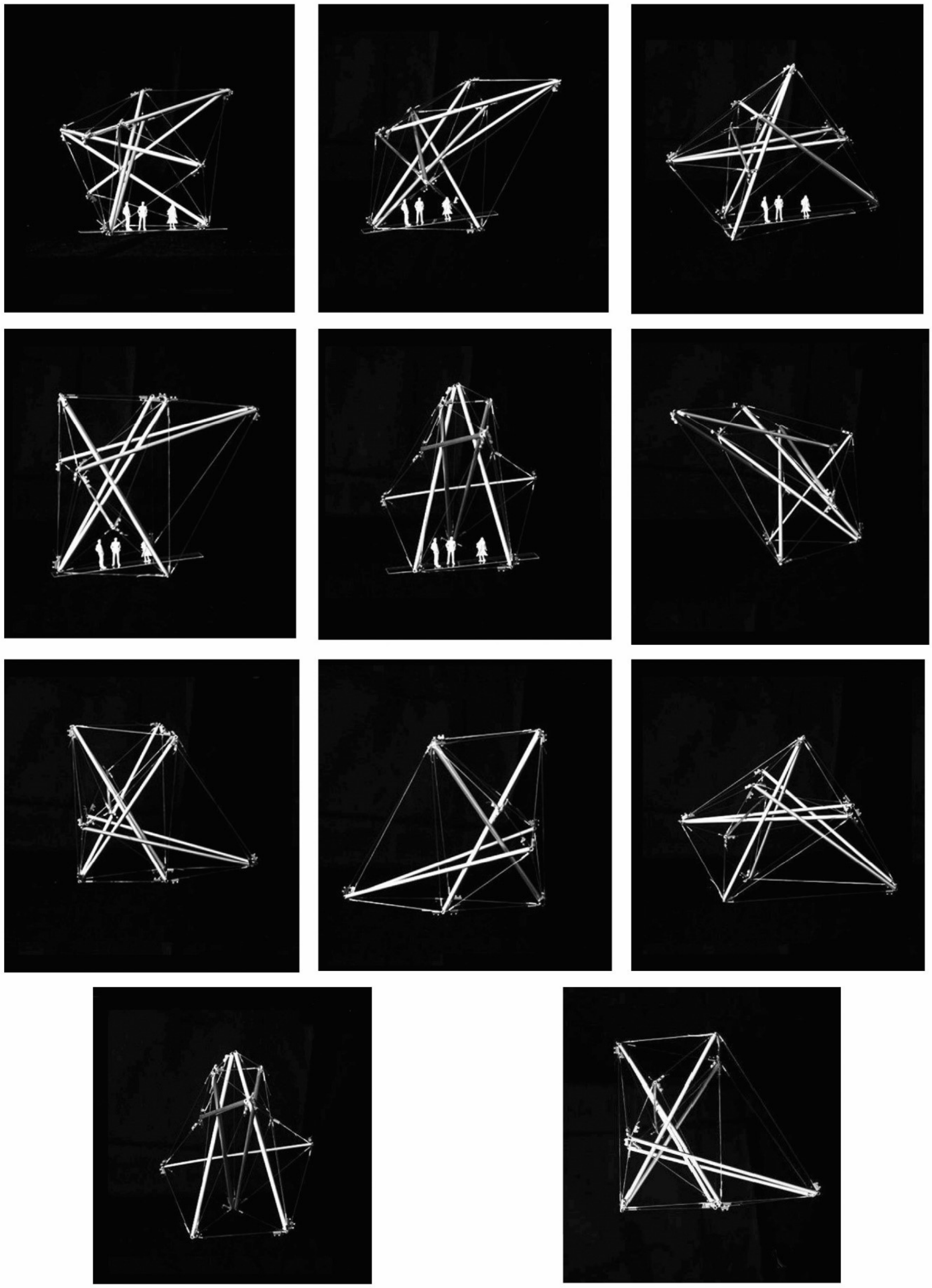


Fig. 1.1.16. Tensegrity Form Finding-Physical Models as Sculpture II(models created by the author)

1.2 ANTI-GRAVITY TENSEGRITY STRUCTURES

New subgroups of tensegrity forms include unique anti-gravity tensegrity structures which play an important role in today's architecture and design. Our passion for creating beautiful and innovative solutions in the field of tensegrity lightweight structures led us to design “magical floating” tea tables depicted in Fig. 1.2.1. a, b – 1.2.4 [9]. The structures of our models are constructed of simple materials, mostly wood and aluminium. The floating anti-gravity models represent a nice application of the basic tensegrity structure; simple in principle, finicky to build. Anyone can try to create them relatively easily, without using any complex materials. A result is an object that seems to defy gravity and physics.

In one group of anti-gravity tea table models, the load-carrying capacity of the structure is equal to the tensile capacity of the string. It is just a matter of achieving the right tension strings to centre the structure and then connect them in place. The centre string provides tension, and the other strings provide balance (Fig. 1.2.1. a, b). Therefore, all strings are necessary, not just the centre one. By taking any of them out, the whole model falls apart. However, the centre string is the most important and the most elegant one. It seems that the tables fly in the air providing an intriguing sense of freedom. In another type of anti-gravity tea table, the main element (the centre string) was replaced with two opposite magnets which ensure the stability of the entire system (Fig. 1.2.3. a, b). The resulting optical illusion is our favourite demonstration of the charm of physics and the elegance of tensegrity. The main shortcomings of the practical use of tensegrity technology for common practice belong to the relatively high displacements in nodes and low ultimate limit stat of material efficiency compared to traditional, geometrically rigid structures and the difficulty to create the details of joints as well as the selection of suitable material for their realization.

The capacity of a structure increases with the minimal mass design for a given set of stiffness properties. Tensegrity structures use longitudinal members arranged in a very unusual pattern to achieve maximum strength with a small mass.

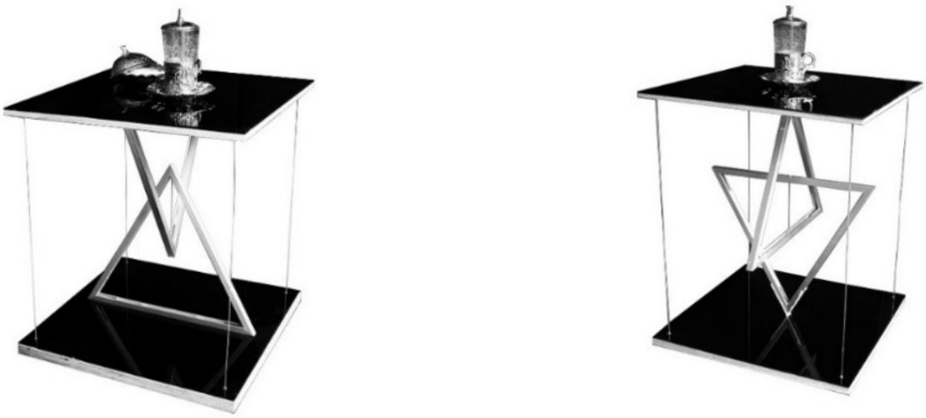


Fig. 1.2.1. a, b Tensegrity Anti-Gravity Tea Table I (models created by the author)

Fig. 1.2.2. a, b Anti-Gravity Tensegrity Tea Table II (models created by the author)

Fig. 1.2.3. a, b Anti-Gravity Tensegrity Tea Table III (models created by the author)

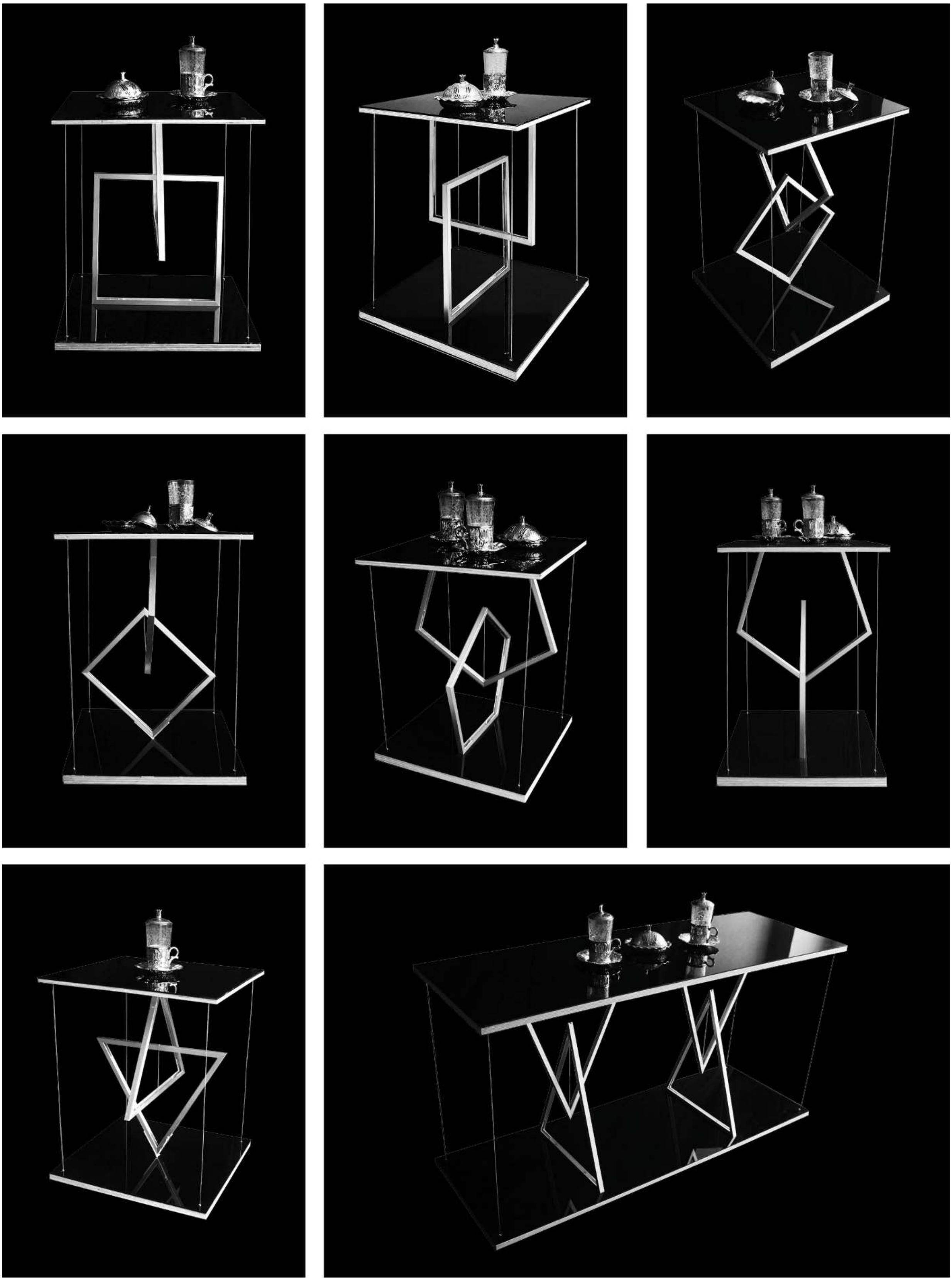


Fig. 1.2.4. Anti-Gravity Tensegrity Tea Table IV

2.0 MEMBRANE STRUCTURES

One of the extremely popular architectural forms of contemporary architecture and design represent the membrane structures. They appeal especially with their non-traditional solution, innovative design, unique shape, and great flexibility. Compared to traditional rigid structures, they allow larger spans with minimal support members [3]. They have the capacity to provide a particular meaning to places where they are installed. Applications such as membrane roofs, airship skins, or sail materials demonstrate their capabilities. Unsurprisingly, experience and good engineering judgment are frequent characteristics among famous designers of membrane structures: Fritz Leonhard, Jorge Schalch, Frei Otto, Horst Berger, and David Geiger, to mention a few.

The idea of making objects using a minimum of material is as old as humanity itself. With frequent population transfers for water and food, it was vital to be able to build a shelter for temporary housing and protect people from the weather or predatory beasts. From ancient times, people used textile constructions made of animal skins or fabrics, for example, to create temporary dwellings or sails. With the general shortage of raw materials, the first lightweight structures were developed that could be rebuilt, decompose, and transported. The first tent constructions appeared in various variations in all cultures throughout the world. During our era, tents and similar light structures were used to temporarily accommodate people on war, discovery, and hunting expeditions, to isolate the sick during epidemics, and increasingly also to shield and temporarily protect the weather during military parades or knightly battles.

However, the technology used by today's lightweight membrane constructions was not developed until the 19th century. With the progress of the industrial revolution, looms were automated, which had a significant contribution to lower prices and higher availability of fabrics. As part of modern permanent structures, membrane structures began to be used in the 1960s, mainly due to the development of new technologies [3].

Membrane structure has always enjoyed the great interest of students. Many different models of textile structures can be produced as physical miniatures of the static-structural system with large spans as shown in Fig. 2.1. The advantage of such models versus virtual 3D models is the possibility to verify the structural scheme.

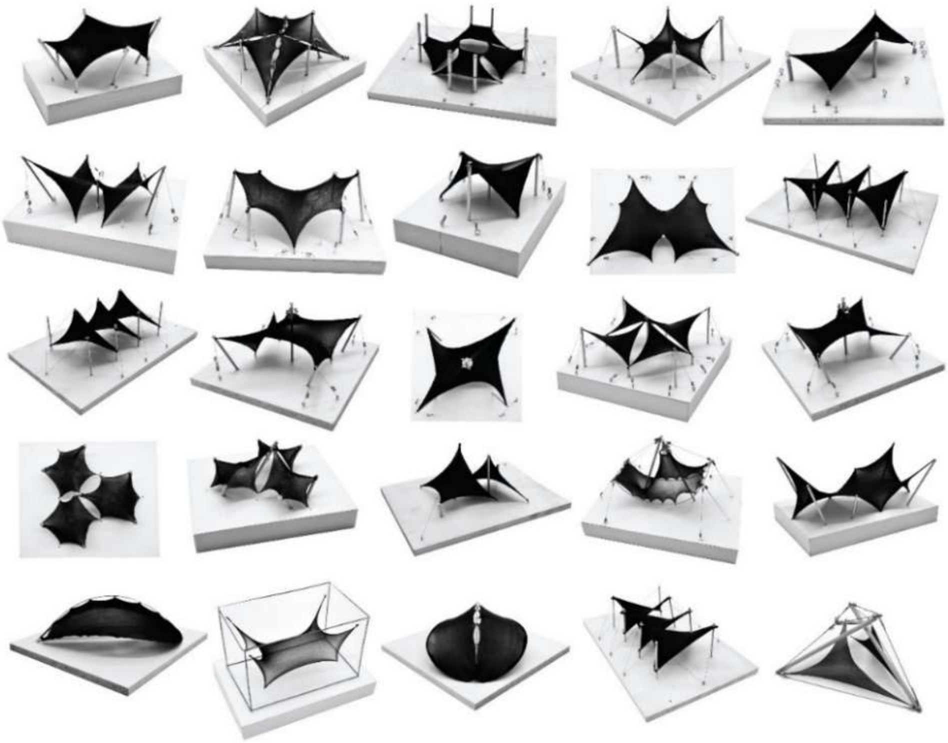


Fig. 2.1. Membrane Tensile Models, Small Scale Counts (Shawkat, 2021)

Instead of the term Membrane Structures, we can also come across designations such as Tensile Structures, Architectural textiles, Fabric Architecture, or Textile Membranes. All these names basically refer to the same concept.

Tensile structure is a type of construction involving the use of elements in which tensional forces are implied, with no compressive forces action, or bending, giving it great construction advantages. That is the quality that offers possibilities of large spanning and utilizing a variety of free-standing forms. The stability of the entire system ensures that the whole is in equilibrium and therefore stable [4]. Due to the negligible flexural stiffness of cables and membranes, the initial configuration of these structures must be stressed, even if the self-weight is disregarded. Thus, before the analysis of the behaviour of the structure to external loads can be performed; the initial equilibrium configuration must be found. The shape of a tensile structure, which very much depends on internal forces, also governs the load-bearing capacity of the structure. Therefore, the process of determining the initial equilibrium configuration calls for the designer's ability to find an optimum compromise between shape, load capacity, and constructional requirements.

