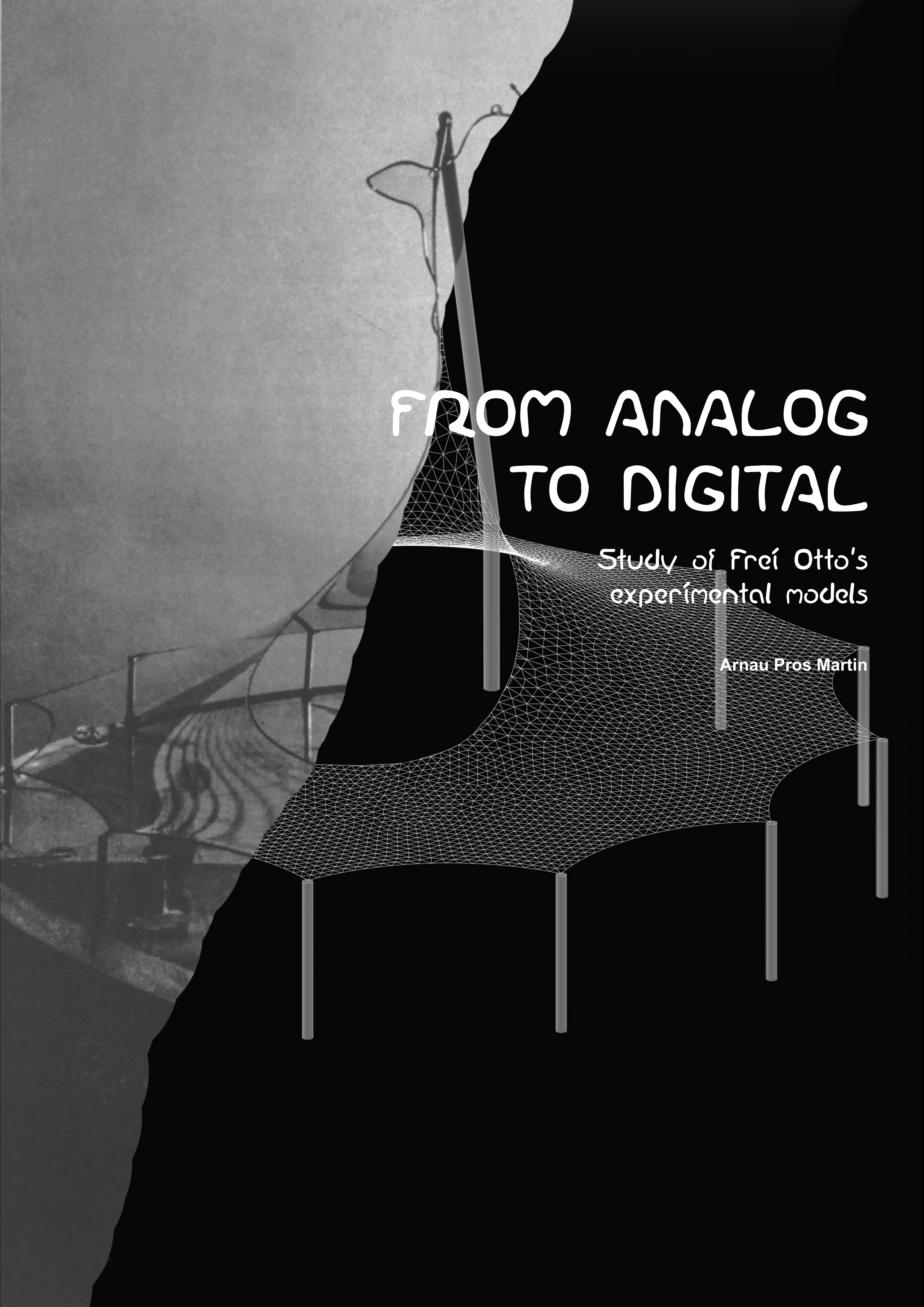


FROM ANALOG TO DIGITAL

Study of Frei Otto's experimental models

Arnau Pros Martin

FROM ANALOG TO DIGITAL

Study of Frei Otto's experimental models

Arnau Pros Martin

Degree's Final Thesis || GArqETSAB 2014

Branch: Architectural Representation

Tutor: Adrià Marco Bercero

Tribunal: Jaime Jose Ferrer Fores
Antoni Ramon Graells
Maria Isabel Zaragoza De Pedro

Barcelona, 10th of February, 2022

ETSAB Escola Tècnica Superior d'Arquitectura de Barcelona
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

“The computer can only calculate what is already conceptually inside of it; you can only find what you look for in computers. Nevertheless, you can find what you haven’t searched for with free experimentation.”

- Frei Otto

Abstract

The need to carry out experiments and physical tests with models is today questioned with the use of the computer; which constitutes an important optimization and a shape search tool. But to what extent?

Frei Otto, a German architect born in 1925 in Siegmar, devoted much of his career to the study of shapes and materials from experimental models. Experimentation in architecture was the central axis of his work. Although the principles of these models cannot be applied directly to buildings, they served a pure research purpose and offered a theoretical point of view in the design of structures. He established an unprecedented working methodology. His experimental models allowed him a further understanding of how materials work at their best when they are under tension, the soap film minimal surface models for tensile membranes and the hanging chain catenary form models for compressive arch and shell structures. This allowed him not only to find an optimal lightweight structure, but also to have a more environmentally friendly approach to architecture.

This research work interrogates, reads, interprets and reconstructs Frei Otto's soap film models in order to find a method of working with digital tools that allows us to deepen the study of these forms. After this study, both methods, analog and digital, will be compared to see which one is better to work with nowadays.

Key words

Experimental model, form finding, Frei Otto, Grasshopper3D, Kangaroo Physics, minimal surface, parametric design, parametric tools, soap film model, tensile structure.

Preface

I remember when I was introduced to the Frei Otto's figure during my first year in the architecture degree. In that year I was introduced to many new architecture references, but among all of them, the work of Frei Otto aroused great interest in me. I was fascinated by the meaningful forms that went above and beyond the simplicity of just being an aesthetic form and responded to the environmental, economic and energy needs. I was hoping that Frei Otto's work would be explained at some point during the degree as it responds to the environmental problem that is really present nowadays, but instead it was only mentioned briefly in some subjects. So whenever I had some time I studied his figure by myself and growth fascinated by his working methodology.

A few years later I was introduced to parametric designing tools in Architectonic Representation IV at university, more precisely to Grasshopper3D with Rhinoceros. I became really interested in these designing tools and thanks to this subject I was offered a job position in the Sagrada Familia architecture department. During my time working there I mainly worked in the bell towers of the Glory façade. The designing tools used there were Rhinoceros for the 3D modeling and Grasshopper3D for the parametric design. A lot of the parts of the Sagrada Familia are designed using form finding as Antoni Gaudí was one of the pioneers of this method. There was where I saw the potential of parametric designing tools used for form finding, the method I was so interested in when I was doing the research of Frei Otto.

Having seen that you can work with the form finding methodology analogically, with physical models, and digitally, with parametric tools, in this research work I wanted to study and work with both approaches and compare the benefits of one another. In orther to do so, I will have Frei Otto's experimental models as a basis and I will study and recreate with both methods, physically and digitally, part of his experiments. As he experimented in a wide variety of fields, I will focus this study on his soap films models related to the minimal surface research. The research will be divided into three different parts, one dedicated to the analog method and one to the digital one, and then I'll compare the benefits of both.

Seeing the potential of digital parametric design and its efficiency instead of the time and resource consuming of the analog approach, before carrying out the research work, my hypothesis is that working with digital models allows us to work with more complex forms and at the same time adapt to the delivery times of the current market, making analog models obsolete.

TABLE OF CONTENTS

1. INTRODUCTION

1.1. WORK OBJECTIVES

The main purpose of this research is to see the potential of current digital parametric tools applied to Frei Otto's work methodology. In orther to do so, I will compare analog and digital experimentation and see the benefits of one versus the other. As I said before, Frei Otto experimented in a lot of fields and this research will focus only in his minimal surface studies, related to the soap film models.

From this objective are derived various necessary analysis that are objectives in themselves. The first one is to study and analyze the work methodology of Frei Otto. After an study of his philosophy and work methodology, I will recreate some of his soap film experimental models myself to experience first hand how is it to work with this material.

The second objective is to check if the statement of Frei Otto quoted at the beginning of this work about digital tools is still valid today. Although he was never adverse to the use of computers, since 1965 all his buildings have been calculated by computer, he assured that in the form finding methodology did not make sense to do it with digital tools because you can only find what has been already put inside the computer. After a research of some parametric tools used for form finding, I will too recreate some of Otto's soap film models digitally to see the benefits of these tools in the minimal surface investigation.

The intention behind combining the sub-objectives helps achieve a sufficient and in-depth knowledge of the form finding methodology - both digital and analogue - enabling comparison.

1.2. STATE OF THE ART

1.2.1 Form Finding With Parametric Design Tools

The number of digital parametric design tools has shown a significant growth over the past few years. Today's computational parametric design tools offer a vast variety of possibilities that have already impacted both academia and the professional field of architecture. These tools have influenced new architectural styles, offering forms that were not possible before. This tool has gradually emerged through a series of technological shifts that happened mostly during the second half of the 20th century leading to the current digital situation.

These applications use various algorithms that calculate optimal structures. Some examples are: Kangaroo as a set of components of Grasshopper3D for Rhinoceros is a Live Physics engine for interactive simulation, form finding, optimization and constraint solving; RhinoVAULT, a tool for designing compression-only structures using Thrust-Network-Approach; CADenary, that uses a spring-particle system for exploring pure-compression and pure-tension structures; Karamba3D as a set of components of Grasshopper3D that is a parametric structural engineering tool which provides accurate analysis of spatial trusses, frames and shells. These tools generate high performing design options. Although they only work for a narrow range of structural typologies, as membrane and shell structures.

1.2.2 Form Finding Applied to Buildings

During the last decades, with the form finding methodology accompanied by the appearance of new materials, the current architecture is capable of adopting forms that were previously impossible. A clear example is the Trumpf footbridge (2018) designed by Schlaich Bergermann Partner, a bridge that covers 20 meters with a double curved stainless steel sheet only 2cm thick. The form finding methodology is clearly visible in other of his works, such as the Schierker Feuerstein Arena (2017) or the National Sports Complex Olimpiyskiy (2012), where it is possible to cover large spaces with as little material as possible.

Other architecture teams such as SL Rasch are also a current reference in form finding. Some of their recent works are the Pavilion for Expo 2012 in Korea or in the Convertible Aircraft Shading (2016) in Abu Dhabi as membrane structures similar to those designed by Frei Otto following a form finding methodology.

2. THEORETICAL FRAMEWORK

2.1. THE PHILOSOPHY OF FREI OTTO

Frei Paul Otto (1925-2015), born in Germany, was an architect and engineer. He studied at the Berlin University of Technology and completed a doctorate in civil engineering. Rather than simply turning his hands to designing after completing his architecture studies, Otto became more of a researcher, conducting experimental analyses of the basics of lightweight construction and adaptable architecture and developing methods for finding unfamiliar forms. He approach his research like a natural scientist: he made observations, developed models, and carried out studies and measurements. In 1964, he founded the Institute for Lightweight Structures (IL) which he developed into one of the world's most important research centers for ecologically minded architecture and engineering.

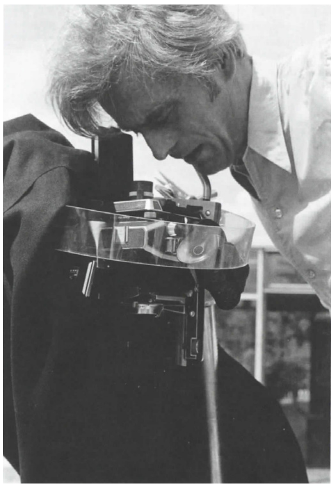


FIG. 2.1_Frei Otto taking photographs on the terrace at the Atelier Warmbronn.

FIG. 2.2_ Frei Otto with his team of collaborators at the Stuttgart Institute for Light Structures.

Frei Otto is considered one of the most unconventional architects of the twentieth century. He was an investigator and an inventor, combining the fields of engineering, biology, architecture and design. Although he built little, Frei Otto had an incredible influence on architecture with his new approach to the idea of design. Form and structure are not defined by the architects, but rather found through a process following physical principles. In Frei Otto's words:

> *"The form of the building develops from a process of intense study and investigation. The more detailed this study the freer it is from the preconceived ideas of the architect, the more chance there is of finding a form of supremely sculptural quality and thus of symbolic expressiveness. The building form should not be designed at all, the architect can only provide assistance at the point when the forms start to take shape."* [1]

1 Frei Otto, "Die kritik", Baukunst und Werkform (1958), 19.

With this statement he attacks the figure of the designer/architect in his traditional role as a creator working intuitively. In his research and experimentation he used an empirical process with which the form is determined via a material approach to the model. His approach was not to impose a preconceived idea about the form, but to see which shapes does the material generate when it's under different types of forces in a self-forming process, like a chain hanging at both ends.

Physical experiments played a central role in his investigations, always keeping in mind the relationship of the material and the form. This methodology of finding the shape through an empirical process and where the shape obtained is the result of the material responding to external forces is called form finding.

With this approach, Otto was able to research the principles of lightweight structures in order to come up with designs based on natural laws. He took nature as a reference and inspiration and investigated the natural process that goes into creating forms. The forms of nature are not random, they follow geometrical patterns. As he said, *''we study nature so we can be a part of Earth''*[2], although he was aware that it is not likely that nature can be fully understood by a creature that is itself a product of nature.

Otto did not seek inspiration from nature in a formal way, but rather from natural processes. He tried to use as little matter and energy as possible. In order to understand the forces that go into creating natural shapes, Otto developed models that allowed him to investigate these natural processes of formation. He studied different types of structures using a wide range of materials for his models. For example, for his membrane structures he experimented with soap films, which form the smallest possible surface area inside a given closed perimeter. With this empirical process, he realized that membranes cannot be freely designed, but that their optimal shape, the minimal surface, is discovered in a natural process of self-formation. He investigated the close relationship between form, force and mass, which were the three main parameters guiding his career and research. About these resulting forms, Otto himself once stated:

2 Frei Otto, 1996. Frei Otto: Architecture Nature.

"An aesthetic form emerges at the end of the process. It cannot be achieved through the will of beauty alone. It suits the function, but, at the same time, has that special characteristic of increased quality required to lift a building out of the range of the merely functional, the merely economical and/or the merely technical, without in any way prejudicing these values, into that range where, perhaps, architecture starts." [3]

It is very difficult to define Frei Otto only as an architect since his field of research covered much more than architecture itself. Other architects and architecture critics defined him as an engineer, an inventor, a researcher, a designer and even a thinker, but Otto considered himself as a form seeker and sometimes as a form finder above all the other tags.