As well-known, the primary advantage of tensile members over compression members is that they can be as light as the tensile strength permits. Fabric-reinforced membranes are a class of lightweight materials that are important for many different engineering branches. They can be used to efficiently cover big areas or enclose large volumes with minimum structural weight [3,5]. Tensile structures have always fascinated architects and engineers, mainly because of the aesthetic shapes they produce. Today, membrane constructions are a common (and at the same time very aesthetic) part of various interior and exterior constructions and are used in every type of design. Exterior membrane constructions made of technical textiles are used as temporary (often mobile) or permanent light roof constructions of stadiums, arenas, cultural stands, shopping centres, exhibition halls, airports, amphitheatres, or as effective dominants of selected spaces. In interiors, textile membranes fulfill an aesthetic function and can also function as thermal or acoustic insulation.

The process of designing the shape of the membrane is called the "form-finding" process. It is an iterative process in which the designer adjusts the boundary conditions (support geometry, external load, structural stress) based on the suitability or unsuitability of the equilibrium state. The geometry of the minimum surfaces is thus unique for each set of boundary conditions. A change in their geometry has a global effect on changing the geometry of the minimum surface.

The main characteristic of the minimum surfaces from the construction point of view is that they are curved in two directions, their mean curvature is equal to zero, and uses the minimum amount of potential energy. It should also be noted that minimum areas also have their physical limits and cannot be created between each set of boundary conditions. The final form of the construction depends mainly on the position of the fixed points. or the magnitude of the prestress force.

Due to the continuous three-dimensionality, the design and shape analysis is practically impossible to perform with conventional design procedures. Several techniques of their physical and numerical modeling have been developed over the past decades to study the shape, control the collision of surfaces with surrounding structures, accurately describe the geometry for static analysis, and create production drawings of elements and membranes.

In general, the design process of membrane and shell structures is inverse to the procedure used in traditional architecture. Traditionally, the first step in the analysis process is the definition of the geometry of the structure, which generally is known as a priori. However, this is not the case for tensile structures. While the shape of the structure is known in advance when designing conventional structures, the state of stress and strain is unknown, the determination of which is subject to static calculation. In the case of lightweight structures, the state of stress, or the magnitude of the deformation, from which the equilibrium geometry is determined, is known in advance (designed by the designer). This inverse procedure makes static analysis and the architectural shape of the structure inextricably linked, and the cooperation of the engineer and architect is necessary for the pre-project preparation.

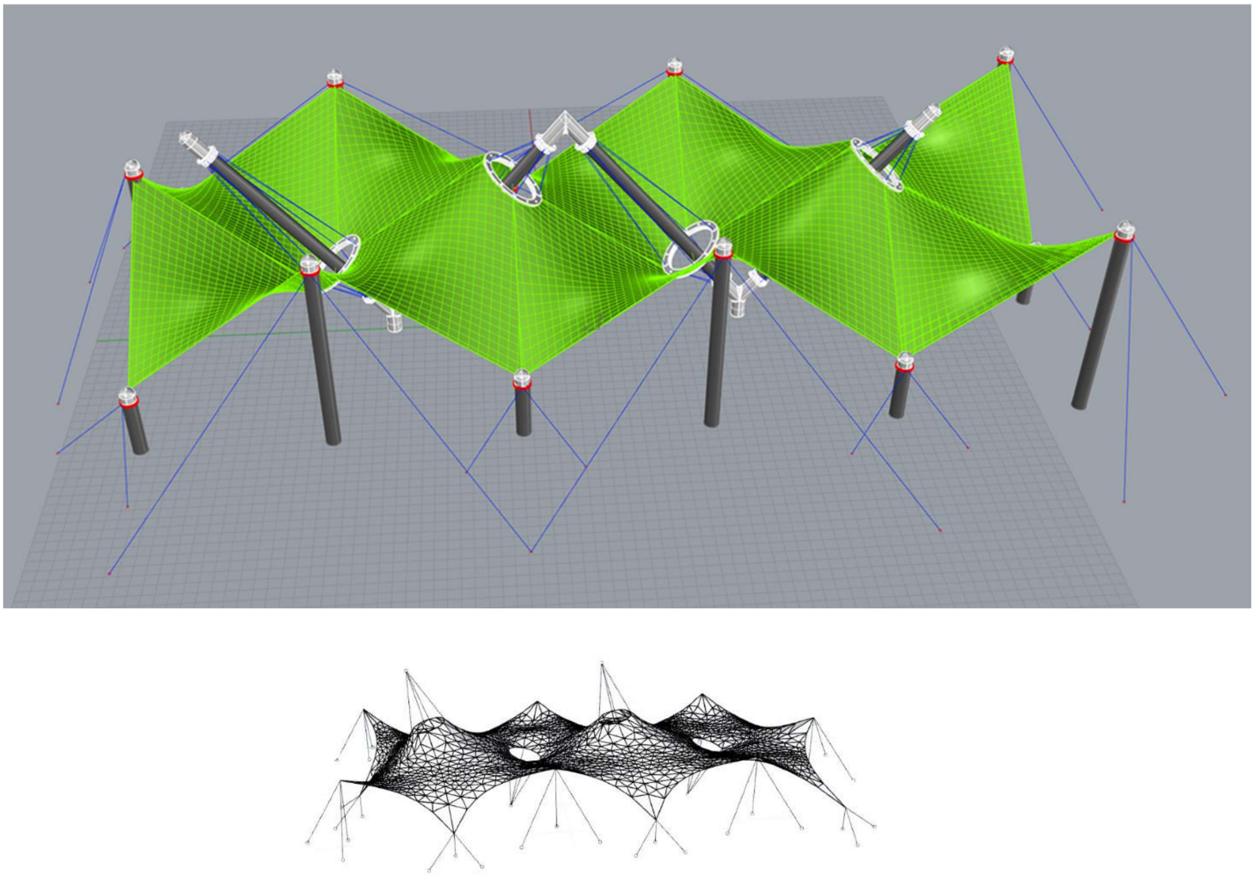


Fig. 2.2. Form Finding of Membrane Tensile Structure (Shawkat, 2021)

Physical models serve to refine the idea of the shape of the surface in space, allow to study and simulate the interior space and allow the designer to observe global changes in the shape and rigidity of the structure with local changes in boundary conditions.

Numerical models prepare geometry data for static analysis and production documentation (Fig. 2.2). Due to the already mentioned interdependence of architecture and the static behaviour of the structure, it is appropriate to combine the knowledge gained from both approaches to their design.

Membrane structures are often referred to as textile structures. However, the actual membrane construction is far removed from the classic tent. The main difference is its exact geometric shape. For the proper functioning of the membrane structure, the exact geometric criteria must be computed.

The basic criterion is to maintain the concavity and convexity of the main directions of the membrane surface (Fig. 2.3.).

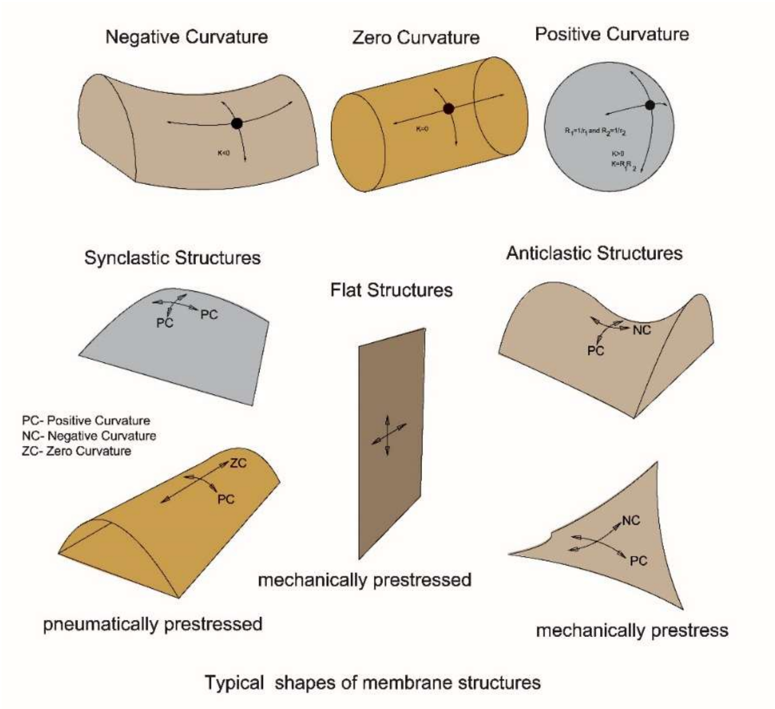


Fig. 2.3 Typical Shapes of Membrane Structures

Another criterion of lightweight membrane construction is its prestress. The correct geometric shape and prestress guarantee its stability, stiffness, and dynamic resistance. At the same time, it allows the structure to resist the effects on which it was designed, rain, wind, and snow.

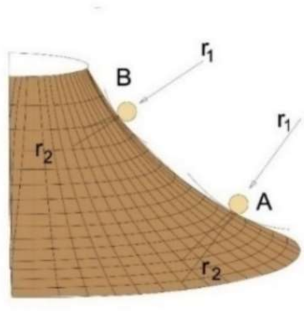


Fig. 2.4 Conical Surface

In the case of a conical surface (Fig. 2.4, 2.5), the boundary conditions which do not allow the formation of a minimum surface, the imbalance is evident from its unequal curvatures. In this case, at points A and B on one meridian section, r, is constant and r2 is variable, which means that r_1/r_2 is not equal to r_1/r_2 [11]. Fig. 2.5 and 2.6 depict the process of thinking showing how it is possible to parametrise a conical shape, while Fig. 3.7 shows parametrising of a synclastic form.

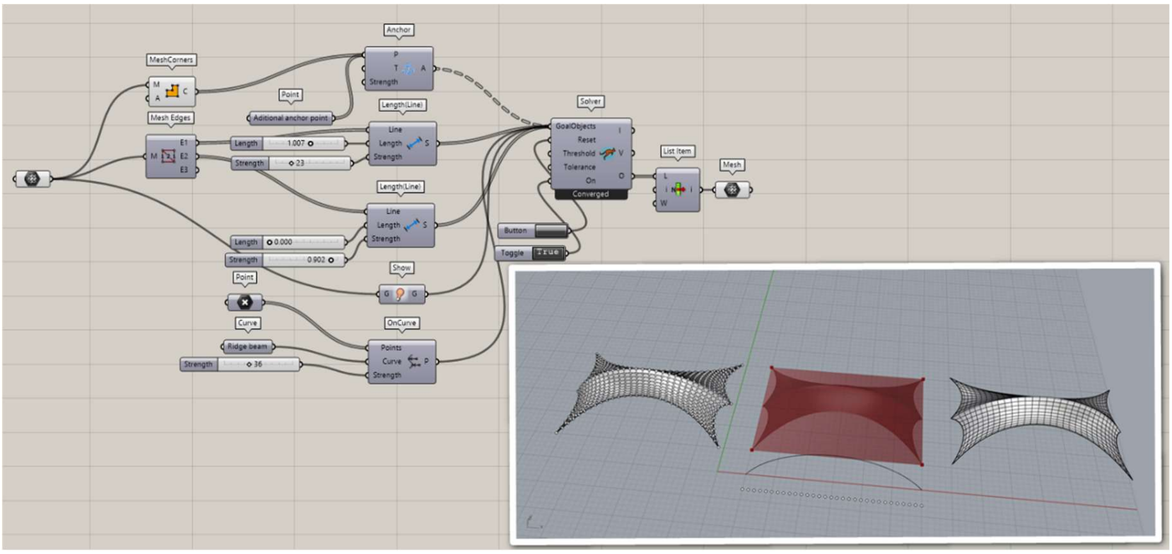


Fig. 2.5 Form-Finding Parametric Design I (script created by the author)

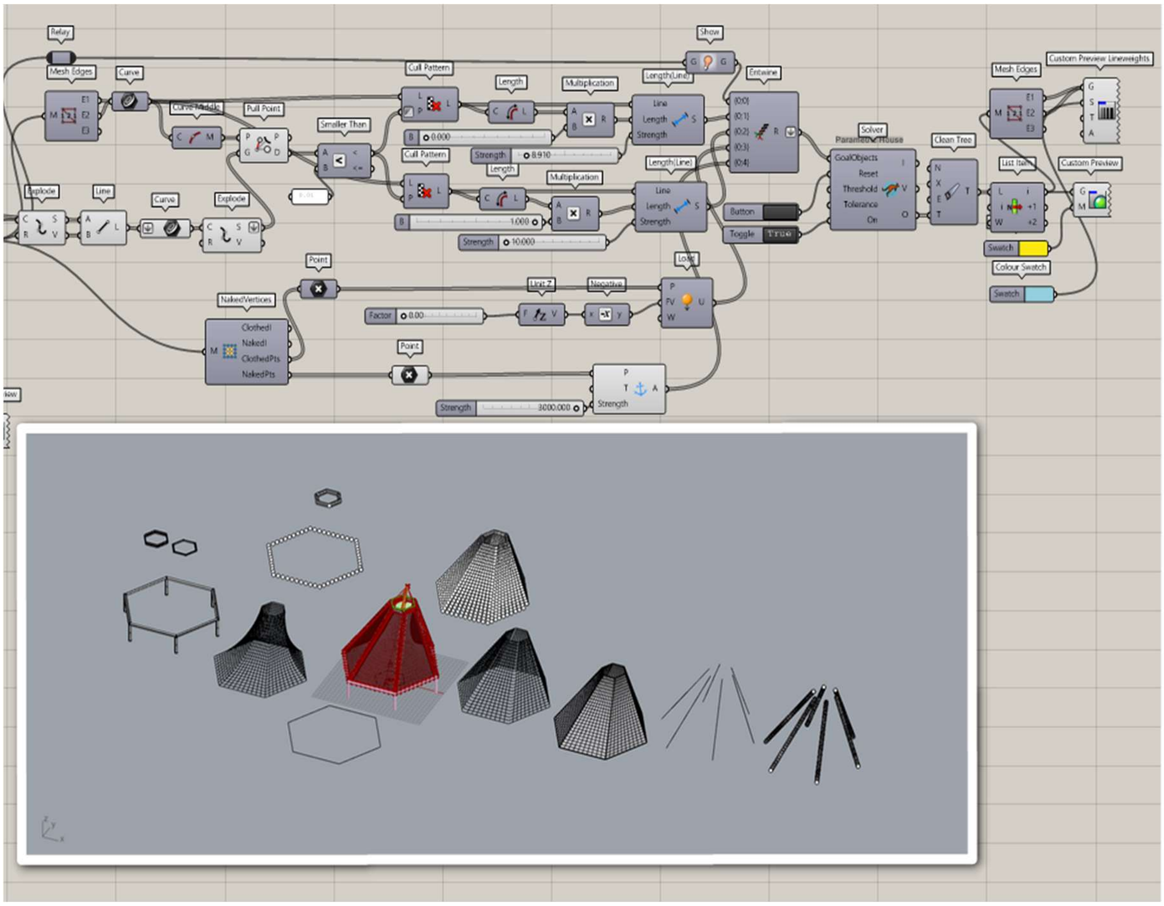


Fig. 2.6 Conic Membrane Structure, Parametric Design II (script created by the author)

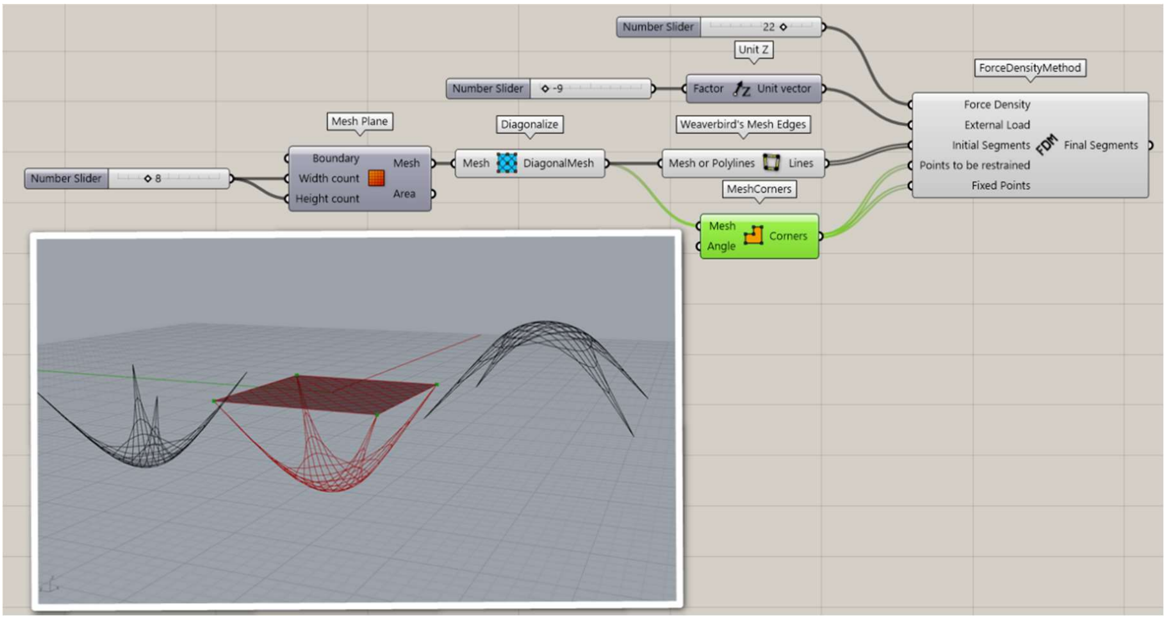


Fig. 2.7 Form-Finding Parametric Design III (script created by the author)

2.1 GEOMETRIC SHAPES OF MEMBRANES

The geometry of membrane structures is an important aspect to consider when designing such structures for architectural applications. The shape of a membrane structure influences its structural behavior, as well as its aesthetic qualities. Membrane structures can take on a variety of geometries, from simple flat planes to more complex forms such as saddles, cones, hyperbolic paraboloids, and toroids. The choice of geometry will depend on a number of factors, including the intended use of the structure, the desired aesthetic, and the structural performance requirements. One of the challenges of working with membrane structures is achieving the desired geometry while maintaining the structural stability and integrity of the system. However, advances in computational design and analysis tools have made it easier to explore a range of geometries and to optimize structural performance, making membrane structures an increasingly popular choice in contemporary architectural design.

The basic geometric shape of the membrane system emerges from the surface of the hyperbolic paraboloid Fig. 2.1.1-. We can describe this area by mathematics [12]:

$$z(x,y) = \frac{x^2}{a^2} - \frac{y^2}{b^2}$$

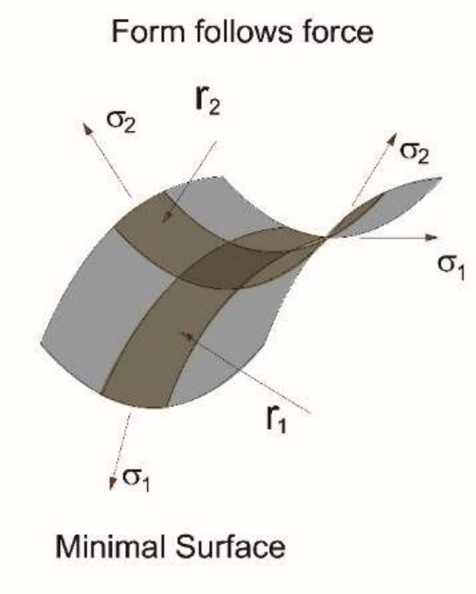


Fig. 2.1.1 The General Area of The Hyperbolic Paraboloid

2.2 TYPES OF MATERIAL OF MEMBRANE STRUCTURES

Modern membranes must fulfill both a load bearing and a roofing function at the same time and are therefore made of high-strength technical textiles. The tensile strength of the membrane material depends directly on the structure of the base fabric. The fabrics are usually made of glass fibres or of polyester, polyamide, polyvinyl alcohol, and polyaramid fibres. To achieve higher strength and durability, the fabrics are coated and laminated with synthetic materials. The most widely used materials include polyvinyl chloride (PVC) laminated or coated polyesters and woven glass fibres coated with polytetrafluoroethylene (PTFE), known under the trade name Teflon or ethylene tetrafluoroethylene (ETFE). The coatings form protective layers of fibres and ensure that the membrane is impermeable to water [13].

A great challenge for today's architects is global warming and membrane structures are increasingly seen in our region as an integral part of sustainable climate solutions for public spaces and parks.

2.2.1 PTFE (Polytetrafluoroethylene)

Teflon is a synthetic fluoropolymer, that has a very wide application in industry and construction. It has a high resistance to chemicals and an extremely low friction coefficient. The most famous PTFE membrane material is Gore-Tex. The largest PTFE construction can be termed the

"Hubert H. Humphrey Metrodome" roof in Minneapolis with an area of approximately 80,000 m2 where a double-layered membrane with a glass fiber construction is used. The strength of the PTFE membrane in tension is 2,300-4,500 N / 5 cm. If glass fibers are used as the support material, the tensile strength of such a membrane will be 3,500-7,500 N / 5 cm.

2.2.2 ETFE (Ethylene Tetrafluoroethylene)

ETFE is a fluorocarbon - a basic polymer (fluoropolymer) type of plastic. It has been designed as a material with high corrosion resistance and resistance over a wide range of temperatures. It was used for example for the pneumatic panels of the "Allianz Arena" football stadium, or for the "National Water Sports Centre" - the world's largest construction made of ETFE membrane. Also, on panels of "Tropical Island" 20 000 m^2 in Germany. Because ETFE has excellent mechanical stiffness and chemical resistance with which it can compete with polytetrafluoroethylene (PTFE). In addition, ETFE has high energy radiation resistance and can withstand moderately high temperatures for a long period of time. The strength of the ETFE membrane in tension is about 1200 N / 5 cm and ETFE foil is 430-500 N / 5 cm.

2.2.3 PVC (Polyvinylchloride)

PVC is less rigid and more deformable but also more resistant to mechanical deformations. It has a lower lifetime compared to PTFE material. The carrier material of these membranes is polyester or aramid fibre. The advantage is the lowest price of all materials used and lower flammability. The strength of PVC membrane in tension in combination with polyester carrier fibre is 3,000-9,800 N / 5 cm and aramid carrier fibre is 7,000-24,500 N / 5 cm. Silicone is a very progressive material, used in combination with a glass fibre construction. It has a high service life of over 30 years, a third of the PTFE material, and, as with the only material used, its smoke is not toxic. Silicone is mainly used in combination with glass fibre and the tensile strength of such a membrane is 3,500-6,000 N / 5 cm.

2.3 FORM FINDING

Form finding is the process of determining the equilibrium state of a membrane structure at a given level of prestressing and selected boundary conditions. For the membrane structure to be able to efficiently transmit the corresponding effects of any loaded vector, its spatial surface must have the shape of a double curvature. It can be achieved in three basic ways, which characterize the three most used types of membrane roofing (Fig. 2.3.1):

1. hyperbolic paraboloid, which is achieved by fixing the membrane to four points, two of which are always at different levels. The flatter the saddle, the smaller the height distance between the upper and lower points, the greater the force effects arising in the corners of the system,
2. conical shape, which is achieved by fixing the membrane to the top of the column and at the bottom to the circular support ring,
3. arch - the membrane hanging between the arches situated in the transverse direction and in the lower longitudinal part is connected to the end ropes [13].

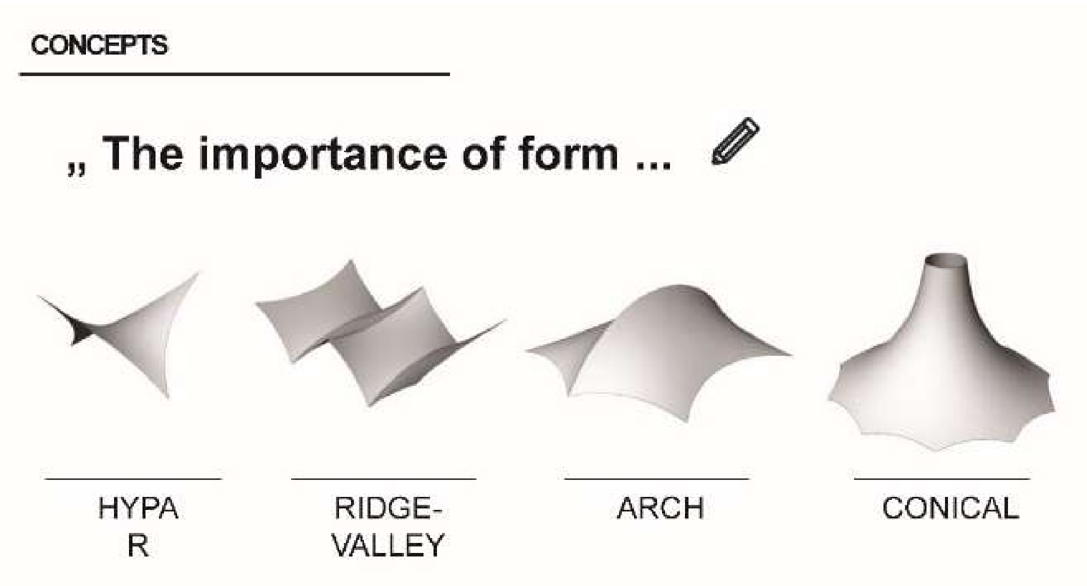


Fig. 2.3.1. Base Forms of Membrane Structures

2.3.1 THE FORCE DENSITY METHOD

The Force Density Method (FDM) is popular among space structure designers and the method was developed at the end of the 1960s by German engineers Linkwitz and Schek for the determination of cable net structures or for the initial equilibrium problem of the cable roofs at the Olympic Games in 1972 hosted by Munich [11]. Their goal was to determine a geometry that would be sufficiently rigid without the addition of load ballasts, a geometry that would be built easily and would efficiently carry the loads over long distances using subtle elements. FDM method became very popular rapidly and designers began to work on research from various countries, which caused its expansion and variation.

Prestressed cable-nets structure and textile membranes are characterized by the inherent interaction between their geometry and stress distribution. This relationship between the form and forces makes it impossible to directly design such structures as is the case with conventional structures. The assumption for using this method is that, that the creating elements of the analysed structure, must be straight and must be pin joined to each other or to the supporting structure (Fig. 2.3.1.1-2), which is fulfilled in this case [12]. First, a graph of a network is drawn, and all nodes are numbered from 1 to Ns, and all the elements are numbered from 1 to m. The N_f nodes which are to be fixed points are taken at the end of the sequence. All the other nodes N are considered free. Thus, the total number of nodes is $Ns= N + N_f$. Then the connectivity matrix Cs is constructed with the aid of the graph. Each element *j* has the node numbers *k* and *l* (from *k* to *l*).

The element between the nodes i and j will be denoted by (i, j). The nodes that are linked with elements by node i will be called "neighbours" to node i, and the set of their labels will be denoted by Ni.

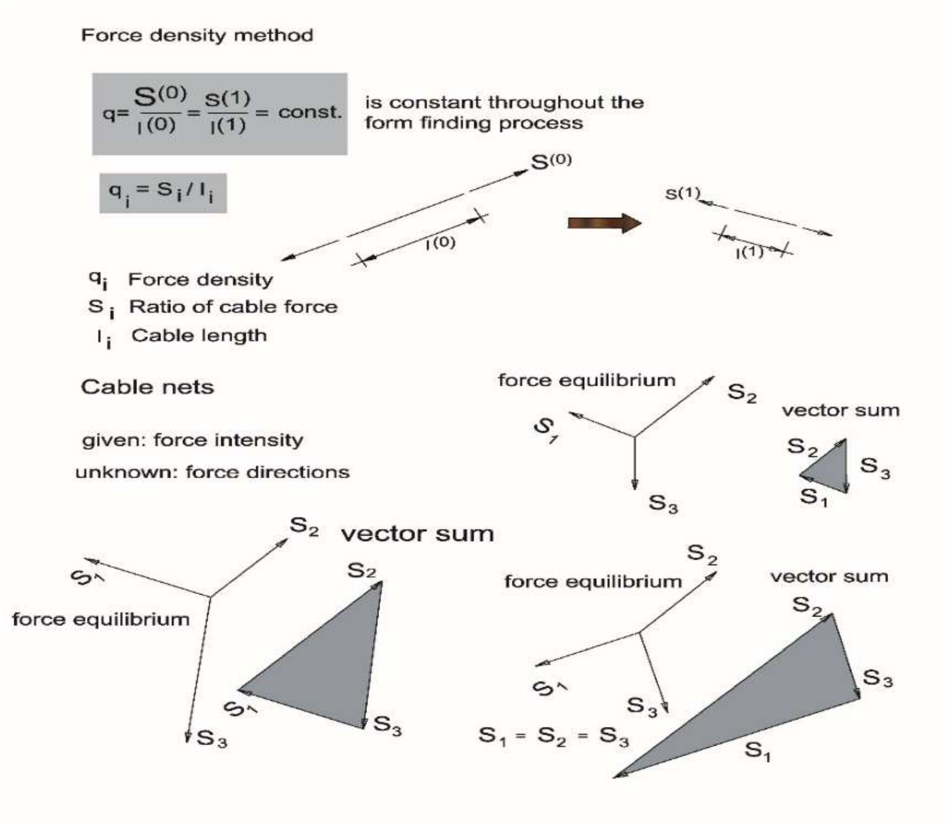


Fig. 2.3.1.1. Force Density Method [12]

$N_f \cup N_s$ means the set of those elements which are either in N_f, or in N_s, or in both

$N_f \cap N_s$ means the set that contains all those elements that N_f and N_s have in common

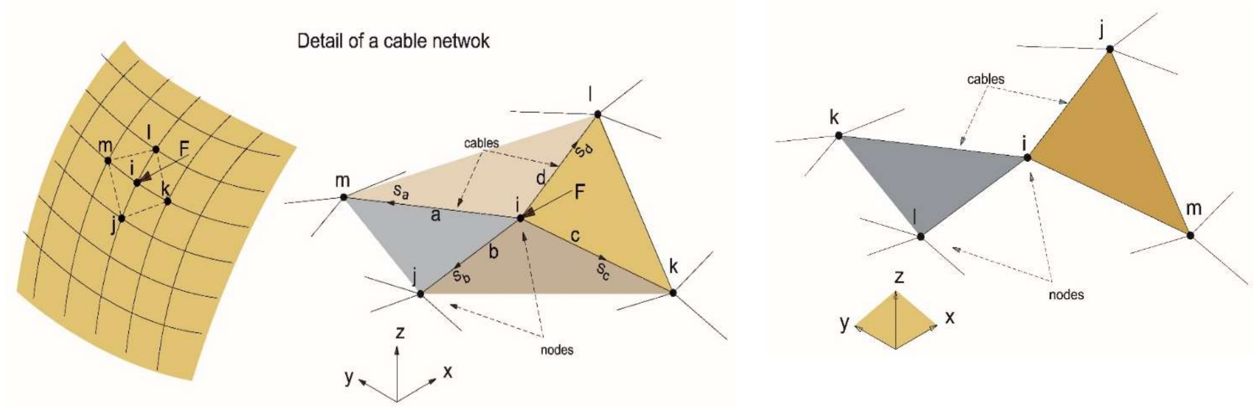


Fig. 2.3.1.2. Detail of Cable Network [12]

By defining the positioning vectors xs, ys, zs which are again based on the partial vectors related to the free node x, y, z and related to the fixed node x_f, y_f, z_f , we can calculate the vector displacement of each node, in all directions of the global coordinate system,

$$C_s = \left(C \cdot C_f\right)$$

where C and C_f contain the free and fixed nodes, respectively. Denoting the vectors containing the coordinates of the n free nodes x, y, z, and similarly for the N_f fixed nodes x_f, y_f, z_f, the coordinate differences for each element can be written as:

$$u = C_s \cdot x_s = C \cdot x + C_f \cdot x_f \qquad v = C_s \cdot y_s = C \cdot y + C_f \cdot y_f \qquad w = C_s \cdot z_s = C \cdot z + C_f \cdot z_f$$