Otto's originality as a draftsman lied in the originality of his processes. The modernity in his work cannot only be seen in his built works, but also in the kind of tools and equipment he used together with the process he followed. Against the idea of eternity, monumentality, symmetry and weight of the german architecture at the time, he presented a light, cheerful, flexible and adaptable architecture. He sought after open structures for an open society. He had a vision of a new way of thinking about architecture. His process can be expanded beyond structural criteria into an environmental criteria and energy and water management.

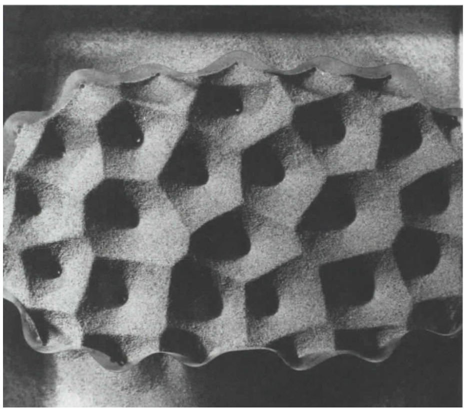


FIG. 2.3_Fill model packed with sand for the convertible tent canopy for the all-weather pool in Regensburg.

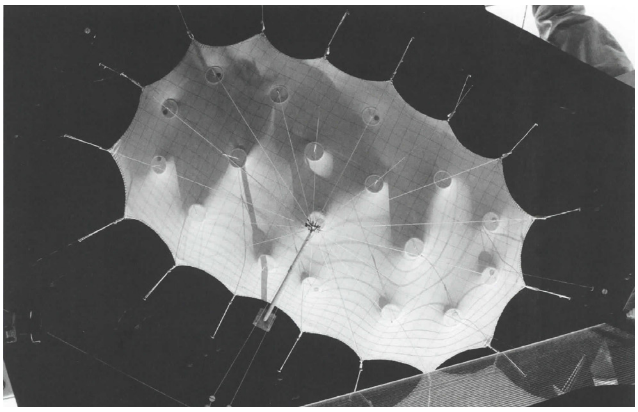


FIG. 2.4_Fabric model of the convertible tent canopy for the all-weather pool in Regensburg.

Frei Otto's legacy is not only his built works or his research or investigations, instead, it is also the philosophy linked to the studies of nature and construction. Some of his words about his vision of the future: *"The secret, I think, of the future is not doing too much. All architects have the tendency to do too much"* [4].

3 Frei Otto, 2008. Conversation with Rudolf Finsterwalder.
4 Frei Otto, 2005. Interview with Icon Eye Magazine.

FIG. 2.5_Frei Otto taking photographs of the model of the canopy for the temporary stand of swimming pool in the Munic Olimpic Park

3. ANALOG MODELS

3.1. WORK PROCEDURE

Frei Otto gave to experimentation in architecture an important role in his research and investigation, placing it as the central axis in his work. As explained before, he used physical models to find forms following natural processes. Although their principles could not be directly applied to buildings, they were able to serve the purpose of pure research and offer important theoretical insights for the self-forming shapes.

Otto's architectural models function not just as ''static'' but, more importantly, also as ''dynamic objects''. In all their fragility, Otto's models are the result of the precision of scientific instruments and the imagination of artistic artifacts. The experiments embraced the idea of adaptive architecture. First of all, they responded to external forces in a highly sensitive way, secondly, in the process of change and transformation, they revealed the close relation between the model and the material of which it was made of.

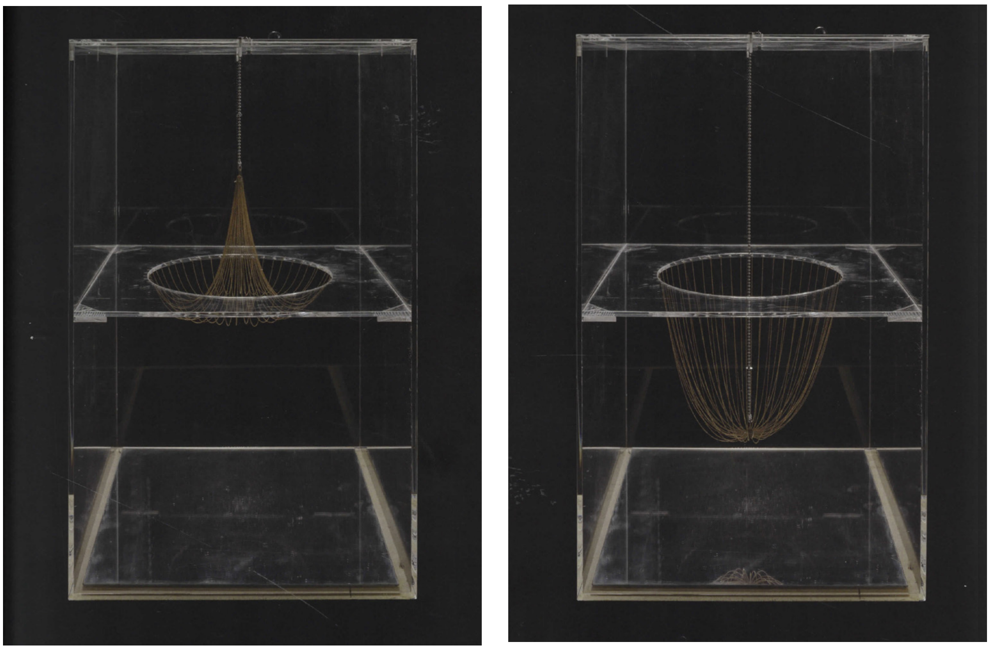


FIG. 3.1_ Adjustable chain design model. 40x40x68.5cm.
Wood, acrylic glss, mirror glass, metal.

In nature, the self-forming form and the material itself have an intrinsic relationship. It becomes clear how radically Otto extended the interaction between the models and their materiality when one considers the diversity of materials, fabrics and substances that he experimented with. Sand, balloons, paper, soap film, soap bubbles, glue, varnish, chains, wool, are some examples of the materials he worked with. In his lightweight structure research, he studied multiple structural systems whose construction does not derive from a planned process, but comes from self-forming or self-organizing processes.

These systems which transmited the forces received to the supporting points with the least amount of material. As a result of doing so, he established a whole universe of ideas based on cable nets, retractable roofs, umbrellas, grid shells, membranes, arches, branching and pneumatic structures.

Although the processes of finding the optimal form of these structures were completely different from each other, the objective was the same, obtaining a resulting shape that is in equilibrium relative to the forces. For example, when Otto was studying arches, he used hanging chains to find a profile that works in perfect tension, and by photographing it, freezing it, and inverting it, the resulting form was an optimal dome shape that works in compression. Compression is much more difficult to build than tension, as tension is always stable.

In the second half of the 50s, Otto started to investigate membrane structures. In this type of structures, the problem is not weight, as they are very light, but designing a form able to stay in the desired shape. He figured out that a very thin and relatively stable membrane could be created from distilled water and a few drops of soap. When a closed frame of curved wire is immersed in the soapy solution and is pulled out again, a thin film of soap is formed.

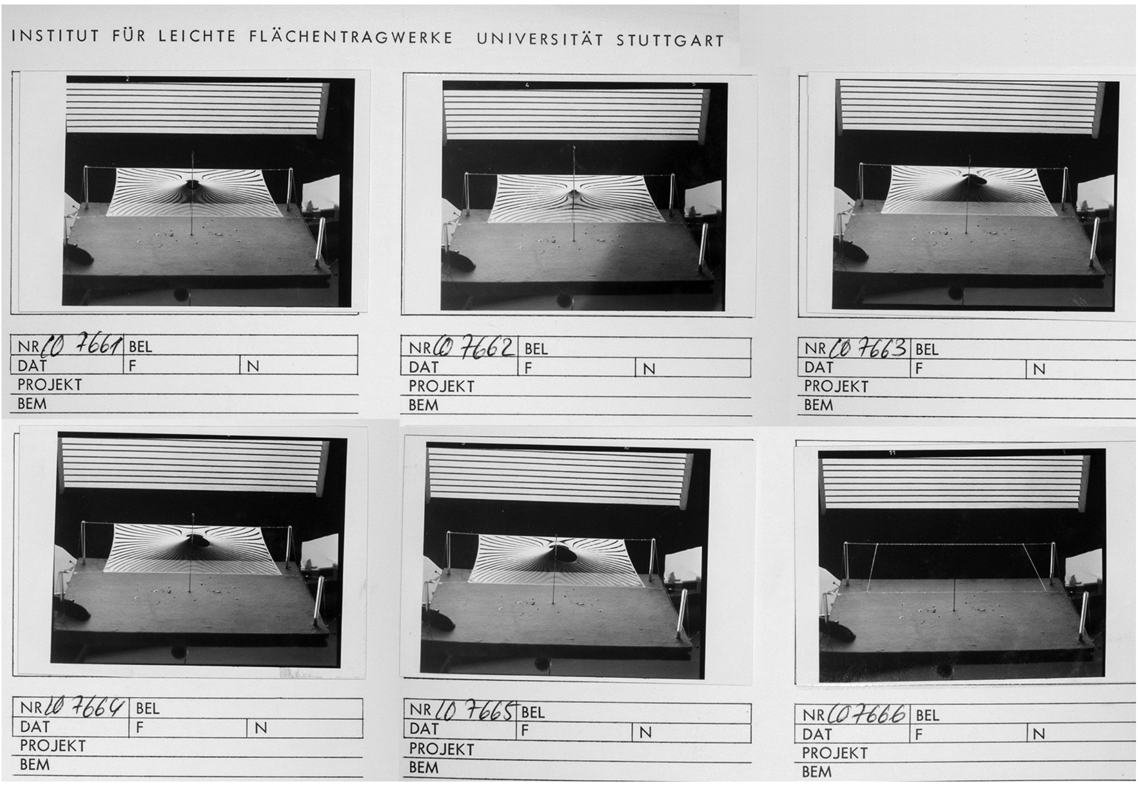
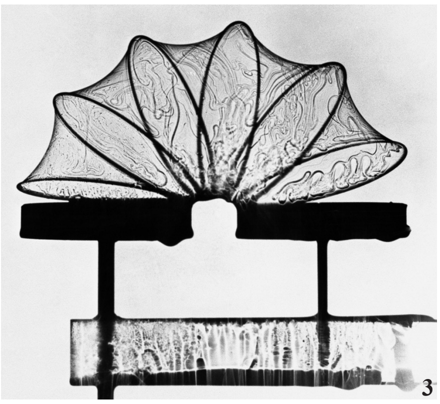


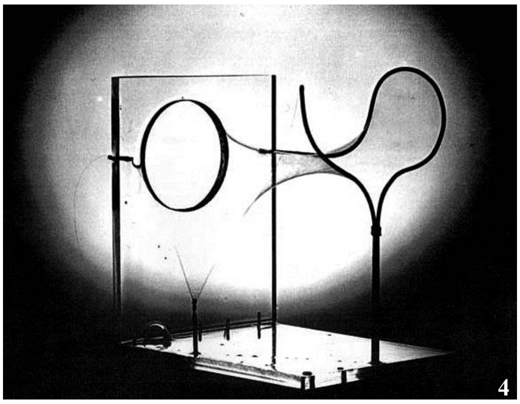
FIG. 3.2_ Soap bubble experiments, Institute for Lightweight Structures (IL) of the University of Stuttgart, contact sheet, circa 1965.

Through experimentation, Otto observed that the generated surface is defined by the edges of the closed frame. Soap film experiments became of fundamental importance as a three-dimensional modeling technique for complex, curved, non-orthogonal structures. As the soap film is a very weak structure and it breaks very easily, the only way this membrane can work is only with tension and not compression.

The superficial tension of the membrane is the same at every point and every direction, thus achieving a unique situation of stability and efficiency. This characteristic membrane forms what it is called a ‘‘minimal surface’’. These membranes require the least amount of material and energy to cover the interior space of a defined boundary. Every point of the surface is double curved, although the local curvature in any point is always zero. The formations did not follow human logic so they could not be calculated nor designed, these forms were new to the eye. Frei Otto found great interest in these resulting shapes and he stated:

> *“In designing the tensioned membranes, it was fascinating to see how the shapes of great clarity and captivating beauty were created in the search for structural forms that used minimum of building material. They were forms that could not be designed.”* [5]





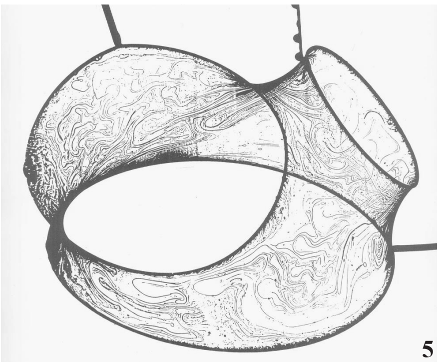


FIG. 3.3_ Minimal surface between multiple moving rings. **FIG. 3.4_** Tenside lamella with complex boarder conditions, Klaus BACH 1987. **FIG. 3.5_** Single minimal surface between three rigid rings of different sizes.

5 Frei Otto, 1960 “Peter Strohmeyer: Frei Otto, Zelte,” in: Deutsche Bauzeitung.

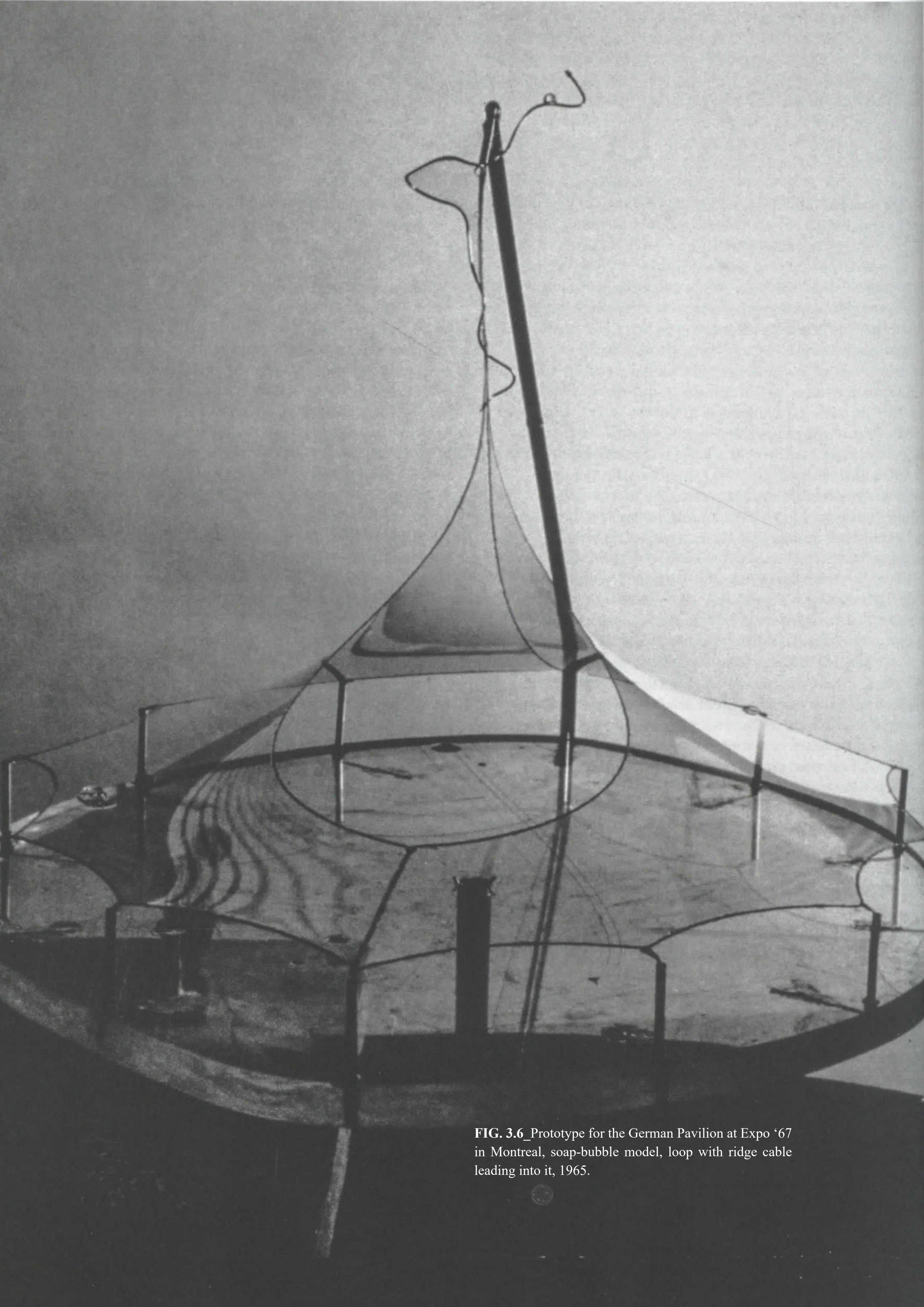


FIG. 3.6_Prototype for the German Pavilion at Expo ‘67 in Montreal, soap-bubble model, loop with ridge cable leading into it, 1965.

Due to their physical and chemical consistency, soap films have a short life, normally only a few seconds. This negative condition is compensated by the fact that the soap film can be made over and over again by dipping the same closed perimeter into the soapy solution. The fragility of the membranes also meant that the models could only be about the size of a hand. At the same time, the small dimensions made it difficult to capture and record the geometry by photographing it. Within their fragile nature, soap films harbor infinite possibilities.

Over the next years, the process of finding forms through soap film models evolved in technical and conceptual parameters. They experimented by changing the consistency of the soap mixture to achieve stronger and more durable films using thicker soap liquids, however, it made it more difficult to create particularly complicated shapes, or change the shape when they were produced, due to unequal stresses in the model. To freeze the soap film was also tried, but it could not adapt to the changing edges so it was quickly dismissed.

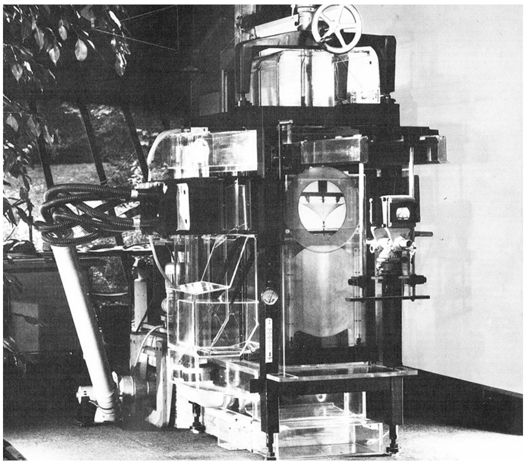


FIG. 3.7_ The climate-controlled soap-film machine at IL.

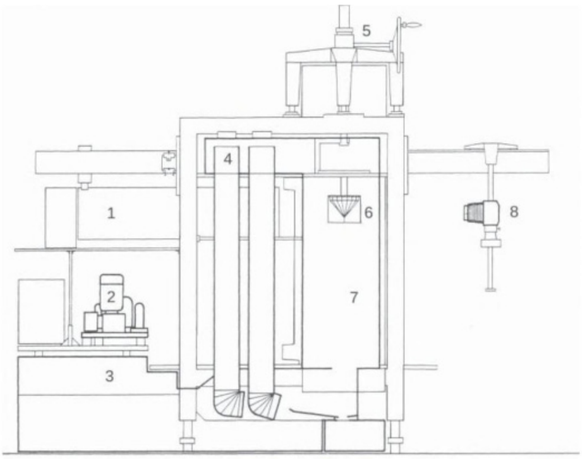


FIG. 3.8_ Section of the climatically-controlled soap -film machine. 1- Parallel light projector; 2- Circulation pump; 3- Cooling unit; 4- Atomizer; 5- Hub spindle; 6- Soap-film model; 7- Air- conditioned chamber; 8- Camera.

To make the fragile soap solution more durable, the air needs a large percentage of humidity. That way, the humidity prevents the superficial evaporation. In order to improve the durability and precision of the geometric recording of soap-film models, Frei Otto's team built soap bubble machine, or as they called it a minimal surface device (FIG. 3.7) in the Stuttgart Insitute (IL). It was a climatic chamber that had a steel frame and transparent glass walls on all sides. It was possible to control the humidity of the air inside and extend the life span of the soap film models for several hours. The machine not only served the purpose to maintain the film for a long time, but also to enable precise measurement.

With the projection of a parallel light installed on the machine, the spatial deformation of the model (FIG. 3.9) can be photographed and recorded against the measuring grid in the background (FIG. 3.10), and rotating the model step by step you can get a precise measurement of the membrane in its full form. A small wind tunnel with a blowing and suction fan allows the observation of the soap film under the action of wind pressure. With this advanced technical process Otto was able to bring to reality forms that seemed impossible at the time. *"Now* [2015] *it can be calculated, something that for more than forty years was impossible. I have not waited for it to be calculated to build them."* [6]

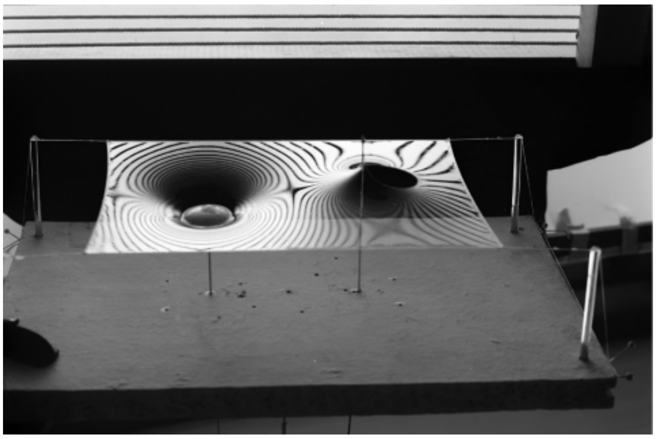


FIG. 3.9_ Grid lines projection on soap film at Institute of Lightweight Structures, Stuttgart.

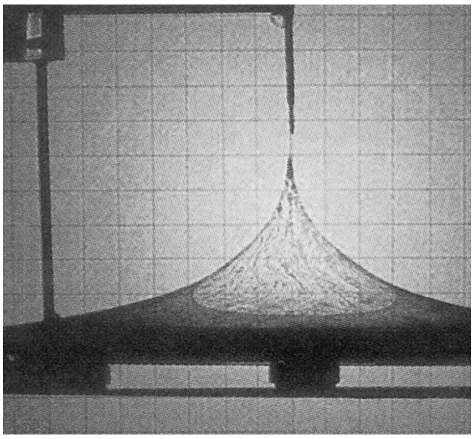


FIG. 3.10_ Soap film model with the measuring grid in the background at Institute of Lightweight Structures, Stuttgart.

It is not possible to apply point loads to the surface of soap films. For example, a needle can penetrate though a soap film without deformation it; it either passes through or bursts it. Flat elements are needed to be able to modify the film and rise (high points) or lower (low points) it. In this way, the forces are transferred over a larger surface.

With a simple rope loop, the so-called eye (FIG. 3.11), it is possible to modify the high and low points of the film without a significant increase in tension. The rope loop causes the same surface tension in all directions to form a space curve of constant curvature.

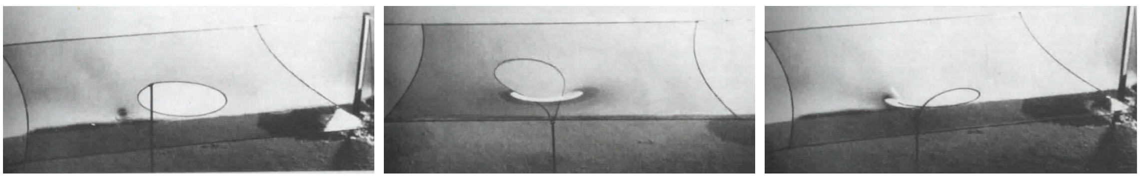
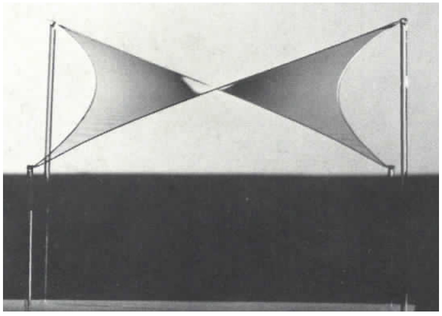


FIG. 3.11_ Frei Otto minimal surfaces of membranes with low-lying points, 1963.

6 Frei Otto, 2008. Conversaciones con Juan Maria Songel, 80.

Although soap film models are optimal to design membrane structures due to its uniform surface tension that translates to a uniform material thickness, buildings must be able to support wind loads and even snow loads. This has to be considered in detail-design calculations and in determining the final form of the building.



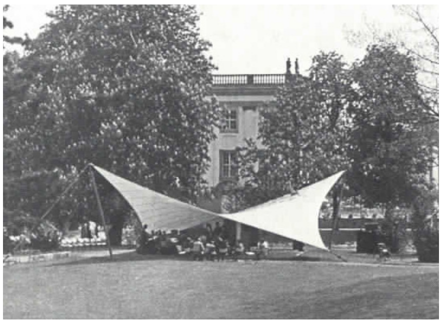


FIG. 3.12_ Soap film model of music pavilion at Kassel. **FIG. 3.13_** Federal Garden Exhibition Kassel 1955. Music pavilion.

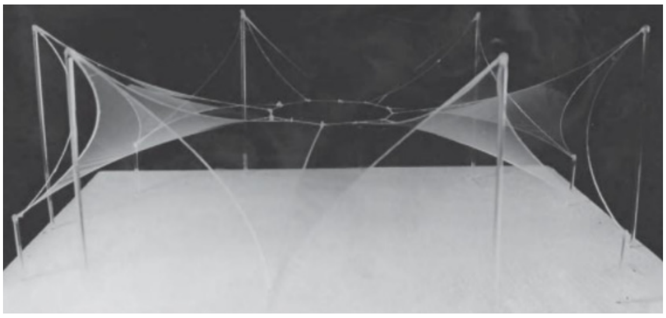


FIG. 3.14_ Soap film model of dance pavilion at Cologne. **FIG. 3.15_** Federal Garden Exhibition Cologne 1957. Dance pavilion.

For the German Pavilion in the Universal Exposition in Montreal 1967, models had a central role in the design process. The structural analysis, the construction and the form of the supporting points could only be found empirically through experiments. To find and study the loops of the building they used soap film models. To define the resulting form, a frame above the model was equipped with a drawing plane with which the XYZ coordinates of any point on the model could be defined. In some models, they used photogrametric pictures with the spatial coordinates saved on a punch tape. They programed the first computer-based graphic system to cover the data from the tape.

To study the wind forces, they placed a model made of layers of plywood at a scale of 1:150 (FIG. 3.17) based on the plan of the contour lines from the soap film model in a wind tunnel (FIG. 3.22). They simulated eight different wind directions at 20 and 40 m/sec.

FIG. 3.16_ German Pavilion at Expo '67 in Montreal, regular high-point/low-point surface, model 1964.