The equilibrium equations for the free nodes for the ***x-, y-,*** and z-directions are written as

$$(C)^T \cdot (U) \cdot (L)^{-1} \cdot S = \left(F_x\right) \qquad (C)^T \cdot (V) \cdot (L)^{-1} \cdot S = \left(F_y\right) \qquad (C)^T \cdot (W) \cdot (L)^{-1} \cdot S = \left(F_z\right)$$

By using the force-to-length ratios for the elements, i.e. the force densities, are written as:

$$(C)^T \cdot (U) \cdot q = \left(F_x\right) \qquad (C)^T \cdot (V) \cdot q = \left(F_y\right) \qquad (C)^T \cdot (W) \cdot q = \left(F_z\right)$$

where the vector q**,** of length ***m*.,** is described as:

$$(q) = (L)^{-1} \cdot (S)$$

We write down the matrix expression of the equation of equilibrium to the shape:

$$(U) \cdot q = (Q) \cdot (u) \qquad (V) \cdot q = (Q) \cdot (v) \qquad (W) \cdot q = (Q) \cdot (w)$$

we can translate equations of equilibrium into shape:

$$(C)^T \cdot (Q) \cdot (C) \cdot (x) + (C) \cdot (Q) \cdot \left(C_f\right) \cdot \left(x_f\right) = \left(F_x\right)$$

$$(C)^T \cdot (Q) \cdot (C) \cdot (y) + (C) \cdot (Q) \cdot (C_f) \cdot (y_f) = (F_x)$$

$$(C)^T \cdot (Q) \cdot (C) \cdot (z) + (C) \cdot (Q) \cdot (C_f) \cdot (z_f) = (F_x)$$

after the introduction of substitution

$$(D) = (C)^T \cdot (Q) \cdot (C) \qquad (D_f) = (C)^T \cdot (Q) \cdot (C_f)$$

continue to shape.

$$(D) \cdot (x) = (F_x) \cdot - (D_f) \cdot (x_f) \quad (D) \cdot (y) = (F_y) \cdot - (D_f) \cdot (y_f) \quad (D) \cdot (z) = (F_z) \cdot - (D_f) \cdot (z_f)$$

from which we express the node's final position

$$(x) = \left[(F_x) \cdot - (D_f) \cdot (x_f) \right] \cdot (D)^{-1} \qquad (y) = \left[(F_y) \cdot - (D_f) \cdot (y_f) \right] \cdot (D)^{-1}$$

$$(z) = \left[(F_z) \cdot - (D_f) \cdot (z_f) \right] \cdot (D)^{-1}$$

The equilibrium equations described above represent the linear system of equations, after the solution, we obtain the equilibrium of the position of the nodes. By introducing a force density coefficient (q) a set of otherwise non-linear equations was modified to allow its solution in one computed step. However, this method of solution is highly difficult for programming.

FDM is commonly used in engineering to find the equilibrium shape of a structure consisting of a network of cables with different elasticity properties when stress is applied. While shape analysis of tensile structures is a geometrically non-linear problem, the FDM linearizes the equations analytically by using the force density ratio for each cable element, $q = S / L$, where S and L are the force and length of a cable element respectively. The method relies on the assumption that the ratio of tension force to the length of each cable can be constant, transforming a system of non-linear equations into a set of linear equations which can be solved directly.

The properties of the force density method were subsequently studied thoroughly, and the method could be implemented in an efficient way by applying special sparse matrix techniques for solving the resulting equations. It proved to be a powerful tool for setting up and solving the equations of equilibrium for prestressed networks and structural membranes, without requiring any initial coordinates of the structures.

The essential ideas are as follows. Pin-joined network structures assume the state of equilibrium when internal forces S and external forces F are balanced.

For the compilation of a computational program, equations of equilibrium can be converted into the following form:

Equilibrium of free node i

j ∈ Ni means j is an element of the set Ni

$$\sum_{j\in Ni} \left[\left(S_{i,j}\cdot\cos\alpha_{i,j}\right) = 0\right] \qquad \sum_{j\in Ni} \left[\left(S_{i,j}\cdot\cos\beta_{i,j}\right) = 0\right] \qquad \sum_{j\in Ni} \left[\left(S_{i,j}\cdot\cos\gamma_{i,j}\right) = 0\right]$$

$$\cos\alpha_{i,j} = \frac{x_j - x_i}{l_{i,j}} \qquad \cos\beta_{i,j} = \frac{y_j - y_i}{l_{i,j}} \qquad \cos\gamma_{i,j} = \frac{z_j - z_i}{l_{i,j}}$$

where

$$l_{(i,j)} = l\left(x_i, y_i, z_i, x_j, y_j, z_j\right) = \sqrt{\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2 + \left(z_j - z_i\right)^2}$$

$$\sum_{j\in Ni} \left[\left(S_{i,j}\cdot\frac{z_j - z_i}{l_{i,j}}\right) = 0\right] \quad \sum_{j\in Ni} \left[\left(S_{i,j}\cdot\frac{x_j - x_i}{l_{i,j}}\right) = 0\right] \quad \sum_{j\in Ni} \left[\left(S_{i,j}\cdot\frac{y_j - y_i}{l_{i,j}}\right) = 0\right]$$

Si,j is the force value in the element (i, j), with positive orientation from the node i toward the node j,

αi,j, βi,j, γi,j are angles between coordinate axes and axis of the element (i, j), oriented from i toward j,

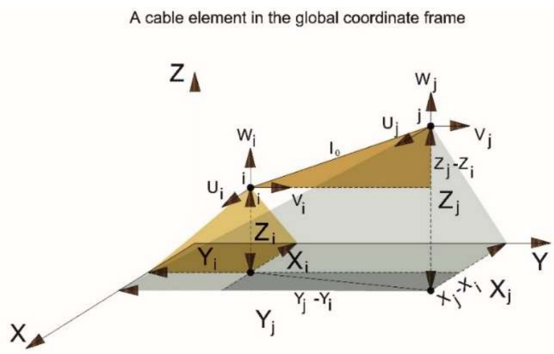


Fig. 2.3.1.3. Cable Element in the Global Coordinate Frame

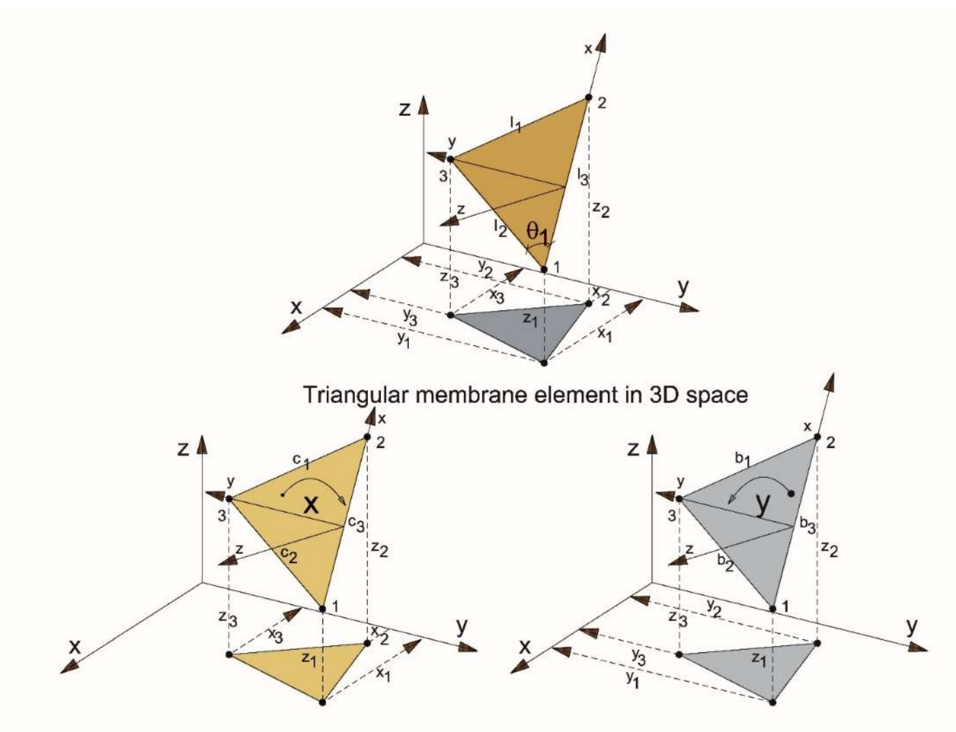


Fig. 2.3.1.4. Triangle membrane element in 3D space

$l_{i,j}$ is the length of the element (i,j).

The nonlinear algebraic equation system will be obtained.

$$\sum_{j\in Ni}\left[\left[S_{i,j}\cdot\frac{x_j-x_i}{\sqrt{\left(x_j-x_i\right)^2+\left(y_j-y_i\right)^2+\left(z_j-z_i\right)^2}}\right]=0\right]$$

$$\sum_{j\in Ni}\left[\left[S_{i,j}\cdot\frac{y_j-y_i}{\sqrt{\left(x_j-x_i\right)^2+\left(y_j-y_i\right)^2+\left(z_j-z_i\right)^2}}\right]=0\right]$$

$$\sum_{j\in Ni}\left[\left[S_{i,j}\cdot\frac{z_j-z_i}{\sqrt{\left(x_j-x_i\right)^2+\left(y_j-y_i\right)^2+\left(z_j-z_i\right)^2}}\right]=0\right]$$

$i \in N_f$ means i is an element of the set N_f

If the relationships $S_{i,j} / l_{i,j}$ in the equilibrium system are denoted $q_{i,j}$, the system becomes

$$q_{(i,j)}=\frac{S_{i,j}}{\sqrt{\left(x_j-x_i\right)^2+\left(y_j-y_i\right)^2+\left(z_j-z_i\right)^2}}$$

are called force densities.

$$\sum_{j \in Ni} \left[\left[q_{i,j} \cdot \left(z_j - z_i\right)\right] = 0\right] \quad \sum_{j \in Ni} \left[\left[q_{i,j} \cdot \left(x_j - x_i\right)\right] = 0\right]$$

$$\sum_{j \in Ni} \left[\left[q_{i,j} \cdot \left(y_j - y_i\right)\right] = 0\right]$$

Force densities $q_{i,j}$ can be set instead of force values $S_{i,j}$.

$$q_{ij} \cdot \left(x_j - x_i\right) + q_{ik} \cdot \left(x_k - x_i\right) + q_{il} \cdot \left(x_l - x_i\right) + q_{im} \cdot \left(x_m - x_i\right) + F_{xi} = 0$$

$$q_{ij} \cdot x_j - q_{ij} \cdot x_i + q_{ik} \cdot x_k - q_{ik} \cdot x_i + q_{il} \cdot x_l - q_{il} \cdot x_i + q_{im} \cdot x_m - q_{im} \cdot x_i + F_{xi} = 0$$

$$-x_i \cdot \left(q_{ij} + q_{ik} + q_{il} + q_{im}\right) + q_{ij} \cdot x_j + q_{ik} \cdot x_k + q_{il} \cdot x_l + q_{im} \cdot x_m + F_{xi} = 0.$$

$$x_i \cdot \left(q_{ij} + q_{ik} + q_{il} + q_{im}\right) = q_{ij} \cdot x_j + q_{ik} \cdot x_k + q_{il} \cdot x_l + q_{im} \cdot x_m + F_{xi}$$

$$x_i = \frac{\left(q_{ij} \cdot x_j + q_{ik} \cdot x_k + q_{il} \cdot x_l + q_{im} \cdot x_m + F_{xi}\right)}{\left(q_{ij} + q_{ik} + q_{il} + q_{im}\right)}$$

what is possible for the general network topology write as follows:

$$x_i = \frac{\sum_{j=1}^{n} \left(x_j \cdot q_{ij} + Fxi\right)}{\sum_{j=1}^{n} q_{ij}} \qquad y_i = \frac{\sum_{j=1}^{n} \left(y_j \cdot q_{ij} + Fyi\right)}{\sum_{j=1}^{n} q_{ij}} \qquad z_i = \frac{\sum_{j=1}^{n} \left(z_j \cdot q_{ij} + Fzi\right)}{\sum_{j=1}^{n} q_{ij}}$$

This suggests that the equilibrium position of each node in the space is a function of the average position of its neighbours, where the great coefficient is the force density of the bristles seizing the solved nodes.

Fig. 2.3.1.5. Prestress Cable Force Density Method

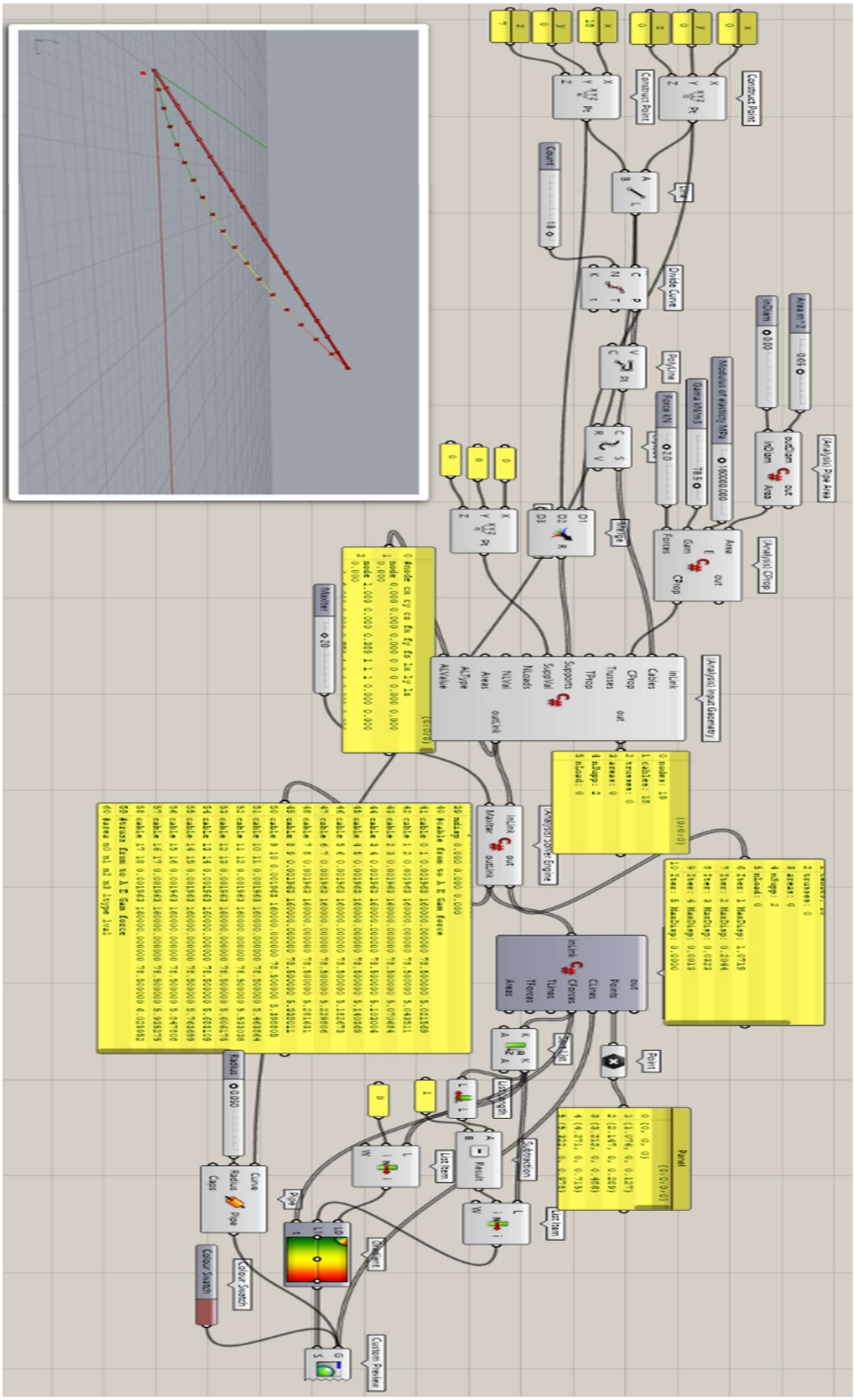


Fig. 2.3.1.6. Analysis of Prestress Cable

2.3.2 ADVANTAGES AND DISADVANTAGES OF MEMBRANE STRUCTURES

As already mentioned, membrane structures are a popular choice for a variety of applications, from sports stadiums and exhibition halls to temporary pavilions and shelters. One of the key advantages of membrane structures is their lightweight and enormous flexibility. Compared to traditional building materials, such as concrete and steel, membranes are significantly lighter, requiring less material and energy to transport and assemble. Compared to traditional rigid constructions, they make it easier to cover large spans with a minimum number of support elements (such as columns). Additionally, membranes can be shaped into complex geometries that would be difficult or impossible to achieve with rigid materials. This can result in striking and unique architectural designs that are both functional and aesthetically pleasing, providing almost unlimited possibilities for finding non-traditional elegant forms [13, 14].

Another advantage of membrane structures is their ability to provide natural lighting and ventilation. Translucent membrane materials can allow natural light to filter through, reducing the need for artificial lighting during the day. Additionally, the permeable nature of membrane structures allows for passive ventilation, reducing the need for mechanical ventilation systems that require energy to operate. This can result in significant energy savings and a more sustainable building design. Economically, membrane constructions are less demanding because they require only minimal maintenance compared to conventional constructions of similar dimensions.

However, membrane structures also have some disadvantages. One of the main challenges is ensuring their durability and longevity. Membrane materials can be vulnerable to weathering, particularly from exposure to ultraviolet (UV) radiation, which can cause fading and degradation over time. Additionally, the tensioning systems required to keep membranes taut can require regular maintenance and adjustment to ensure structural stability. Finally, while membrane structures can be cost-effective in some cases, the need for specialized design and engineering expertise can make them more expensive than traditional building materials in other cases.

In 2010, the independent association Tensinet, which covers universities, scientists, designers, material manufacturers, and light construction contractors, tasked its members with finding and describing the shape and geometry of a cone and hyperbolic paraboloid between given support points and with a given internal prestress. This task aimed to gather information on the method of analysis and procedures for finding the shape from all globally relevant organizations. Although the tasks had an exact solution, the results varied by up to 200% between the organizations [Tensinet].

3.0 FREE-FORM IN ARCHITECTURE

Free-form architecture refers to a design approach that deviates from conventional, rectilinear forms and instead incorporates irregular, organic shapes and curves. It emphasizes the importance of fluidity, motion, and sculptural qualities, using advanced computational tools and fabrication techniques to realize complex forms.

One of the key advantages of free-form architecture is its ability to create unique and memorable buildings that stand out in the urban landscape. The use of free-form shapes allows architects to design buildings that are not limited by traditional geometric constraints, resulting in visually striking structures that can evoke a sense of wonder and awe in viewers. Additionally, the use of parametric design tools and digital fabrication techniques allows for greater precision and customization, enabling architects to create complex shapes that would be difficult to achieve through traditional construction methods.

However, the complex shapes and non-standard geometry of freeform architecture can also present challenges. It can be more difficult and expensive to construct and maintain, as well as requiring specialized expertise in design, engineering, and construction. Furthermore, it may be more difficult to integrate freeform buildings into the surrounding urban fabric, and they may not always meet functional requirements as efficiently as more conventional forms.

Overall, freeform architecture has the potential to shape the future of architecture, allowing architects to explore new forms of expression and push the boundaries of what is possible in design. Freeform architecture is characterized by irregular, non-rectangular shapes and forms, whereas conventional architecture typically adheres to traditional rectangular or linear shapes. Freeform structures often have more organic shapes that mimic natural forms, whereas conventional structures tend to be more rigid and geometric. Freeform architecture relies heavily on advanced digital design and fabrication techniques, while conventional architecture often utilizes more traditional construction methods.

One of the main advantages of free-form architecture is the increased design flexibility and potential for creative expression. Free-form structures can be designed to more closely reflect the natural environment, and can create unique and memorable spaces that stand out from conventional designs. Additionally, free-form structures often have improved structural efficiency due to their unique shapes, which can allow for lighter and more efficient use of materials.

Overall, the use of free-form architecture is becoming increasingly popular as architects and designers seek to push the boundaries of traditional design and create more unique and memorable spaces. However, it is important to carefully consider the advantages and disadvantages of freeform design in order to ensure that the final structure is both aesthetically appealing and structurally sound.

Our contribution to this topic was the creation of free-form geometry by means of parametric programming using the Grasshopper inside Rhino software presented in the following sub-chapters for each category. The process of thinking when creating the scripts for grid shells is depicted on Fig. 3.1.1. and 3.1.2. Other examples are presented for the corresponding categories in Fig. 3.3.2, 3.4.2, and 3.5.2. After preparing the script, we printed the physical models based on the scripts by 3D printing. Examples of several free-form physical models created in this way are shown in the following sub-chapters in Figures 3.1.3., 3.1.4., 3.2.2, 3.3.1., 3.3.3., 3.4.3., and 3.5.3.

3.1 GRID SHELLS IN ARCHITECTURE

Grid shells are innovative and structurally efficient architectural design elements that offer several advantages and creative possibilities. Here are some of the advantages and creative design aspects of grid shells in architecture:

Advantages of using grid shells:

1. Lightweight and efficient: Grid shells are typically lightweight and require less material to construct than traditional building structures, making them more environmentally friendly and cost-effective.
2. Flexibility: Grid shells can be designed to fit a variety of shapes and sizes, making them a versatile choice for architects.
3. Durability: Grid shells can withstand natural disasters such as earthquakes and high winds, making them a safer choice for buildings in areas prone to these types of events.
4. Aesthetics: The complex and intricate patterns created by the grid structure can be visually stunning and enhance the overall design of the building.

Creative design aspects:

1. Complex forms: Grid shells can be designed to create complex shapes and forms that would be difficult or impossible to achieve with traditional building materials.

2. Customizable patterns: The grid structure of the shell can be designed with various patterns and densities, allowing architects to create unique designs and patterns on the exterior of the building.
3. Lighting effects: The grid structure of the shell can be designed to create unique lighting effects, such as the diffusion of natural light into the building's interior.
4. Integration with nature: Grid shells can be designed to integrate with the natural environment, such as incorporating plant life into the structure, creating a green facade, or allowing for natural ventilation.

Overall, grid shells offer several advantages and creative design possibilities that make them a popular choice for architects looking to create visually stunning and structurally efficient buildings.

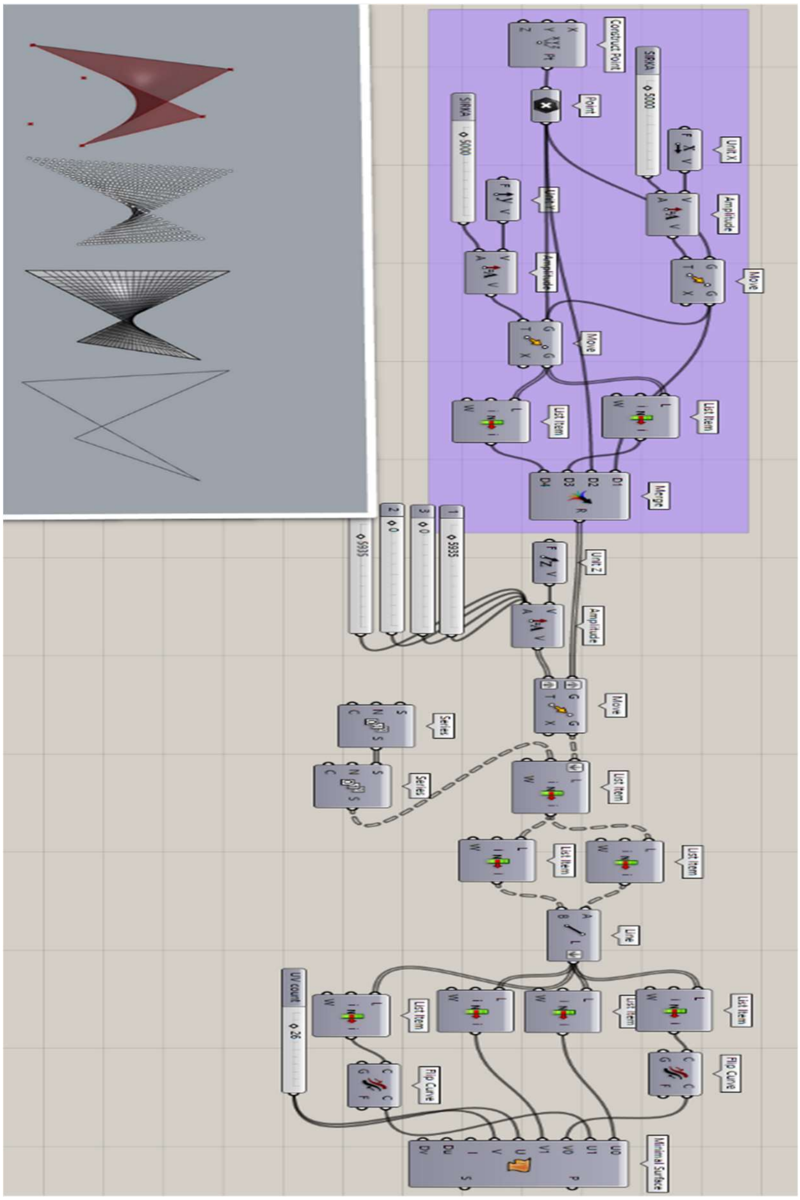


Fig. 3.1.1. Tensile Structures, Form-Finding (script created by the author)

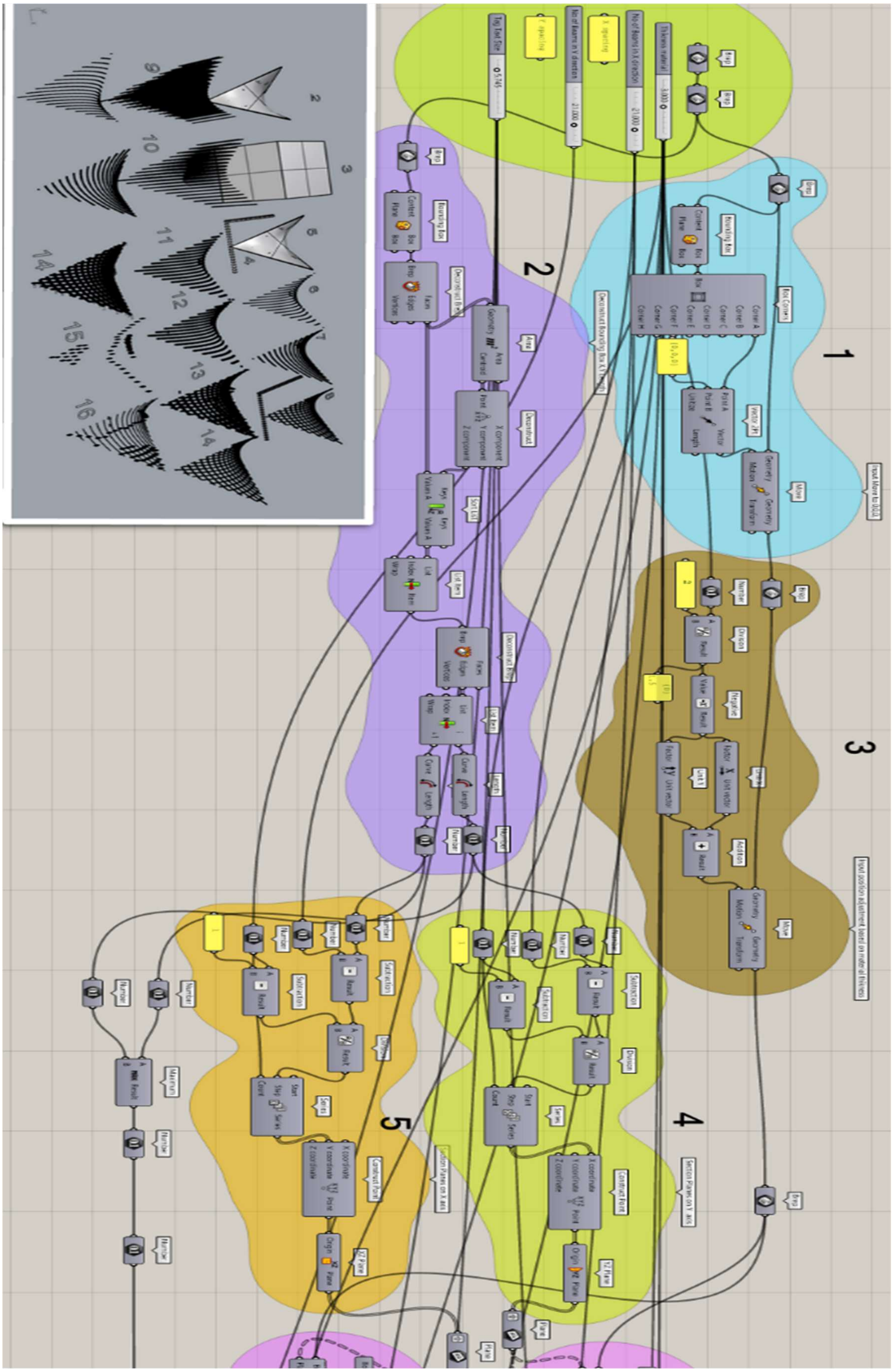


Fig. 3.1.2. Grid Shell Parametric Design I (waffle created by the author)

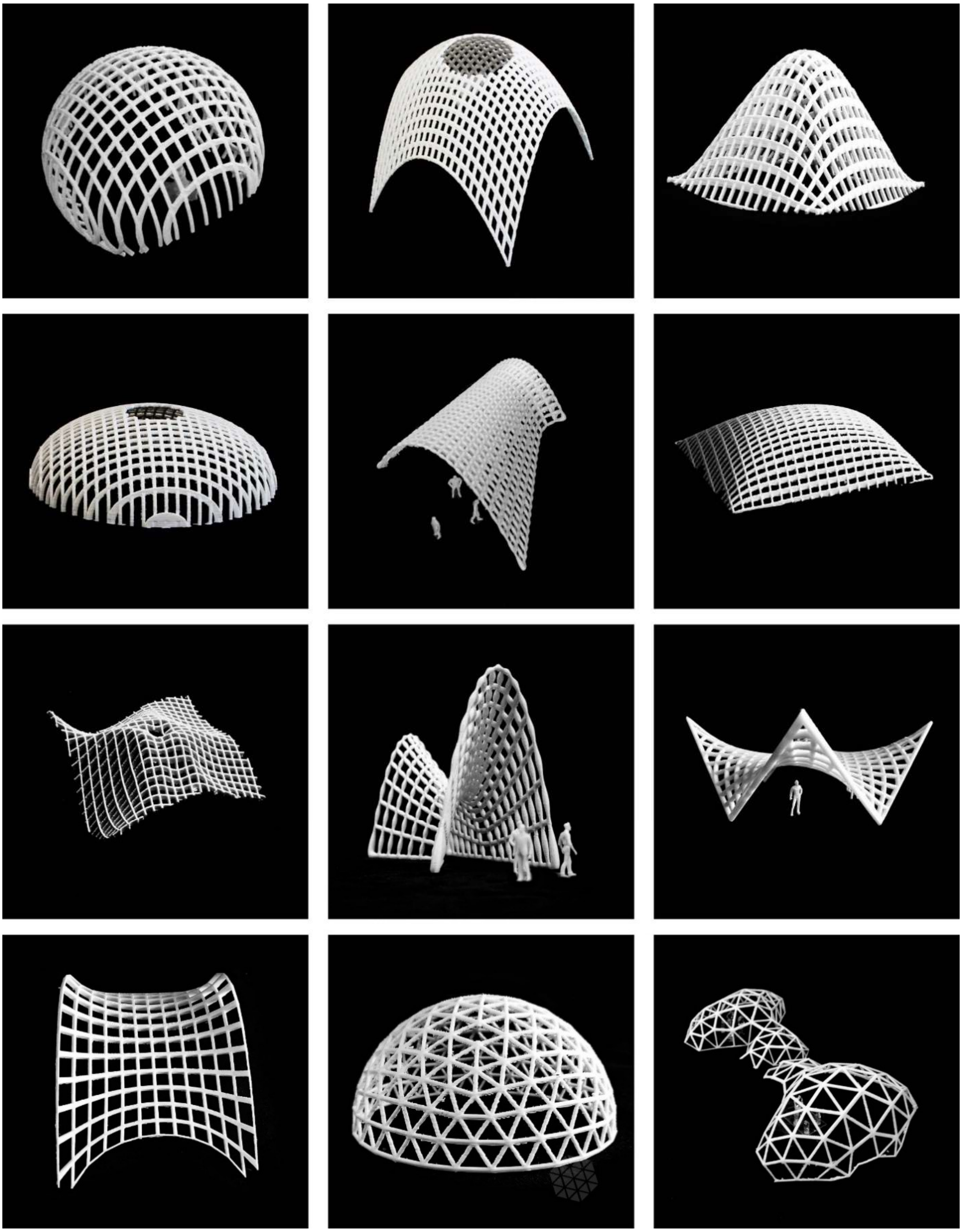


Fig. 3.1.3. Grid Shell Parametric Design II (models created by the author)