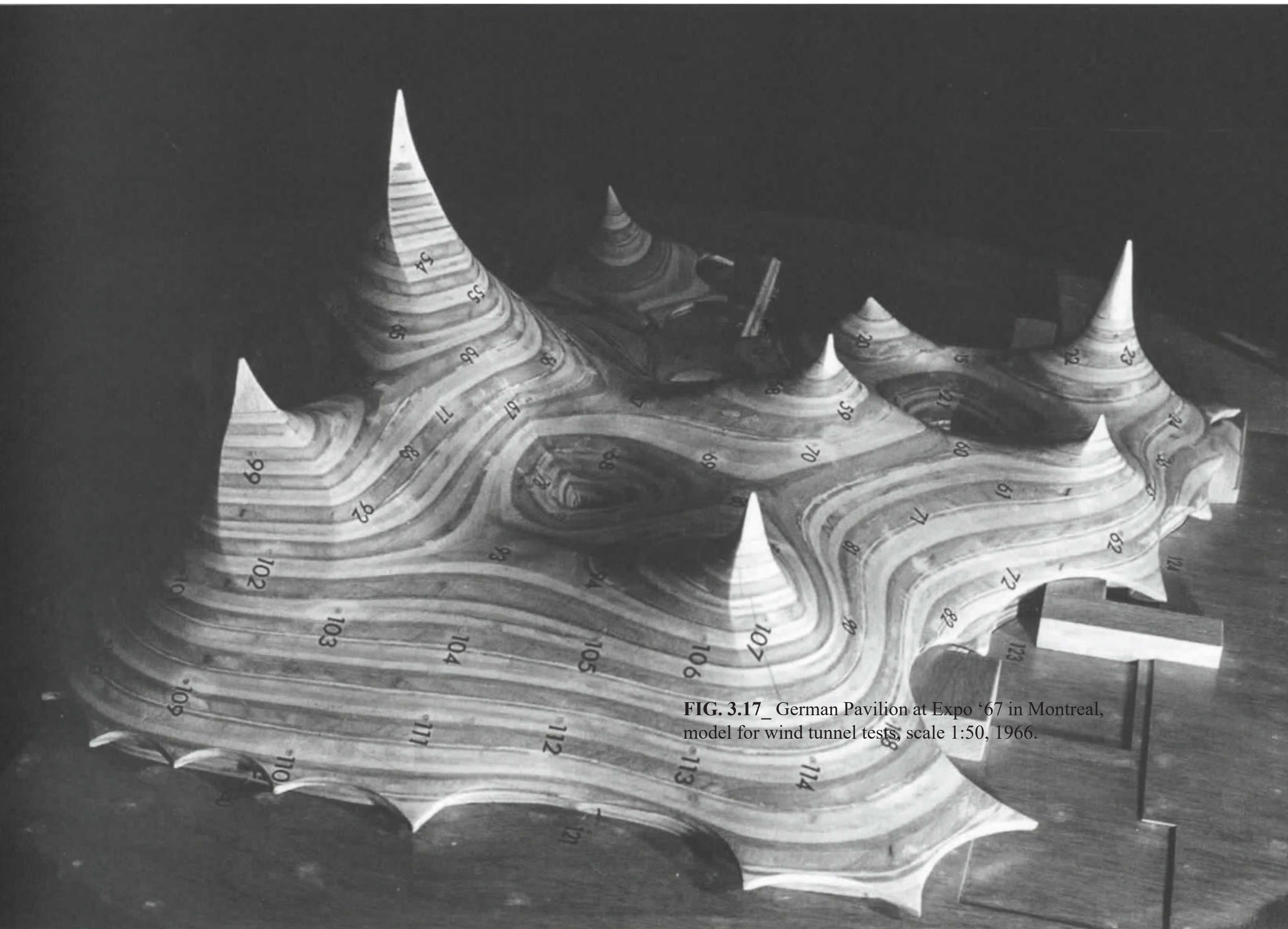


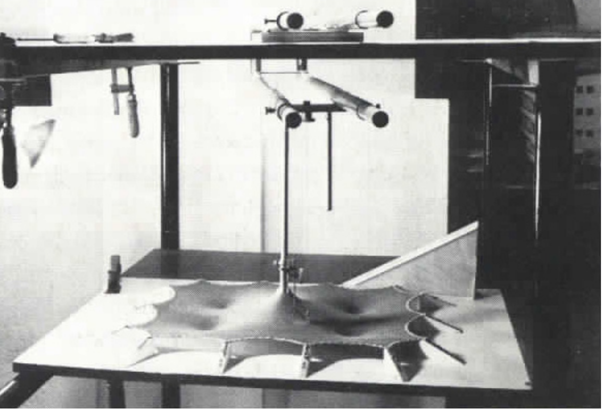
FIG. 3.17_ German Pavilion at Expo '67 in Montreal, model for wind tunnel tests, scale 1:50, 1966.

For Otto, experimentation with the model aims not only at the form, but also on the graphic and photographic measurement of the forces involved. Although they used mainly soap film models to find and study the forms, they built multiple types of models in all kinds of materials and scales, from 1/150 to 1/1. As he said: *"We build models to know the shape and, once obtained, we also build models to find out what happens in it."* [7] Only for this project, they spent around 25.000 hours of work for the model related studies. Not only the models, but also the measuring equipment became protagonists of the experimentation process.

FIG. 3.18_ Measuring model of the German Pavilion at the Montreal Worl's Fair Expo '67.

All these measuring models and methods allowed him to translate the intangible form from the soap film models to architecture planes (FIG. 3.23). Knowing the form is useless if you can not do anything with it. It is when these forms are brought to reality that soap film models have served their full purpose.

7 Frei Otto, 2008. Conversaciones con Juan Maria Songel, 48.



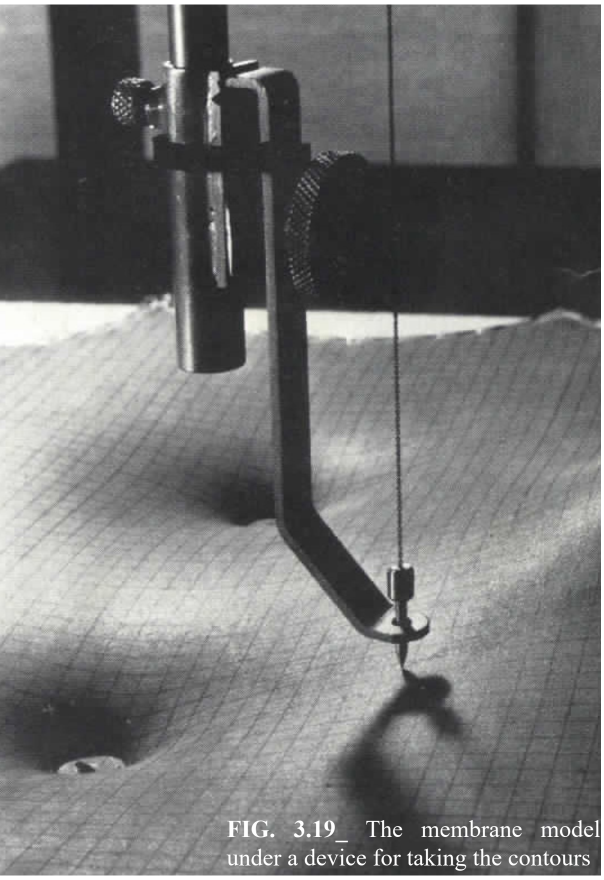


FIG. 3.19_ The membrane model under a device for taking the contours

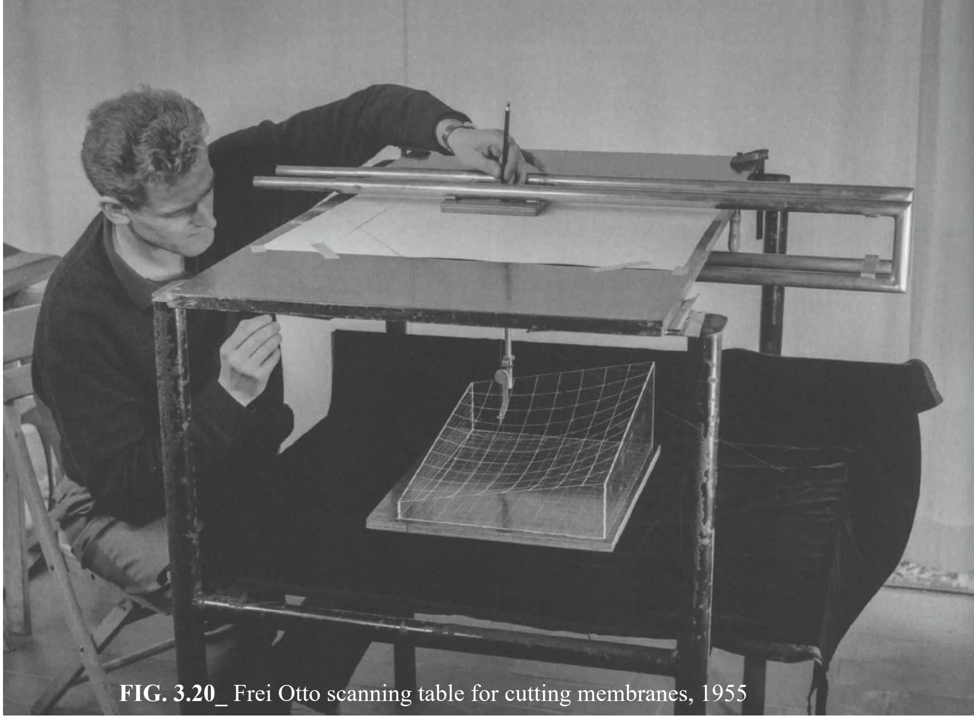


FIG. 3.20_ Frei Otto scanning table for cutting membranes, 1955

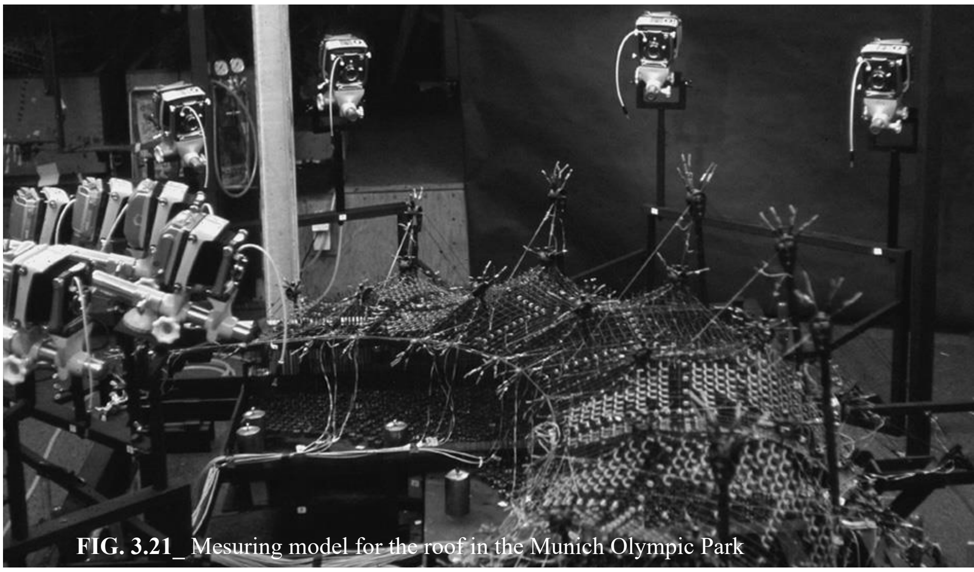


FIG. 3.21_ Mesuring model for the roof in the Munich Olympic Park

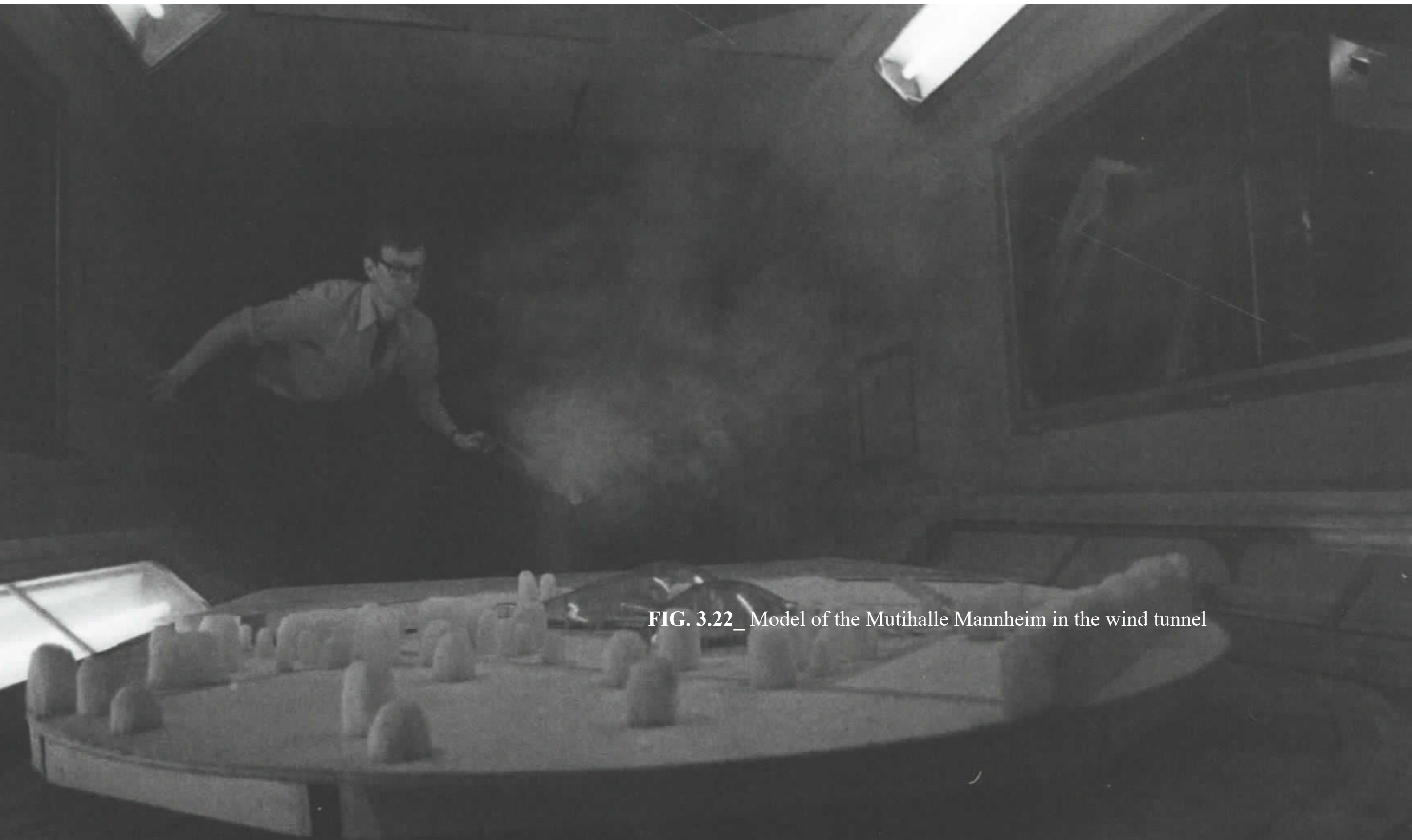


FIG. 3.22_ Model of the Mutihalle Mannheim in the wind tunnel

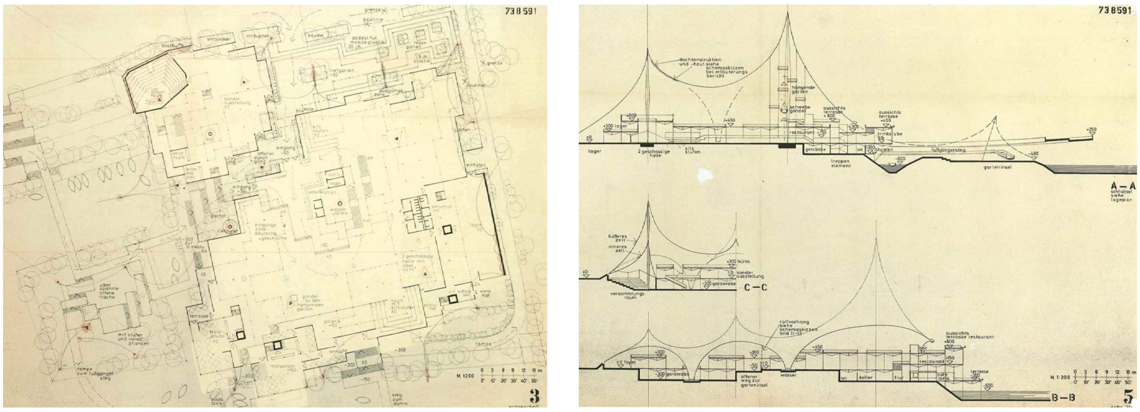


FIG. 3.23_ Ground floor plan and section of the German Pavilion at the Montreal Worl's Fair Expo '67.