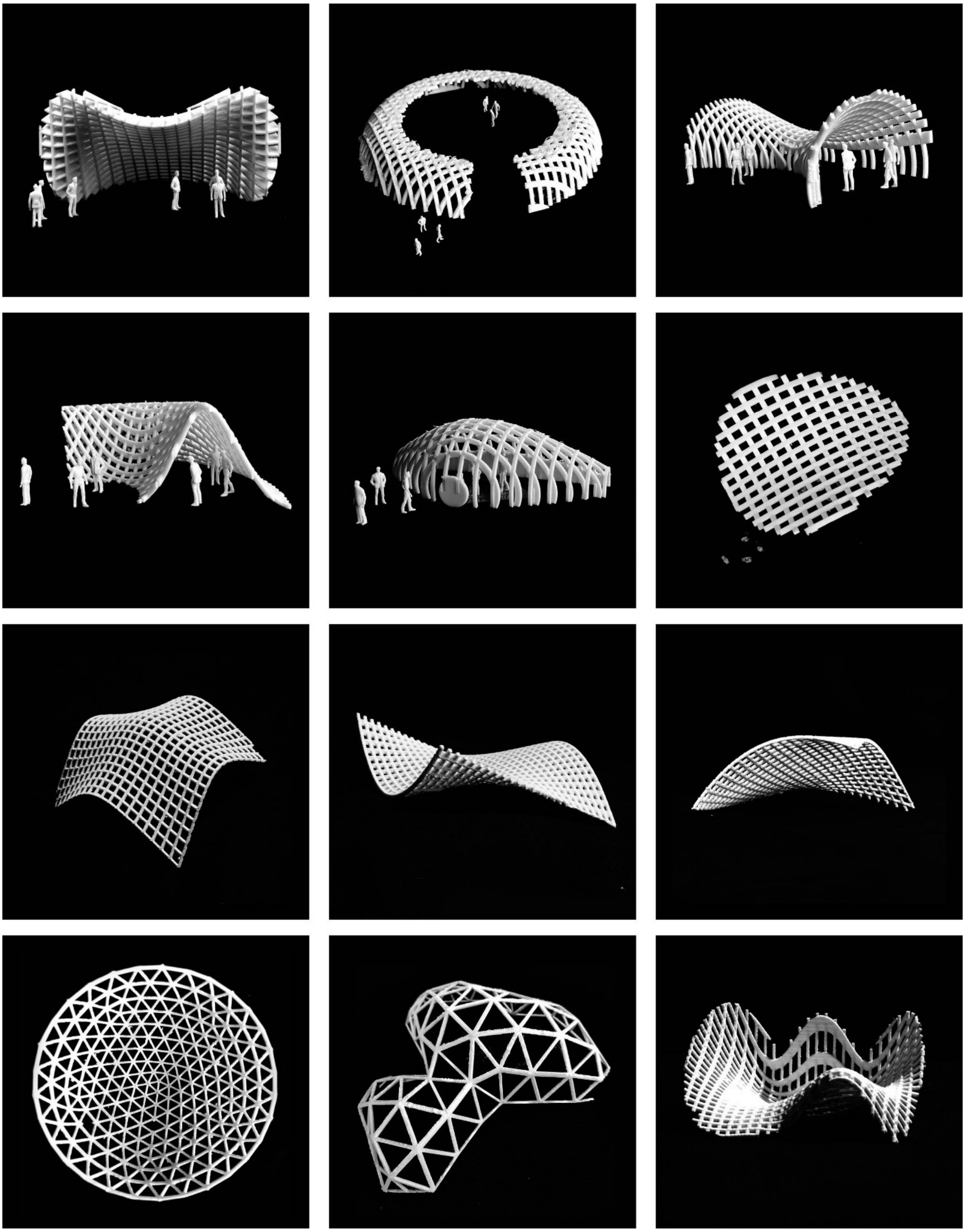


Fig. 3.1.4. Grid Shell Parametric Design III (models created by the author)

3.2 BIOMIMICRY DESIGN IN ARCHITECTURE

Biomimicry is a design approach that draws inspiration from nature to create innovative solutions for human challenges. In architecture, biomimicry has become increasingly popular as designers seek to create buildings that are not only aesthetically pleasing but also efficient, sustainable, and resilient. By studying the natural world and its systems, architects can learn from billions of years of evolution and apply these principles to their designs. One of the advantages of biomimicry in architecture is that it can lead to more sustainable and energy-efficient buildings.

For example, the design of the Eastgate Centre in Harare, Zimbabwe, was inspired by the cooling systems used by termite mounds. The building uses natural ventilation and thermal mass to regulate its temperature, reducing energy consumption by up to 90% compared to a conventional building. Another example is the Lotus Building in China, which was designed to mimic the lotus flower, using its self-cleaning properties to keep the building's exterior free of dirt and pollution.

Biomimicry can also lead to more resilient buildings that are better able to withstand natural disasters. By studying the structures and materials found in nature, architects can design buildings that are stronger and more durable. For example, the design of the Bionic Tower in Shanghai was inspired by the structure of a bamboo stalk, which is known for its strength and flexibility. The building's structure can withstand earthquakes and high winds, making it more resilient in the face of natural disasters. Overall, biomimicry design in architecture offers a range of advantages, including sustainability, energy efficiency, and resilience. As architects continue to explore the natural world for inspiration, we can expect to see more innovative and inspiring buildings that are not only beautiful but also functional and sustainable.

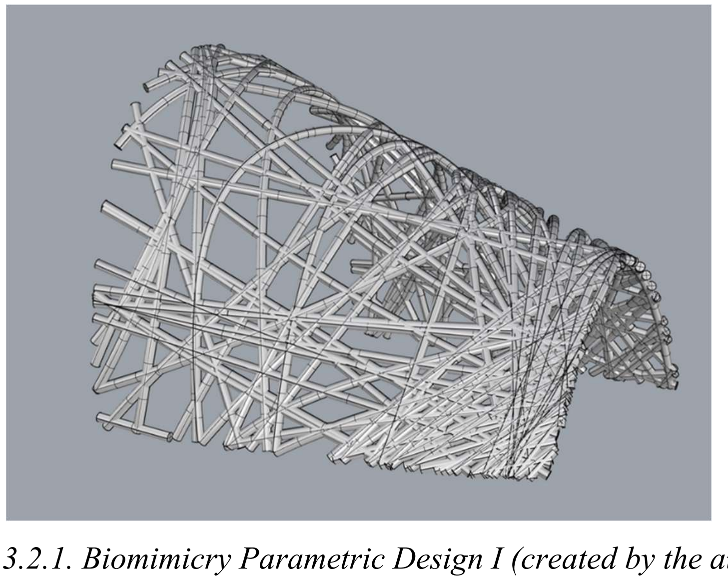


Fig. 3.2.1. Biomimicry Parametric Design I (created by the author)

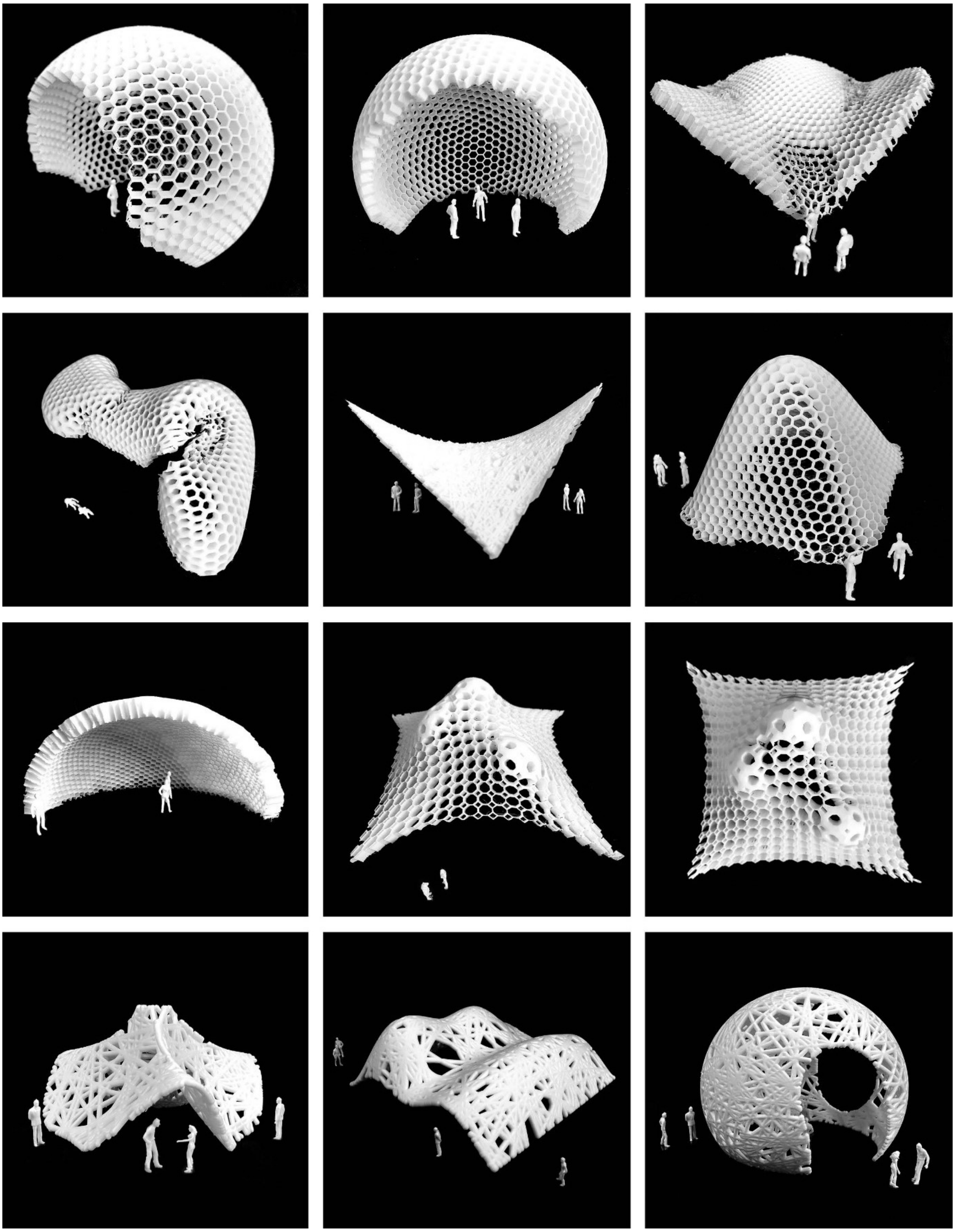


Fig. 3.2.2. Biomimicry Design Parametric Design II (models created by the author)

3.3 TOPOLOGY IN ARCHITECTURE

Topology is a branch of mathematics that studies the properties of space that are preserved under continuous transformations, such as stretching, bending, and twisting. In recent years, topology has become an increasingly popular tool for architects and designers, as it offers a new way of thinking about space and form. The use of topology in architecture allows for the creation of complex, non-Euclidean forms that challenge our traditional understanding of space and geometry. By using topological principles, architects can create buildings and structures that are not limited by the constraints of traditional geometry, resulting in unique and innovative designs.

One of the creative advantages of using topology in architecture is the ability to create structures that are both aesthetically pleasing and functional. For example, the design of the Heydar Aliyev Center in Azerbaijan, by architect Zaha Hadid [16,17] uses topological principles to create a fluid, organic form that is both visually striking and functional. The building's curved surfaces and irregular shapes create a sense of movement and fluidity, while its efficient use of space allows for optimal functionality. Another advantage of using the topology in architecture is the ability to optimize the use of materials and minimize waste. By using topological principles to design structures, architects can create forms that require less material and energy to construct, resulting in more sustainable and efficient buildings. Overall, topology offers architects and designers a new way of thinking about space and form, allowing for the creation of unique and innovative designs that are both aesthetically pleasing and functional. As topology continues to gain popularity in the field of architecture, we can expect to see more creative and inspiring designs that challenge our traditional understanding of space and geometry [18].

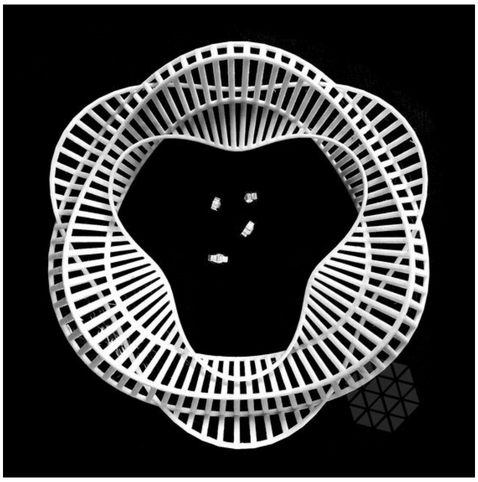


Fig. 3.3.1. Topology in Architecture (models created by the author)

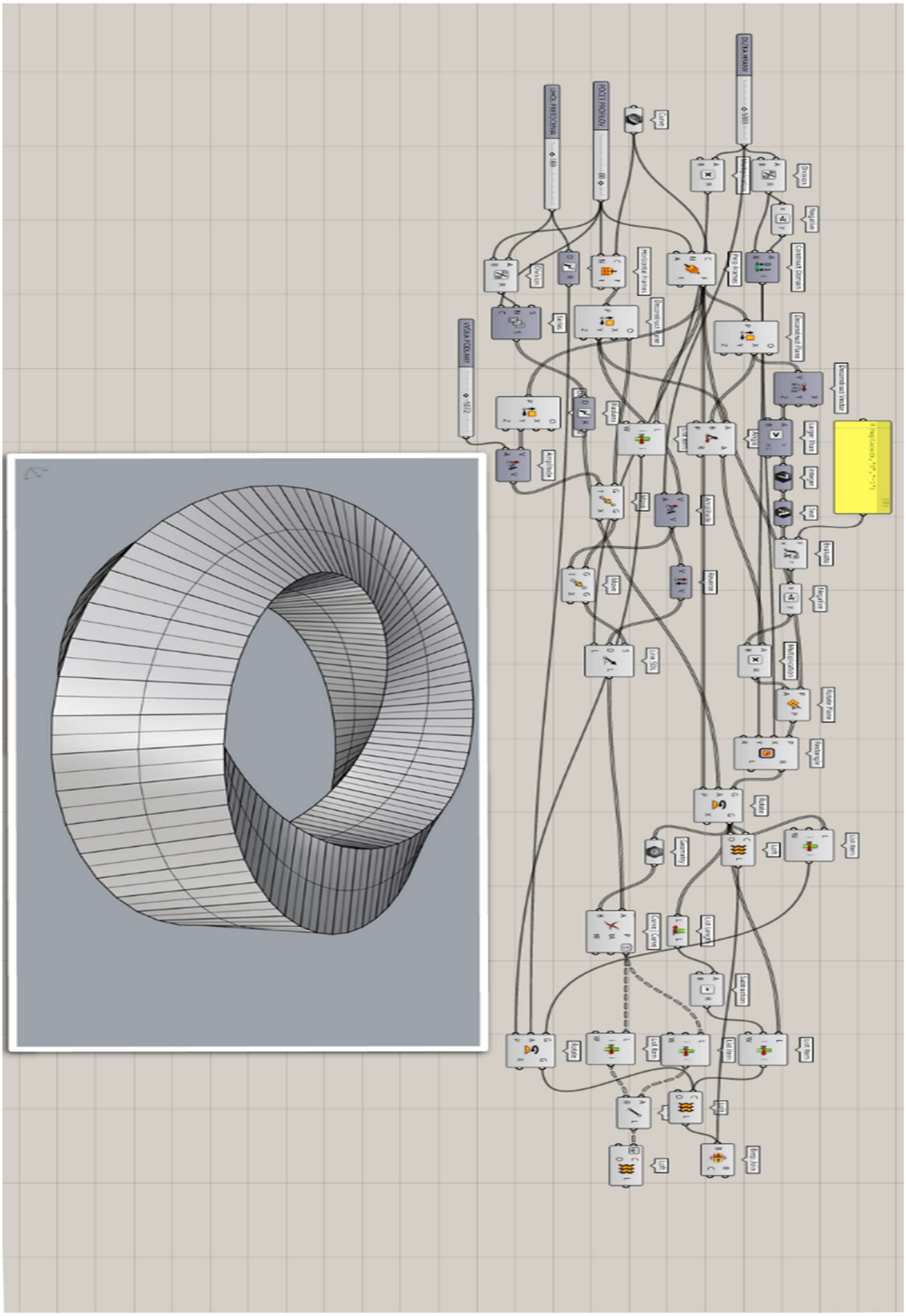


Fig. 3.3.2. Mobius Band (script created by the author)