The result of all this empirical process is a lightweight membrane structure with an efficient material distribution and forms of undeniable beauty.

FIG. 3.24_ German Pavilion at the Montreal Worl's Fair Expo '67.

The learning that Otto obtains after all his years experimenting with soap film models is to work with very thin surfaces and to detect the most natural way to bend and curve them to obtain a useful result in the structural field and with architectural capabilities, always avoiding imitation to nature but rather understanding its internal mechanisms.

3.2. MODELING

The basis for modeling with a form finding methodology is to fully understand the internal behavior of the material with which you want to work. Before starting to work with complex geometries and models with an architectural purpose, I saw the need to start working with simple geometries to understand the behavior of the material and to do tests to find the best soap dissolution for these experiments. The only information about the solution Otto used was distilled water and a few drops of soap. I started with a proportion of 10 parts of distilled water and 1 part of soap to see the consistency of the soap film.

The first experiment consists in dropping a simple rope loop into a planar soap film to see the strength of the superficial tension trying to minimize the energy. When there is soap on both sides of the rope, inside and outside, the pressure equal out and there is not one side pulling harder than the other (FIG. 3.23), but if you pop the soap film in the middle of the loop, the outside pulls on it more than the inside and it forms a perfect circle (FIG. 3.24). Every point of the loop is being pulled by the same tension.

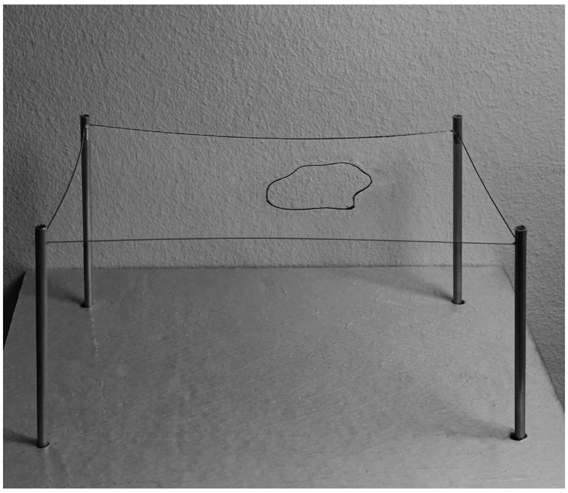


FIG. 3.25_ Study of the equal superficial tension through all the soap film.

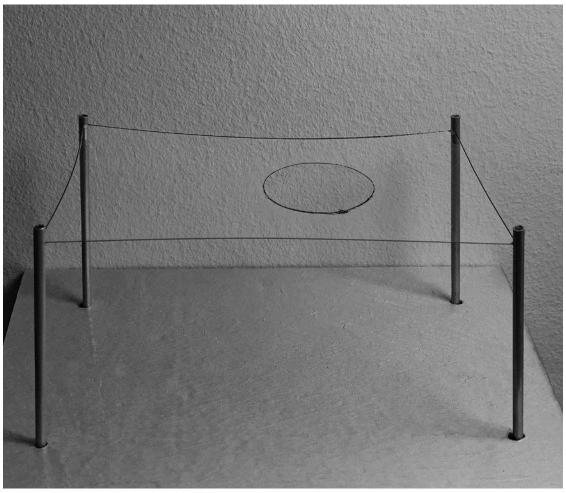


FIG. 3.26_ Study of the equal superficial tension through all the soap film.

If this closed loop is raised or lowered carefully without a significant increase in the tension of the exterior soap film, it is possible to study the high (FIG. 3.25) and low points (FIG. 3.26). The resulting form is the so-called eye that Otto frequently used in his buildings. The surface has a constant curvature due to the equal surface tension. The consistency of the soap solution was good enough for this experiment.

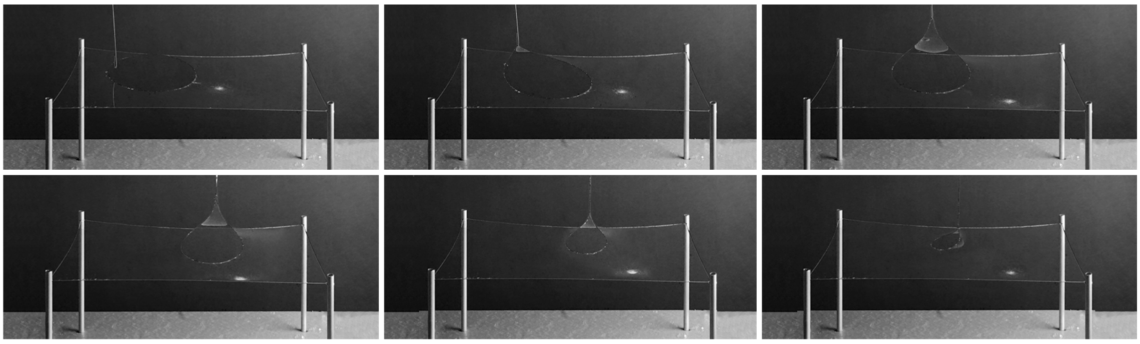


FIG. 3.27_ Minimal surfaces of membranes with low-lying points.

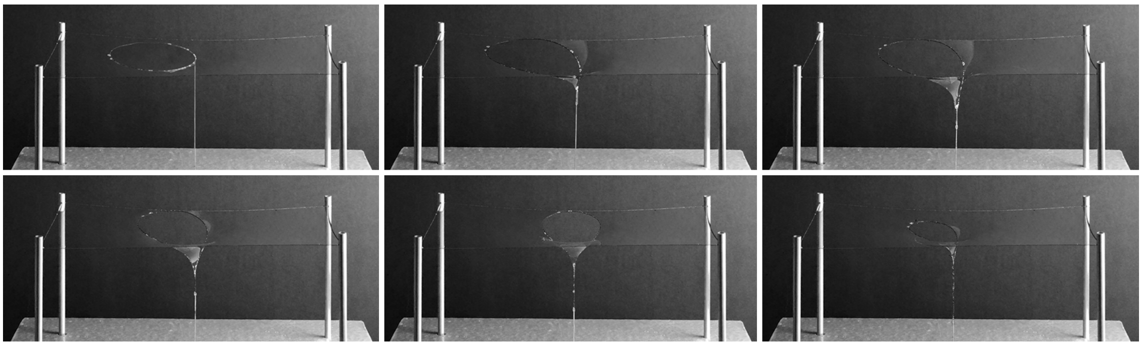


FIG. 3.28_ Minimal surfaces of membranes with high-lying points.

To better understand the spatial deformation when working with three-dimensional perimeters, I took two simple perimeters, a circumference (FIG. 3.27) and a rectangle (FIG. 3.28), and deformed them in different ways to study the behavior of the soap film. Although in these cases the result may seem predictable, they are necessary experiments to understand the most natural way in which this material works.

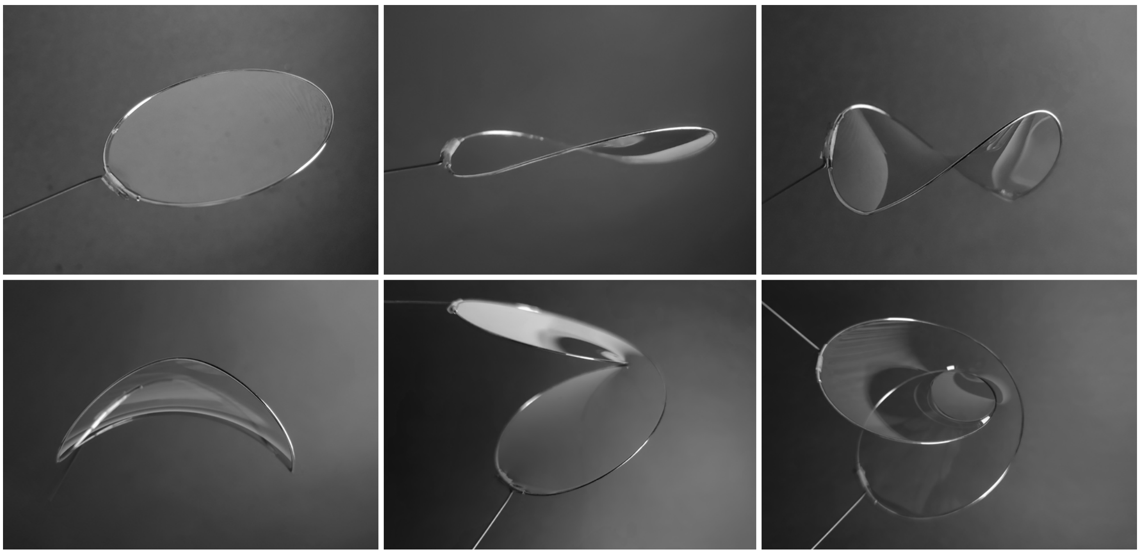


FIG. 3.29_ Simple circular perimeter with different deformations.

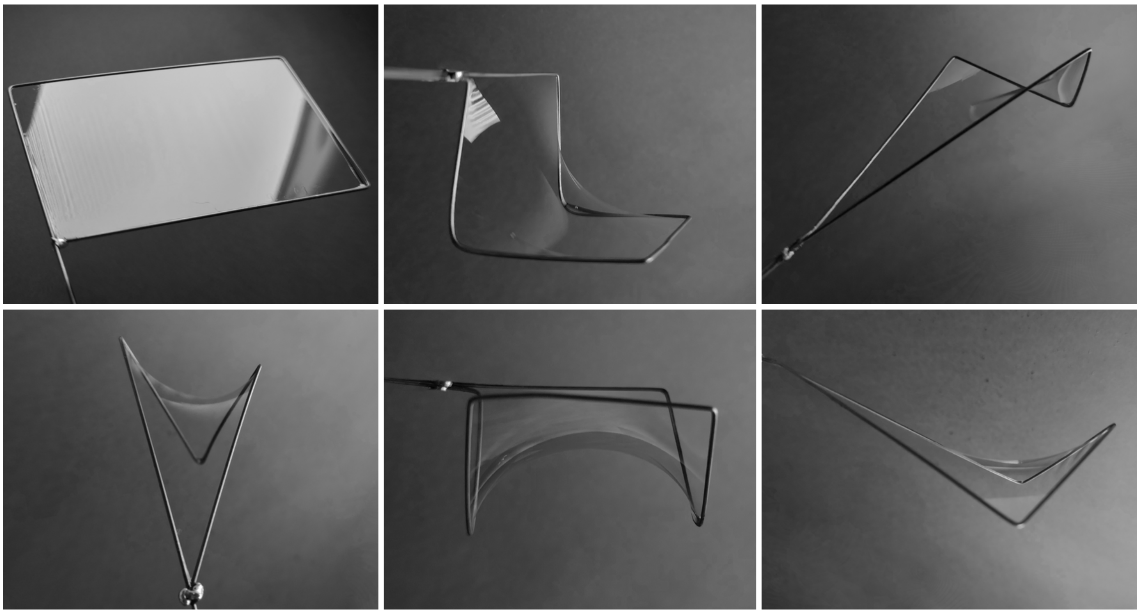


FIG. 3.30_ Simple ortogonal perimeter with different deformations.

The first two three-dimensional minimal surfaces discovered from a mathematical process in the 18th century were the catenoid (FIG. 3.28) and the helicoid (FIG. 3.29). In the process of experimenting with minimal surfaces with soap films. The first form is the result of joining two flat surfaces with a circular perimeter and separating one from the other, the second one is obtained by surrounding a central axis with a helical-shaped wire, forming a closed perimeter. The catenoid is a great example to experience the adaptability of the soap film to a changing perimeter by separating the two rings further and further.

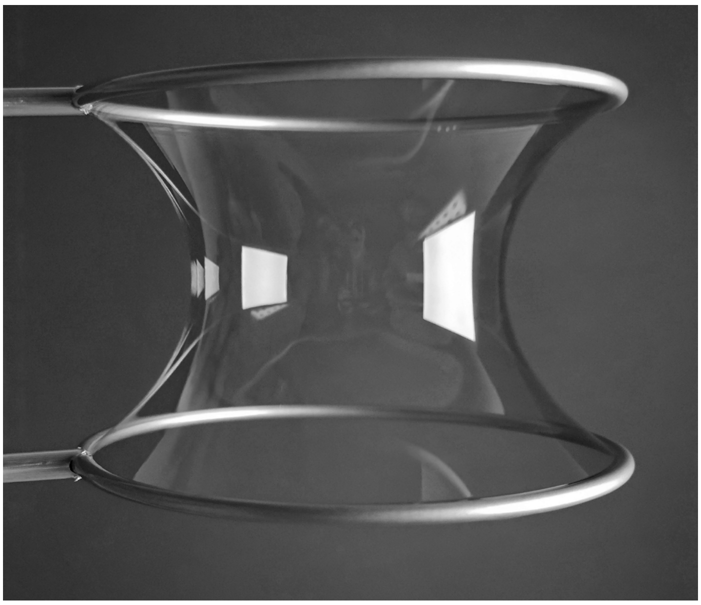


FIG. 3.31_ Soap film catenoid.

FIG. 3.32_ Soap film helicoid.

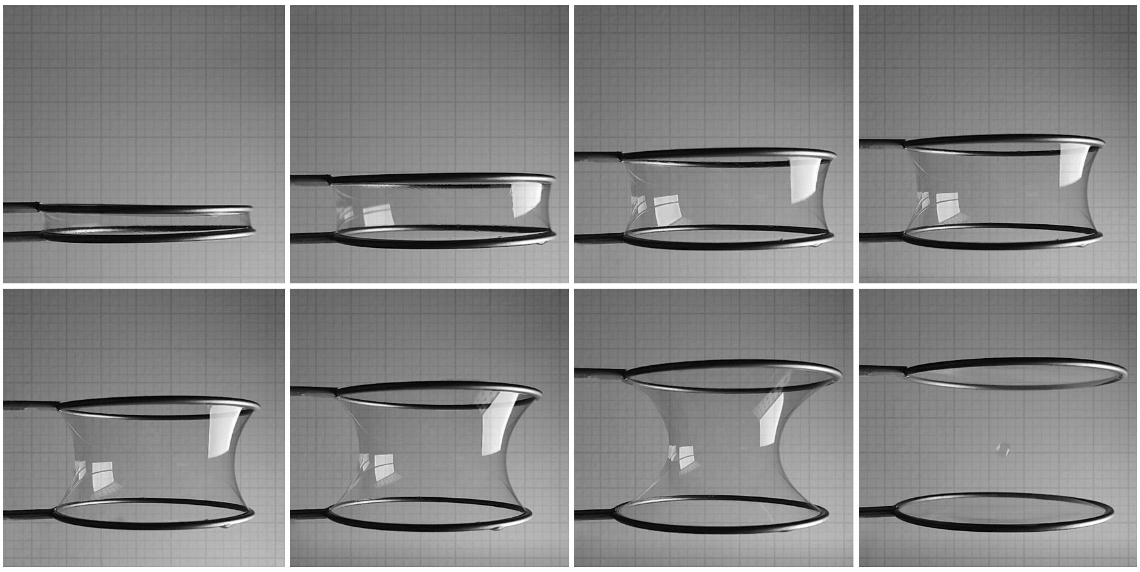
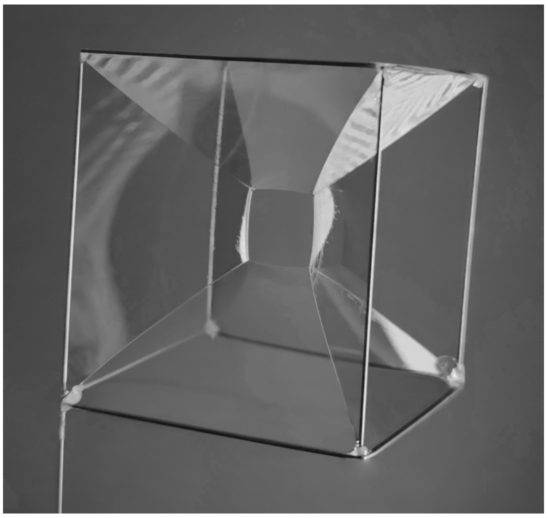


FIG. 3.33_ Sequence of catenoids obtained by separating the two rings with a measuring grid in the background to be able to measure the deformation.

When one begins to model more complex perimeters, it is a little harder to predict what the minimal surface would be. For example, if we take a wire cube and dip it in the soap solution, the resulting form consists of a square in the middle and not a surface on each face as one would think. In order to minimize the area of this, on each face of the cube there are four surfaces that connect to the inner square in there. With this shape, the surface is reduced by about 30% with respect to the surface of the six flat faces of the cube. It is very important that on the surface of the solution, there are no bubbles created from the mixture of water and soap, otherwise these bubbles will add weight to the soap film causing it to burst.



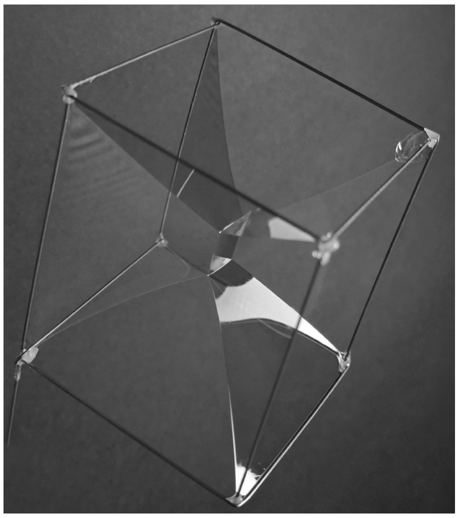


FIG. 3.34_ Minimal surface of a cube.

Before starting to experiment with more complex shapes, I did other simpler experiments, documented on the next page, to to have further understanding of the behavior of soap films.

FIG. 3.35_ Set of forms found from the form finding methodology with soap films.

Although most of the forms obtained through experimentation shown above do not have a direct architectural application, they are very important to understand the behavior of the material and thus be able to design lightweight structures following its logic. To use the form finding methodology, the more you understand the internal behavior of the materials, the faster the design process is.

In the experiments where the perimeter was modified while the soap film was created, the film was too fragile to maintain under some changes. For these cases and for the following models, where the geometry is more complex and with larger dimensions, a little glycerin has been added to the soap solution, leaving the solution to 10 parts of distilled water, 1 part of detergent and 3/4 parts of liquid glycerin. This composition is important to obtain a long-lasting and easily observed result. Glycerin provides flexibility and resistance to the soap film.

For the base of these models I used extruded polystyrene. This material allows me to change the support points of the metal wire easily, thus obtaining new shapes.

FIG. 3.36_ Soap film model with differential high and low points.

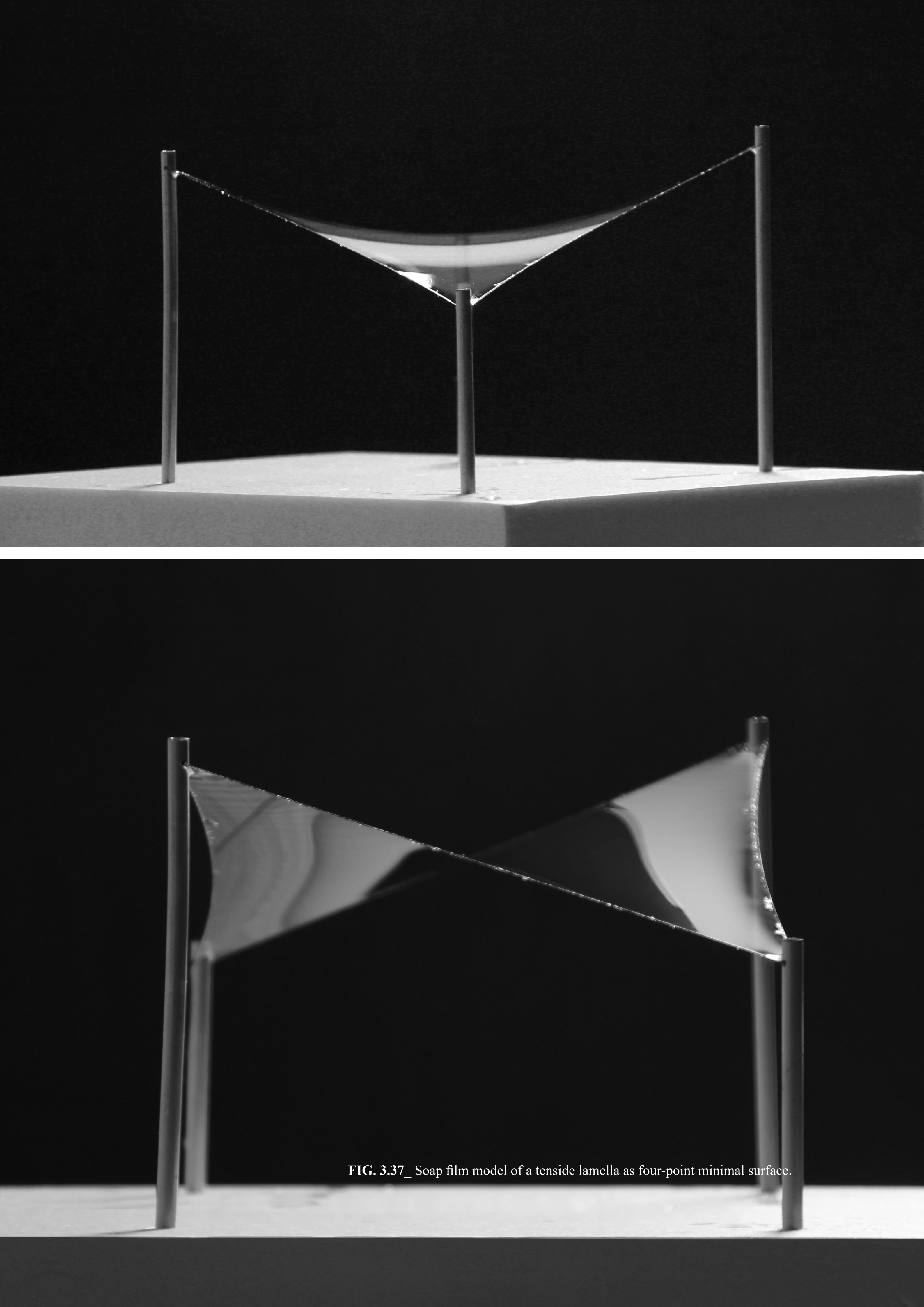


FIG. 3.37_ Soap film model of a tenside lamella as four-point minimal surface.

3.3. CONCLUSIONS

Although soap film experiments could be performed by a child by simply dipping a simple wire frame into a soapy liquid, such experiments had a greater role in advancing the growth of tensile structures. Nowadays, soap films are investigated for what they can tell us about the material responding to external forces and how an understanding of the inner behavior of the material can be applied to solve design problems. Once the minimal surface is known, it is possible to build better tensile structures with an efficient distribution of materials. Even though Frei Otto and his team built a very sophisticated machine to carry out these experiments, most of them can be done with few and inexpensive resources.

In order to apply these experiments to architecture, it is very necessary to understand in depth the behavior of the material since it does not follow a human logic and when working with more complex shapes the result can be a bit unpredictable.

The result of the uncontrolled self-forming process can be influenced by the perimeter given by the architect or designer. The more this internal process is understood, the more accurate the perimeter design will be for the desired resulting shape.

The most sensitive part and for which Frei Otto has been most criticized regarding these experiments is the way in which the obtained form is translated onto paper. Obtaining a minimum surface is relatively easy once you know the process of formation of these membranes, but bringing this geometry to planes is a much more complex task. Otto used a measuring grid and photographing the contour of the shape while rotating the model little by little allowed him to get a full understanding of the complete resulting form. The accuracy of this process depends on the quality of the work done by the person responsible.

Another negative part regarding soap models is that, due to their fragile nature, no external load can be applied to them to carry out wind studies or structural analysis. Only, and although it is not little, its only purpose is to find the form.

Making these types of models first hand has helped me understand the complexity of this seemingly simple process. These models not only generate forms of overwhelming beauty, but they carry intrinsic qualities of energy and resource efficiency necessary for a lighter and more sustainable architecture.

4. DIGITAL MODELS

4.1. WORK PROCEDURE

Nowadays, the applications of computational design tools in architecture have radically changed the way people work in the design process. They have influenced the creation of new styles in architecture and above all in the way of teaching architecture and in the way of thinking about it. These changes have appeared gradually from technological changes that occurred during the second half of the 20th century.

With the raise of digital designing tools in the last two decades, Frei Otto's ideas are more relevant and important than before, when he developed them. Through computing, a lot of Otto's experiments were refund again. Although Otto preferred to find the form through an empirical process, he did not wait much in incorporating computer aided design (CAD) in his work methodology. Although analog models provide us with reliable information and do not require sophisticated technologies for their testing, they do require very sophisticated methods for their transcription to paper. For example, as explained above, to capture the resulting shapes from the soap films models, they needed to build a machine equipped with special photographic cameras. Computational design made it possible to mathematically define the same minimal surfaces obtained until then by an analog method and facilitating the management of the resulting form. As Frei Otto himself stated: *"One can think of everything, one can calculate everything using a computer"*[8].

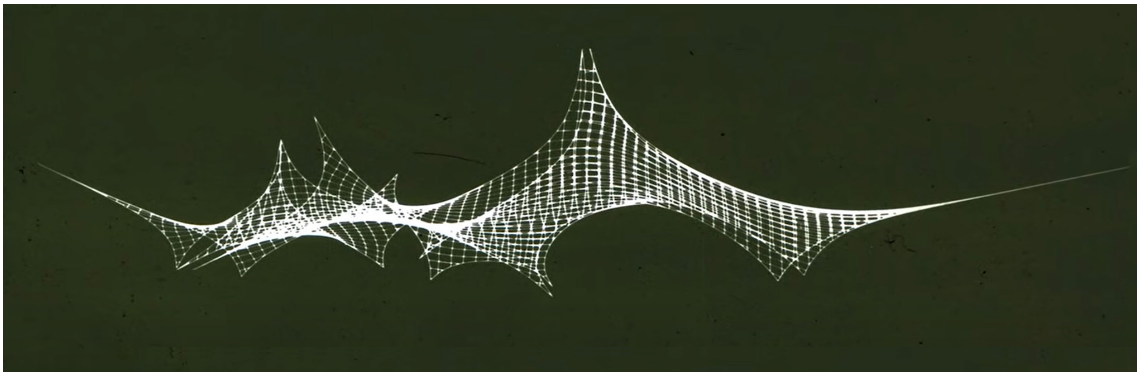


FIG. 4.1_ Olympic Stadia, Munich 1972. Roof configuration above entrance area (drawn by computer).