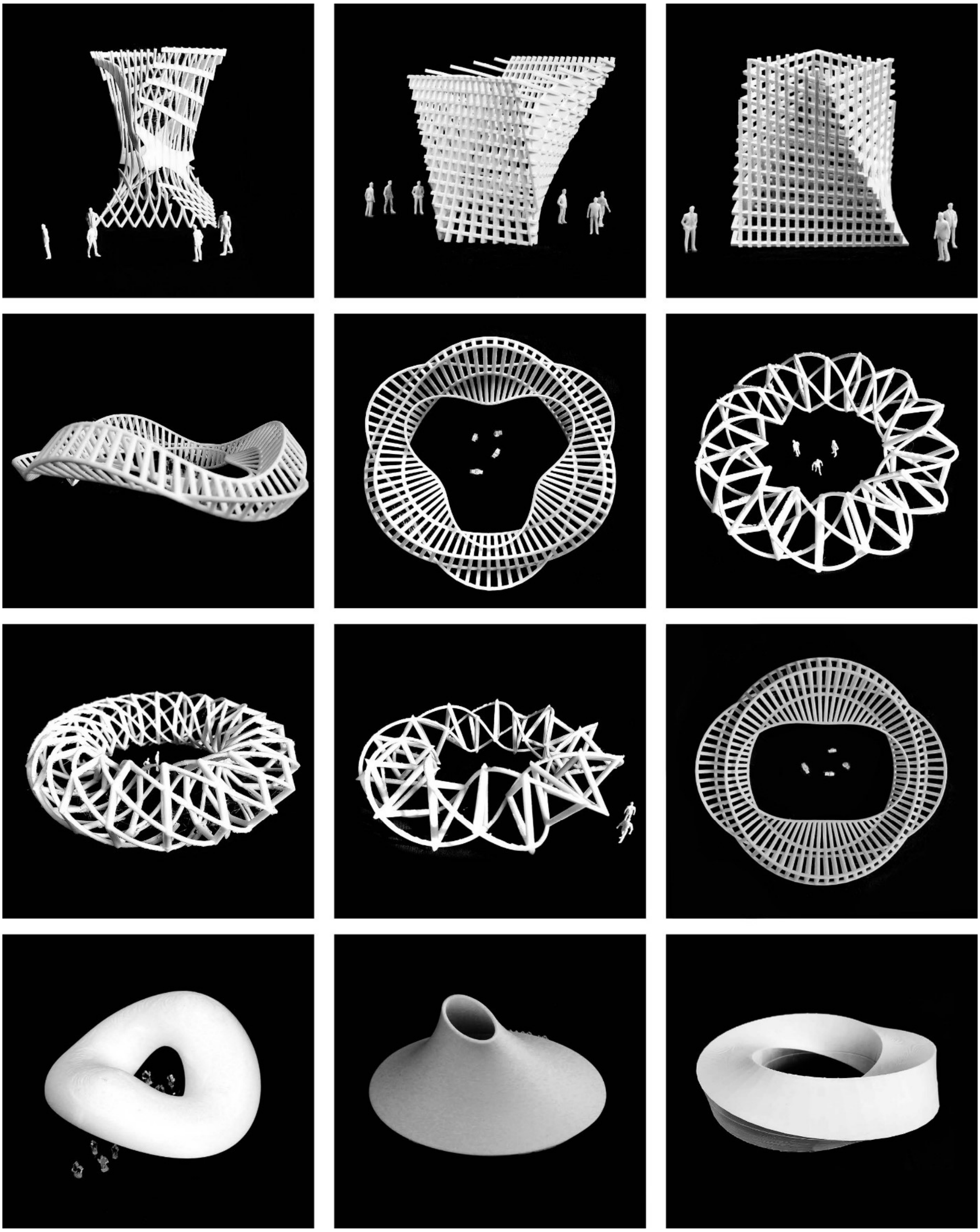


Fig. 3.3.3. Topology Parametric Design (models created by the author)

3.4 TESSELLATION DESIGN IN ARCHITECTURE

Tessellation, also known as tiling, is a mathematical concept that involves covering a surface with a repeating pattern of geometric shapes without any gaps or overlaps. In architecture, tessellation has become an increasingly popular design technique, as it offers a range of advantages in terms of aesthetics, functionality, and sustainability. One of the advantages of tessellation design in architecture is the ability to create visually striking and cohesive designs. By using a repeating pattern of geometric shapes, architects can create a sense of order and unity in their designs, while also adding visual interest and complexity. This technique has been used in a variety of architectural styles, from ancient Islamic architecture to contemporary buildings like the Guggenheim Museum Bilbao, which features a tessellated titanium exterior.

Tessellation design can also offer functional advantages in architecture, such as improved acoustics and thermal performance. By using regular and repeating shapes, architects can create surfaces that reflect and absorb sound in a predictable manner, leading to better acoustics in spaces like concert halls or lecture theatres. Additionally, tessellation can be used to optimize the use of materials and reduce waste, as it allows for the efficient use of standardized building components. Another advantage of tessellation design in architecture is its potential for sustainability. By using a repeating pattern of modular units, architects can create buildings that are easy to disassemble and recycle, reducing the environmental impact of construction and demolition.

Overall, tessellation design offers a range of advantages in architecture, from improved aesthetics to functional and sustainable benefits. As architects continue to explore this design technique, we can expect to see more innovative and inspiring designs that make use of tessellation to create unique and efficient buildings.

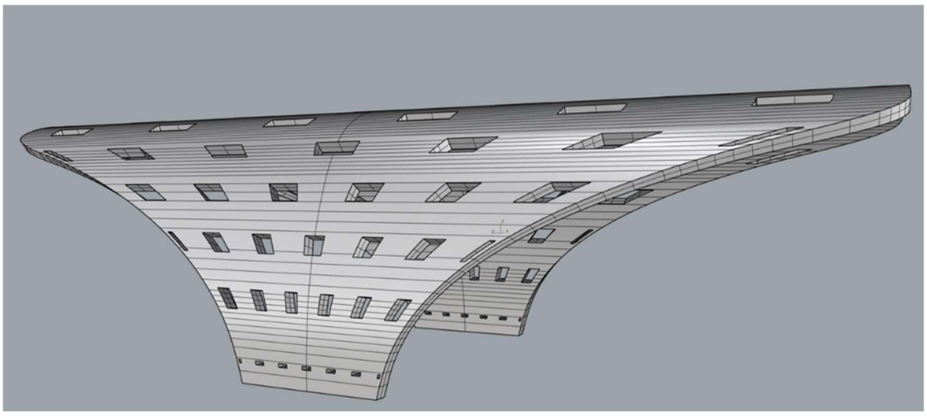


Fig. 3.4.1. Tessellation Design (created by the author)

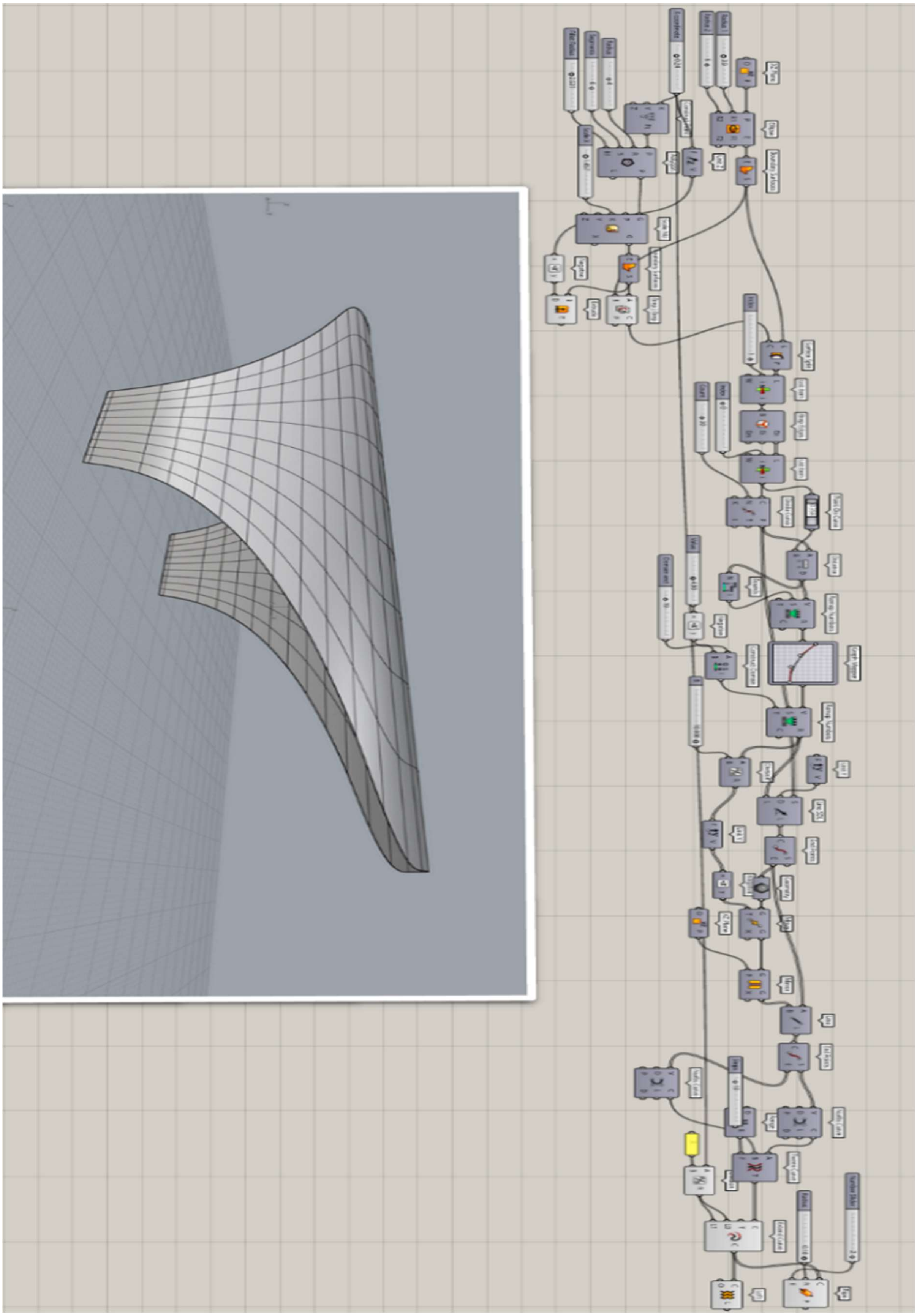


Fig. 3.4.2. Process of Form-Finding Geometry (script created by the author)

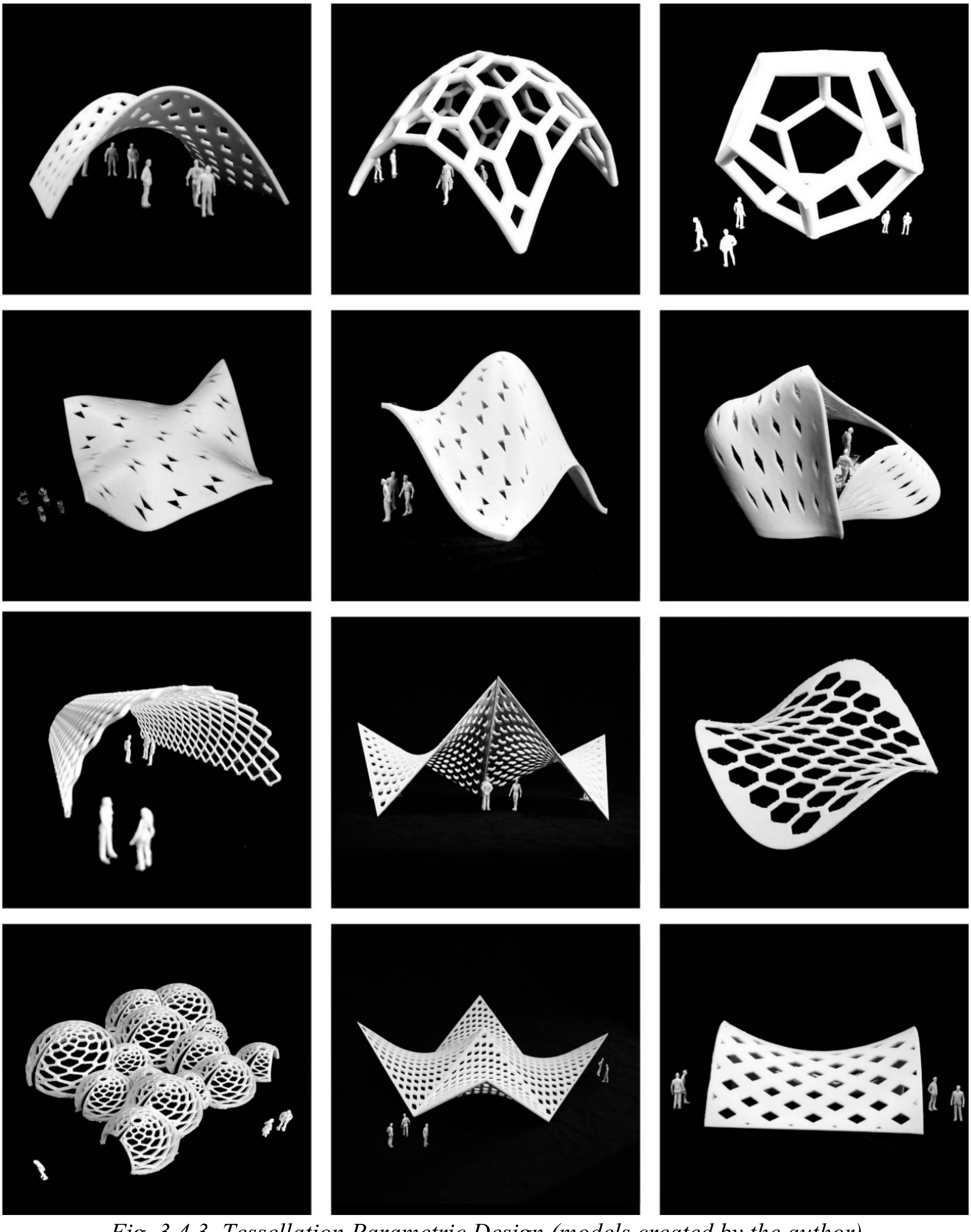


Fig. 3.4.3. Tessellation Parametric Design (models created by the author)

3.5 VORONOI DESIGN IN ARCHITECTURE

Voronoi design, also known as Voronoi tessellation, is a geometric pattern that is created by dividing a surface into irregular, but interconnected polygons. In architecture, Voronoi design has gained popularity due to its ability to create visually striking and functional designs.