As Frei Otto's changing models that responded to an external stimulus, digital parametric design main characteristic is the ability to easily change the design with a mathematical formula that requires a few parameters that can be modified. A parametric model can be defined as a set of equations that, through a series of functions and numerical parameters, are translated to a geometric model. These tools use multiple algorithms to find configurations in equilibrium spatial structures.

---

8 Frei Otto, 2008. Conversaciones con Juan Maria Songel, 40.

A comprehensive definition of parametric design by a Ph.D. in Computer-Aided Design in Architecture, Wassim Jabi is:

> *"Parametric Design is a process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response."*[9]

This forms a logic in which the designer can easily modify the parameters, such as the dimensions of an object, the number of elements, the way different elements interact between them... obtaining as a result the automatic updated and regenerated object following the same logic. This way of designing has the ability to explore different design spaces while maintaining inherent logic.

Grasshopper3D (version 1, 2007) is a visual programming language that runs within the Rhinoceros3D computer-aided design application. This parametric design tool enables its user to combine parametric modeling and finite element analysis, allowing the creation of geometries from the most primitive ones to the most complex ones from generative algorithms. Kangaroo Physics (2011, by Daniel Piker) is a set of components for Grasshopper3D used as a Live Physics engine for form finding, interactive simulation, constraint solving and optimization. This physics engine enables the computer to simulate some aspects (specifically particle dynamics) of the behavior of real-world objects.

For example, with Kangaroo Physics the user is able to generate structures in pure tension or compression as a form finding technique. A simple funicular form is generated using the following definition:

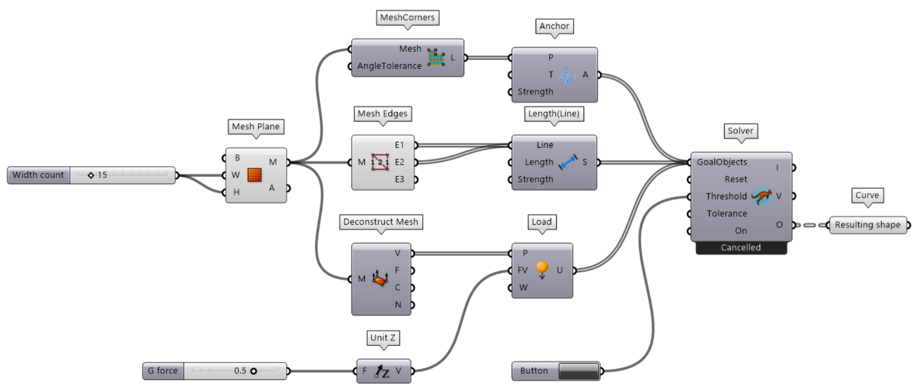


FIG. 4.2_ Grasshopper3D definition of a simple funicular form using Kangaroo Physics.

---

9 Wassim Jabi, 2013. Art: Parametric architecture, the present.

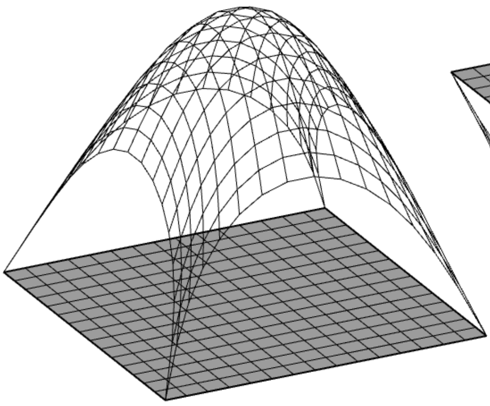


FIG. 4.3_ Simple funicular form with a positive load.

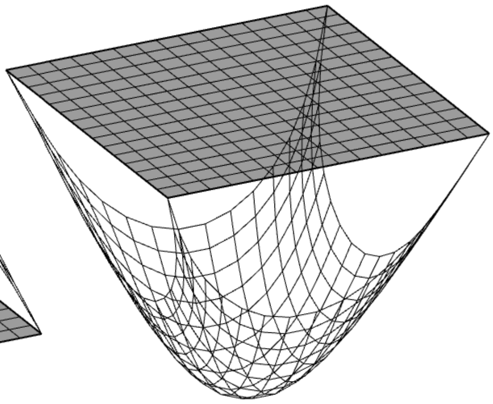


FIG. 4.4_ Simple funicular form with a negative load.

From a divided mesh, anchor points and a given load, Kangaroo Physics generates a catenary form as a result of a form finding process. If the force is positive, the structure obtained will work in pure compression, but if on the contrary, the force is negative, it will work in pure tension.

When you set the goal or goals of the Kangaroo 'Solver' component it solves the system and outputs the solved shape. In this definition, the goals were a divided mesh, with its corner points as anchors and a given load to this mesh and when solving it, the resulting form is a simple funicular form. If you connect a button in the Threshold connection of the Solver component it is possible to reset the solved system if any of the given information is changed.

With this plug-in it is also possible to recreate and study Frei Otto's form finding experiments, including the minimal surface studies related to the soap film models. With the following Grasshopper3D definition by Daniel Piker it is possible to turn an ortogonal mesh into a minimal surface recreating soap film behavior. In Kangaroo physics there is even a component called 'Soap Film' that generates zero mean curvature meshes to simulate the soap film material.

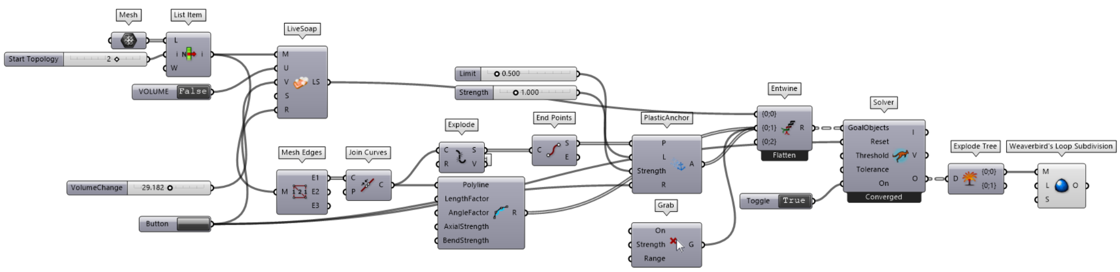


FIG. 4.5_ Grasshopper3D definition to recreate a minimal surface with soap film from an orthogonal mesh.

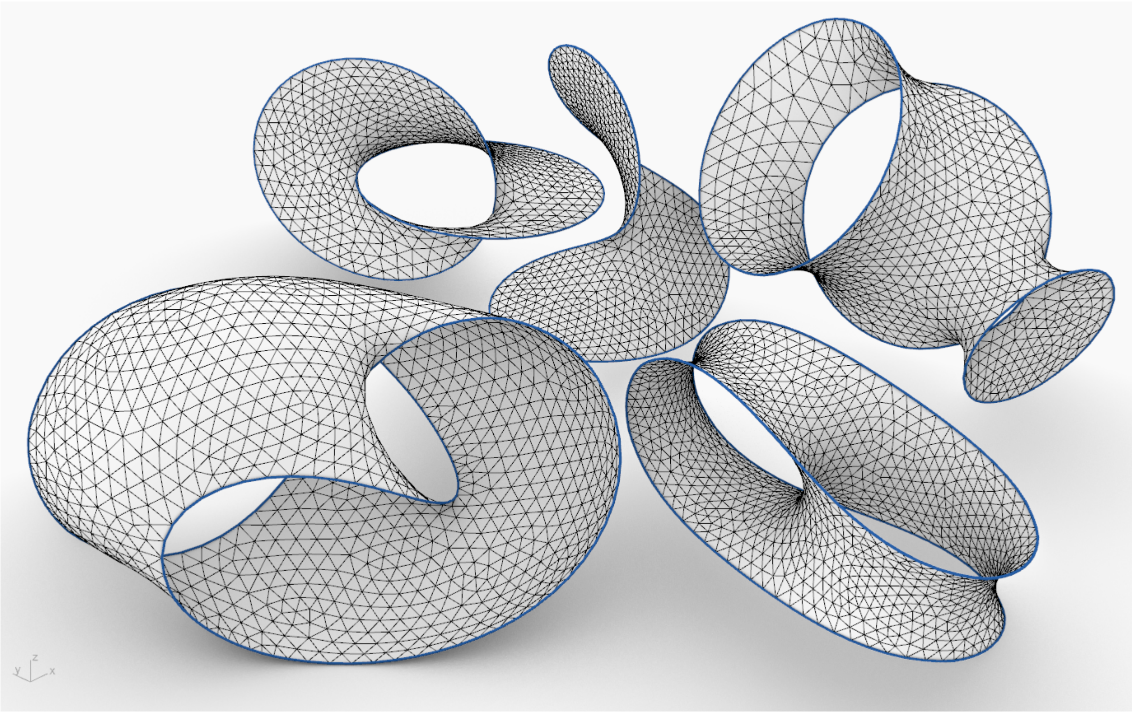


FIG. 4.7_ Minimal surfaces from ortogonal meshes.

When the form is found, working with the shape obtained from Grasshopper3D in Rhinoceros can be done directly with the 'BAKE' action that passes the Grashopper3D interface element to Rhinoceros, although you can also continue working parametrically from Grashopper3D. From the 3D file, plans and sections can be obtained in a simple and fast way.

For example, when this 3D model (FIG. 4.8) of the Frei Otto's Dance pavilion in Cologne (1957) fully modeled in Grashopper3D is baked to Rhinoceros you can make sections and floor plans from it, render it or export it to other softwares.

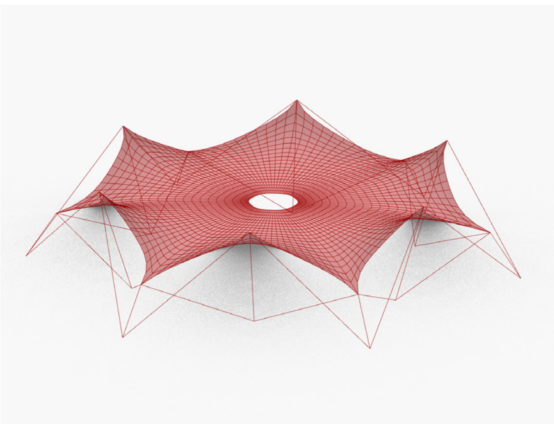


FIG. 4.8_ Grasshopper3D model of the Dance pavilion in Cologne.

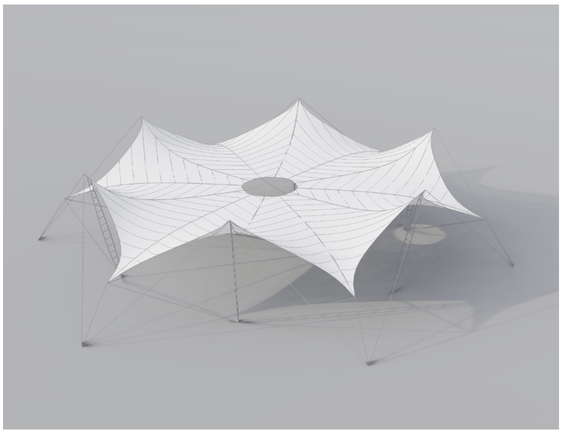


FIG. 4.9_ Render of the digital model of the Dance pavilion in Cologne with Rhinoceros.

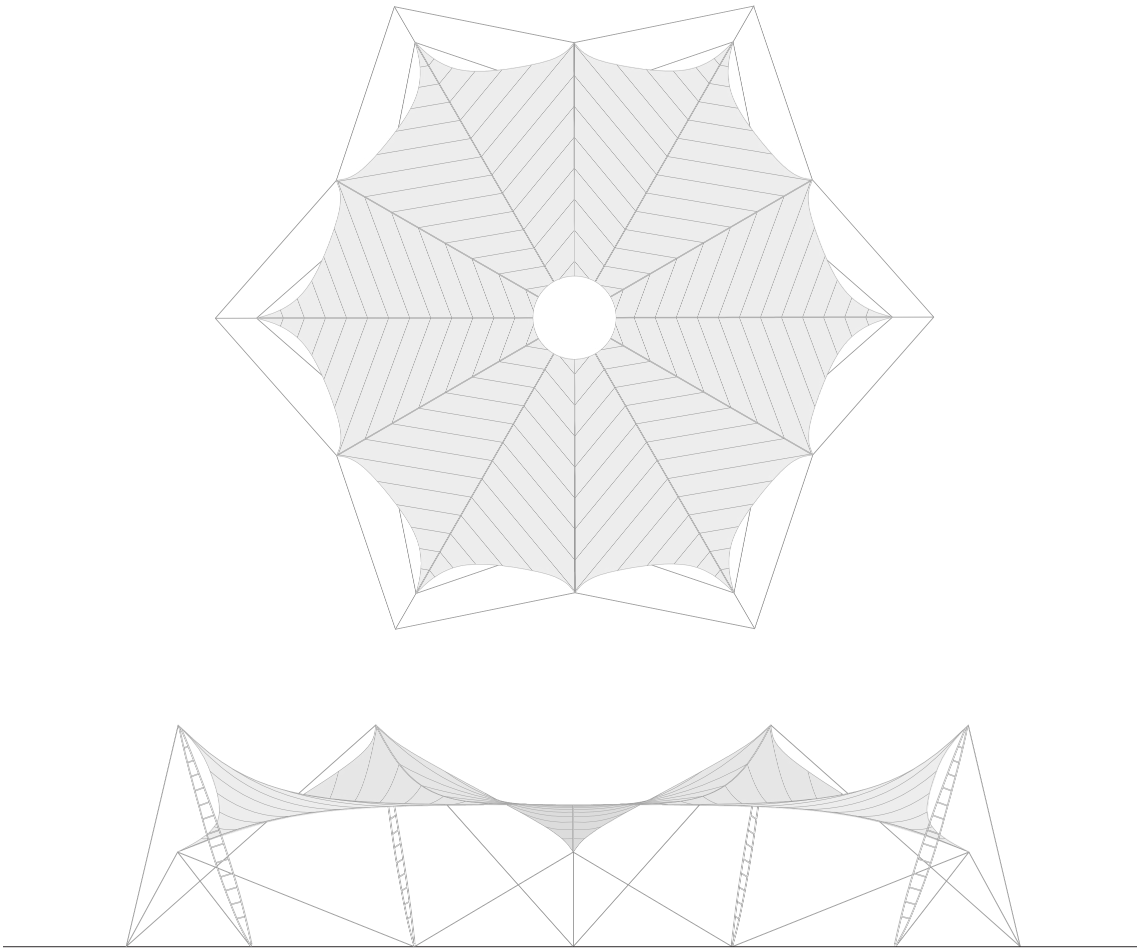


FIG. 4.10_ Section and floor plan and of the Dance pavilion in Cologne with Rhinoceros.