One of the advantages of Voronoi design in architecture is its ability to optimize the use of space and material. By using a Voronoi pattern, architects can create buildings that are more efficient in their use of materials and energy, leading to more sustainable and cost-effective designs. The Voronoi pattern can also be used to create facades that provide shading and natural ventilation, reducing the need for artificial cooling and heating. Another advantage of Voronoi design in architecture is its ability to create unique and visually interesting buildings. The Voronoi pattern creates a complex and irregular geometry that is different from traditional geometric shapes, resulting in structures that are visually striking and aesthetically pleasing. This design technique has been used in a variety of architectural styles, from modernist buildings like the Gherkin in London to organic structures like the Eden Project in Cornwall.

In addition to its functional and aesthetic advantages, Voronoi design has also been used in architectural research to optimize building performance. By using computer simulations to analyse the Voronoi pattern, architects can optimize the shape and size of the polygons to improve factors such as natural lighting, structural stability, and energy efficiency. Overall, Voronoi's design offers a range of advantages in architecture, from sustainability and efficiency to unique and visually interesting designs. As architects continue to explore this design technique, we can expect to see more innovative and inspiring buildings that make use of Voronoi tessellation to create efficient, functional, and beautiful structures.

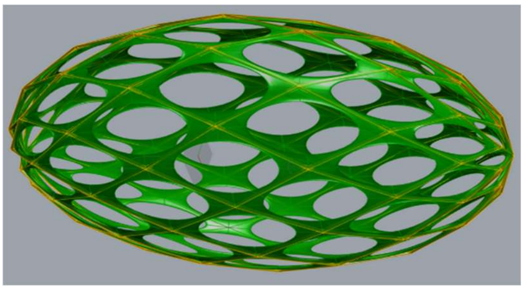


Fig. 3.5.1. Voronoi Design

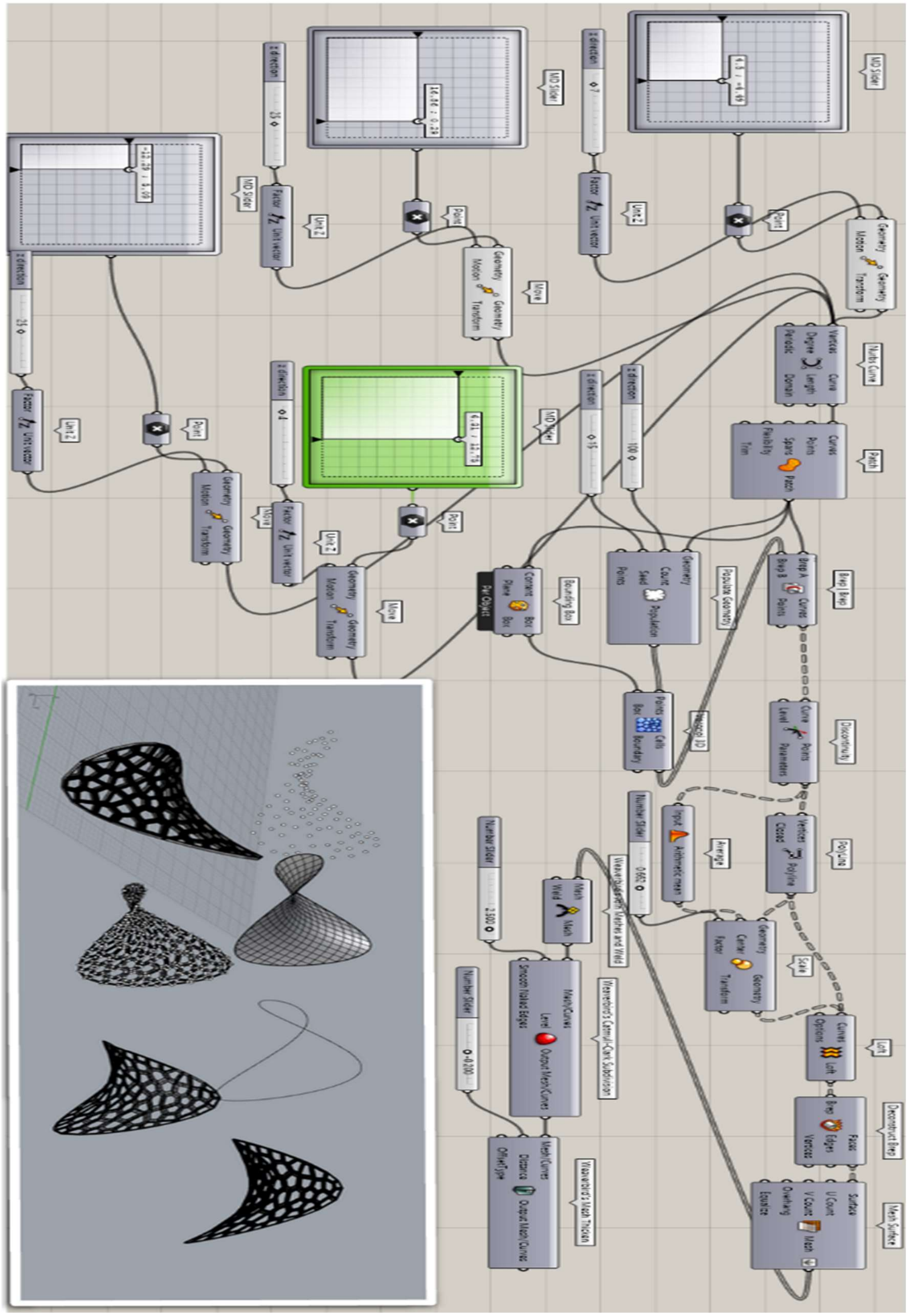


Fig. 3.5.2. Voronoi, Parametric Design I (Script created by the author)

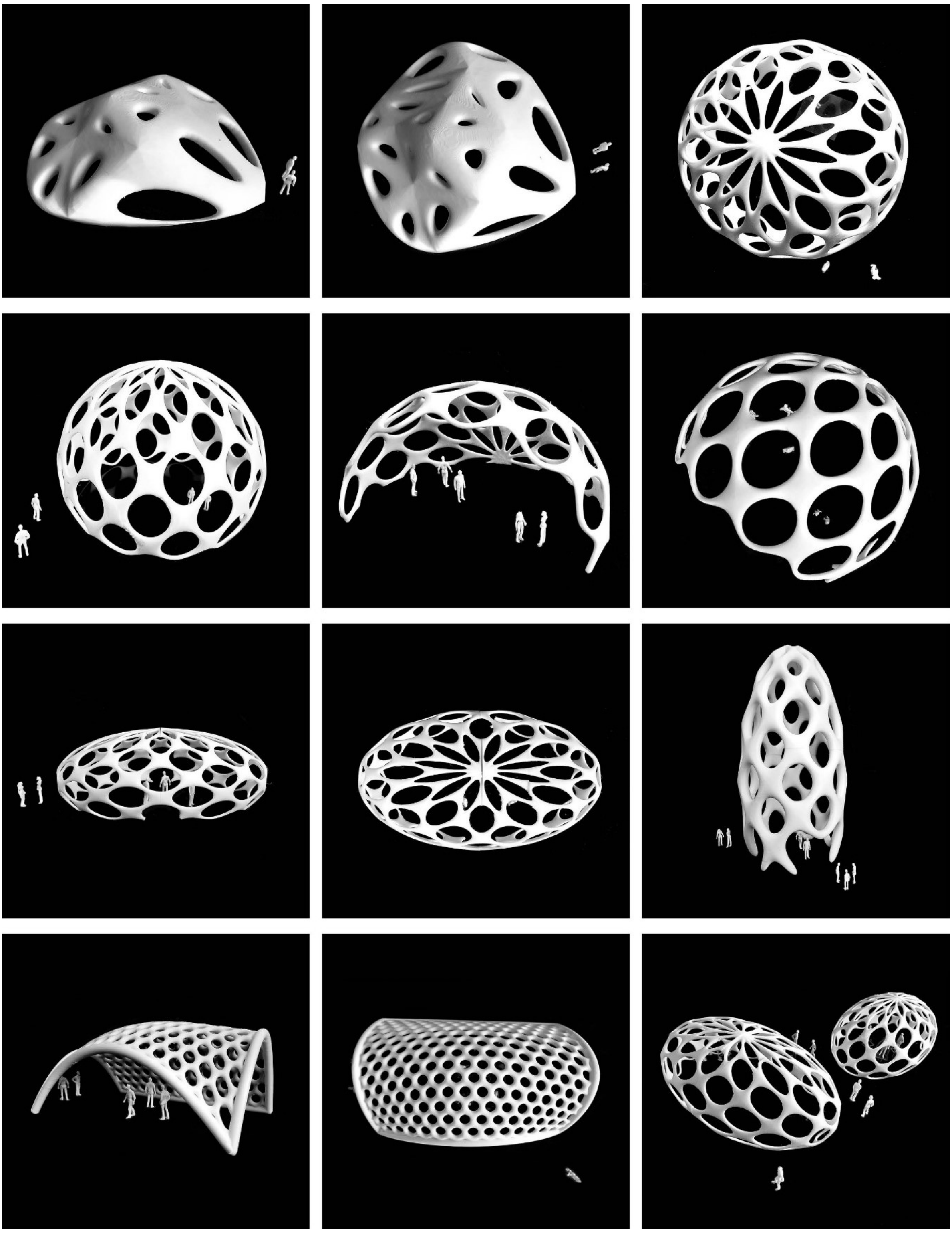


Fig. 3.5.3. Voronoi Parametric Design II (models created by the author)

4.0 CONCLUSION

Designing architecture is a fascinating process that requires a combination of creativity and professional knowledge to achieve a truly spectacular result. The goal of any architectural design is to create a structure that not only serves its intended purpose but also captures the imagination and inspires those who experience it. To achieve this, it is important to approach the design process with a creative mindset that is open to new ideas and possibilities. One way to achieve this is to think outside the box when it comes to architectural form. By experimenting with unconventional shapes and structures, architects can create truly unique and memorable buildings that stand out from the crowd. From curving walls and unusual angles to asymmetrical facades and unexpected materials, there are countless ways to push the boundaries of traditional architecture and create something truly remarkable.

As part of our work, we created several dozen unique physical models of tensegrity constructions, which we transformed into components that can serve indoors (such as table and stationary lamps, anti-gravity tables, and non-traditional chairs), but also outdoors, such as sculptures or hammocks for public spaces.

Furthermore, we realized more than 60 models of unconventional forms, which are divided into five subcategories: grid shells, biomimicry design, topology, tessellation design, and Voronoi design. For each model from these subsets, we first created different form-finding scripts using visual programming involving the specialized software Rhino/Grasshopper and Kangaroo. Subsequently, we created the so-called waffles for 3D printing and laser cut. In order to implement tesselation and Voronoi design, we also created a special script. Building a script involves defining the inputs (e.g. geometry, dimensions, materials), the operations or functions (e.g. creating the grid, applying loads, analyzing the structure), and the outputs (e.g. visualizing the results, exporting the data). Overall, the process of creating a script using visual programming requires a combination of design skills, technical knowledge, and programming expertise.

Free forms of lightweight constructions nicely reflect that, on the one hand, it is necessary to respect the construction and, on the other hand, find the expression for its aesthetic beauty. The results of our work can also be used in the schooling of architecture students, as well as in cooperation with colleagues from related fields, or they can inspire everyone who likes architecture and design.

In conclusion, grid shells, biomimicry design, topology, tessellation design, and Voronoi design are all innovative techniques that are increasingly being used in architecture to create functional, sustainable, and visually striking structures. Grid shells are known for their efficiency in using materials and their ability to create large and lightweight structures, while biomimicry design draws inspiration from nature to create buildings that are optimized for their environment. Topology offers a new way of thinking about space and form, resulting in unique and innovative designs, while tessellation design allows for the creation of visually striking and cohesive designs. Voronoi design, on the other hand, provides the ability to optimize the use of space and material while creating unique and visually interesting forms.

Overall, as architecture continues to evolve, it is likely that we will see more innovative and inspiring designs that make use of these techniques, resulting in geometries that are not only functional and efficient but also beautiful and inspiring.

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Životopis

Osobné údaje

Meno Priezvisko	**doc. Ing. Sabah Shawkat, PhD.**
Adresa	Brigádnická 56, 481 10 Bratislava, SR
Telefón	+421 910 989 753
E-mail	shawkat@vsvu.sk
Štátna príslušnosť	Slovenská Republika
Dátum narodenia	22. 02. 1957

Pedagogická činnosť

Od - do	**r. 2003 – doteraz**
Pracovné zaradenie	**VŠ pedagóg – docent, vedúci kabinetu inžinierskych predmetov**
Zamestnávateľ	**Katedra architektonickej tvorby VŠVU v Bratislave**
Hlavné činnosti a zodpovednosť	Pedagogická činnosť (bakalársky a magisterský stupeň, smer architektonická tvorba), školiteľ doktorandov, garancia inžinierskych predmetov, spolupráca s realizačnými stavebnými firmami, vedenie exkurzií a workshopov pre študentov, spolupráca s ostatnými vysokoškolskými inštitúciami doma a v zahraničí

Od - do	**r. 1999 – 2003**
Pracovné zaradenie	**VŠ pedagóg – docent**
Zamestnávateľ	**Katedra konštrukčno-technických disciplín** **Fakulta architektúry, Slovenská technická univerzita v Bratislave**
Hlavné činnosti a zodpovednosť	Pedagogická činnosť (bakalársky a magisterský stupeň, smer architektúra), garancia inžinierskych predmetov, príprava exkurzií, výstav a workshopov pre študentov doma a v zahraničí

Od - do	**r. 1993 – 1998**
Pracovné zaradenie	**VŠ pedagóg - odborný asistent**
Zamestnávateľ	**Katedra betónových konštrukcií a mostov** **Stavebná fakulta, Slovenská technická univerzita v Bratislave**
Hlavné činnosti a zodpovednosť	Výskumná činnosť v oblasti železobetónových a predpätých konštrukcií v spolupráci s Ústavom architektúry a staviteľstva Slovenskej akadémie vied Pedagogická činnosť (3.-5. roč., smer pozemné stavby), vedenie diplomových prác, ŠVOČ, príprava konferencií

Odborná prax

Od – do	**r. 1997 – doteraz**
	Shawkat ateliér, s.r.o.
	Projektová a odborná činnosť vo výstavbe - autorizovaný stavebný inžinier Slovenskej komory stavebných inžinierov

Od - do	**r. 1988 – 1989**
Pracovné zaradenie	**Projektant**

Zamestnávateľ	**Architektonski studio, Daruar, Chorvátsko**
Hlavné činnosti a zodpovednosť	Projektant – administratívne budovy, rodinné domy, haly
Od - do	**r. 1983 – 1988**
Pracovné zaradenie	**Hlavný inžinier**
Zamestnávateľ	**Organisme de control technique de la construction, Konstantin, Alžírsko**
Hlavné činnosti a zodpovednosť	Projektant a kontrolór spôsobu realizácie projektov domácich a zahraničných firiem

Vzdelávanie

	r. 2000
Názov získanej kvalifikácie	**Docent** v odbore Teória a konštrukcie inžinierskych stavieb Téma habilitačnej práce: Deformačné vlastnosti železobetónových nosníkov Stavebná fakulta, Slovenská technická univerzita v Bratislave
	r. 1997
Názov získanej kvalifikácie	**autorizačné osvedčenie v odbore Statika stavieb -** autorizovaný stavebný inžinier Slovenskej komory stavebných inžinierov
	r. 1993
Názov získanej kvalifikácie	**PhD.** v odbore Pozemné stavby Téma dizertačnej práce: Vplyv priečnych síl na priehyb prútových nosníkov
Od - do	**r. 1975 - 1981**
Názov získanej kvalifikácie	**Ing. - magisterské štúdium, odbor Pozemné stavby** Téma diplomovej práce: Prefabrikované stavby, Bratislavské nové konštrukčné systémy Stavebná fakulta, Slovenská technická univerzita v Bratislave

Jazykové znalosti

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Autor: doc. Ing. Sabah Shawkat, Ph.D.
Vydavateľ: Shawkat Ateliér, spol. s r.o., Brigádnická 56, 841 10 Bratislava
Počet strán: 68
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