It is also possible to calculate wind simulations with a set of components in the LadyBug Tools family available for Grasshopper3D. The Butterfly component set is a Grasshopper3D plug-in that creates and runs computational fluid dynamics simulations. It runs several common types of airflow simulations that are useful in building design.

The Rhinoceros file can be exported in other file types in order to work with different software in order to carry out other calculations, renderings, etc... It is important to highlight that this calculations can be done in any part of the process and not only when the desired form is found.

4.2. MODELING

When working with digital models to find the form, understanding the internal behavior of the material you want to recreate is not as important as understanding how the computer program you want to work with works. In this case, understand the operation of Grashopper3D and its Kangaroo Physics plug-in.

Something very important to keep in mind before starting a Grashopper3D definition is the logic of the relationship that the different elements will have between them. Although in many cases the same script can be used to find different shapes giving a different perimeter, in some cases it is necessary to change some element of the definition for it to work. This depends on the relationship that the different elements have between them. Unlike analog models, where a more complex perimeter resulted in a more complex surface, in this case, a more complex definition does not equal a more complex surface, but rather a definition where more elements are involved.

To be able to work with soap films digitally, it is necessary to establish an initial mesh to which the qualities of the soap will be attributed. The output of the 'Solver' is another mesh. For example, this simple definition finds the minimal surface of different given closed perimeter (by setting a different curve to the component highlighted in green in the following definition). In this case, the definition is very simple since only two elements are involved, the initial mesh and the perimeter. The more subdivisions the mesh has, the better the resulting mesh will fit the given perimeter, but the longer the program will take to model it.

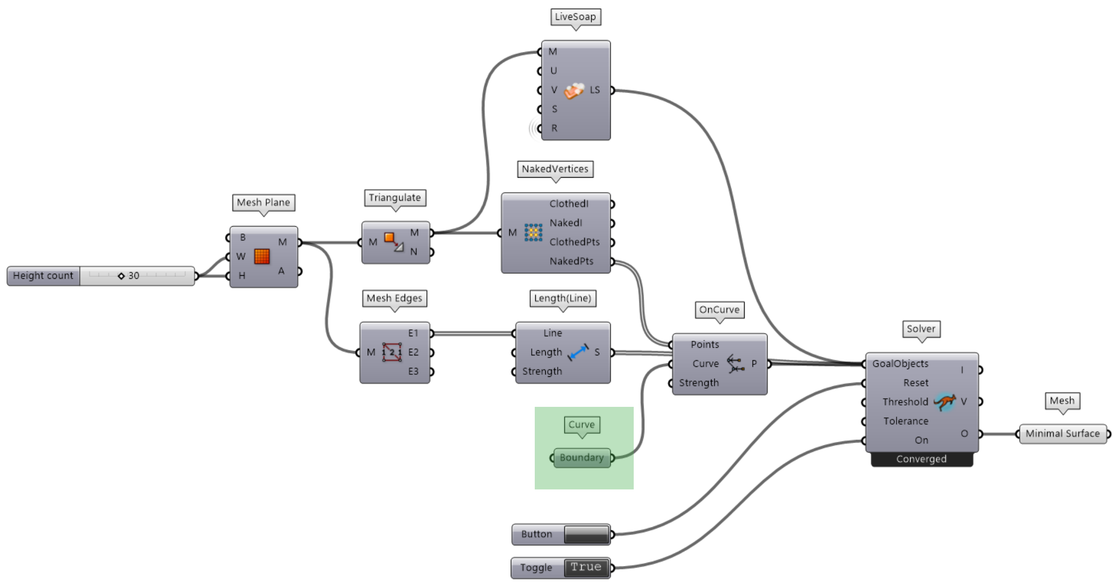


FIG. 4.11_ Grashopper3D definition that allows to find the minimal surface from a given boundary.

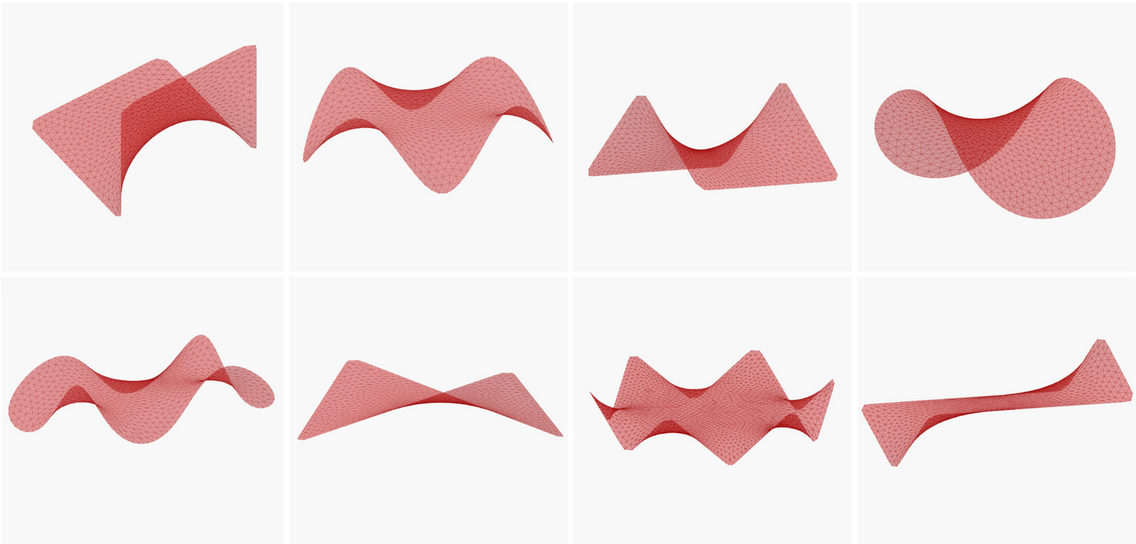


FIG. 4.12_ Different minimal surfaces obtained with the same script.

The same adaptability of soap films that we saw on analog models can also be found in digital models. In the following definition we can see the formation of a catenoid and its deformation as the two circles (the two components highlighted in green in the following definition) move away from each other. When the tension is too high, it will not be possible for the surface to stay connected, and it will "burst" forming a single thread. In this case the definition needed to be different from the previous one since the relationship between the elements is different, in this case the minimal surface is generated between two closed perimeters instead of one.

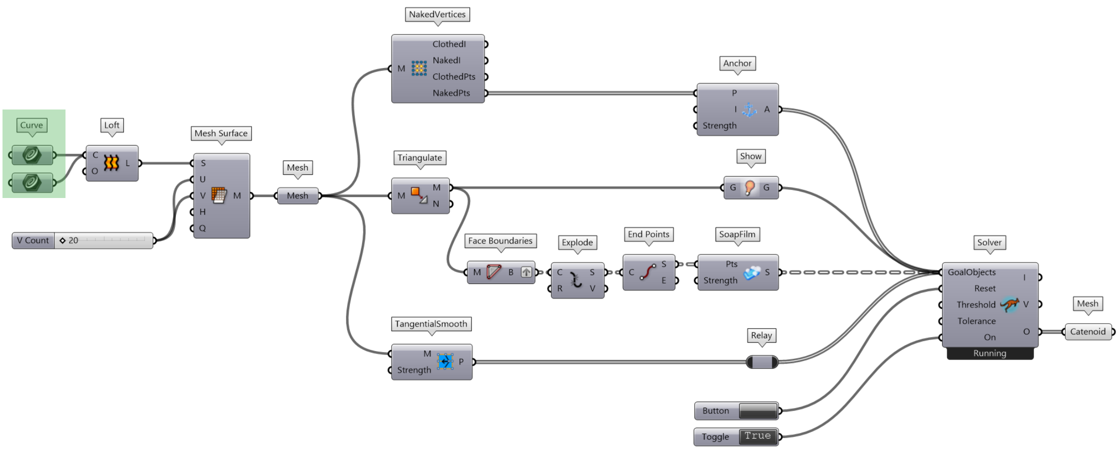


FIG. 4.13_ Grashopper3D definition of a catenoid.

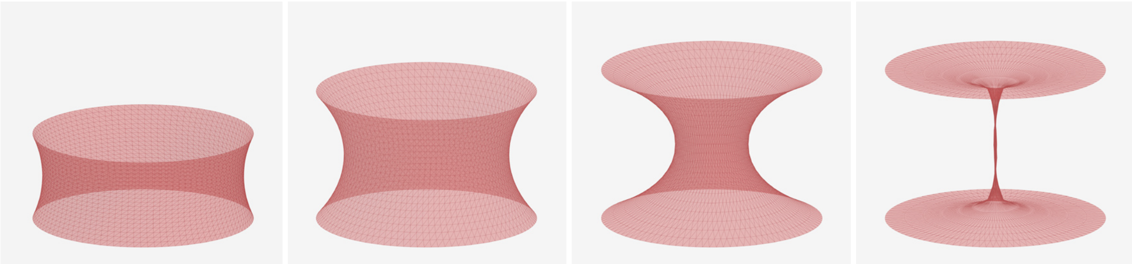


FIG. 4.14_ Sequence of catenoids obtained by separating the two circumferences using Grashopper3D.

It is also possible to study the high and low points of the soap film from digital models. The 'Grab' component allows you to interact directly with the resulting mesh by simply grabbing the surface with the computer mouse cursor. The result is the same as with analog models.

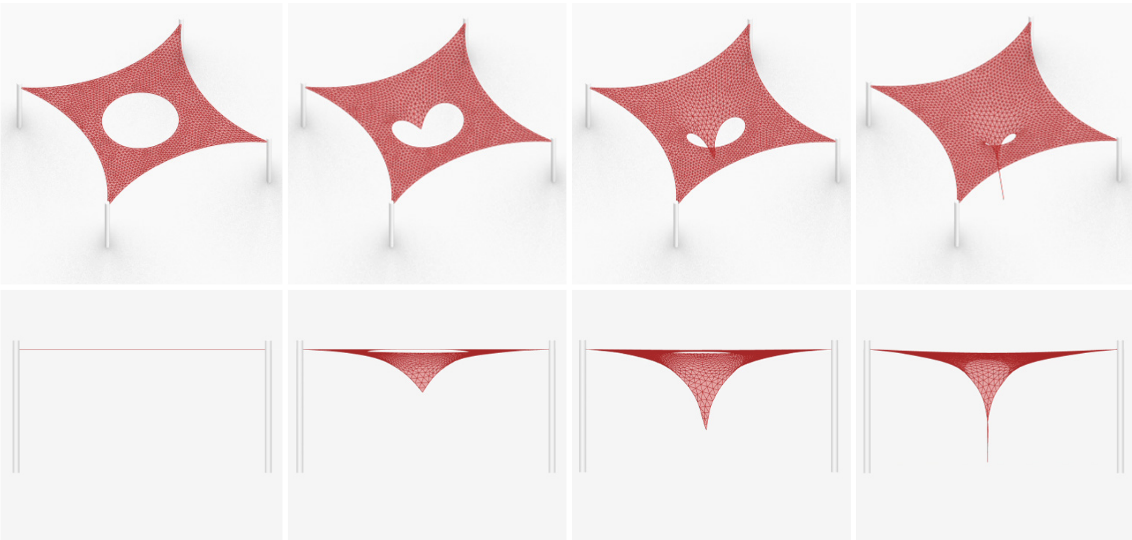


FIG. 4.15_ Digital study of the low-points of a membrane.

Other types of studies can be carried out at any time during the design process directly on the digital model. For example, with the family of components called LadyBug for Grashopper3D you can do solar radiation studies, shadow studies , wind load calculations, etc... Structural analysis can also be carried out using the set of components called Karamba3D. In the following images (FIG. 4.16) you can see the shadow study of the Dance Pavilion on the 10th of February, 2022 at 9am, 12pm and 4pm respectively.

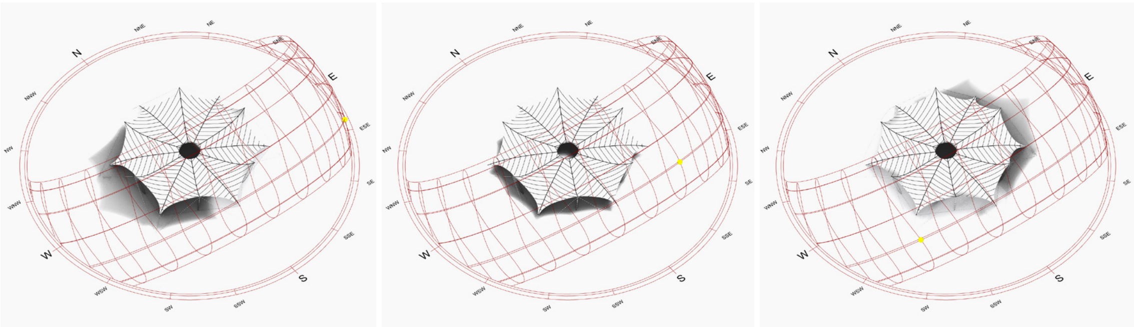


FIG. 4.16_ Sun study with the set of components LadyBug in Grashopper3D.

When working with digital models applied to architecture, the Grashopper3D definitions become more complex as there are more elements to take into account. Masts, cables, environment, etc. are some elements that can be added to the definition. Although they do not make the process excessively more difficult, they do increase the complexity of the definition. That is why the Grashopper3D definition of the following models can be found in the corresponding Annexes section. The following digital models show the possibility of recreating forms found in an analogical way and some very complex forms that would have been very difficult to model analogically.

It is important to note that the digital model can be rendered at any time during the process. It is even possible to render the soap material itself using a Rhino material with alpha transparency, an environment map and Fresnel reflectivity, as shown in the following model.

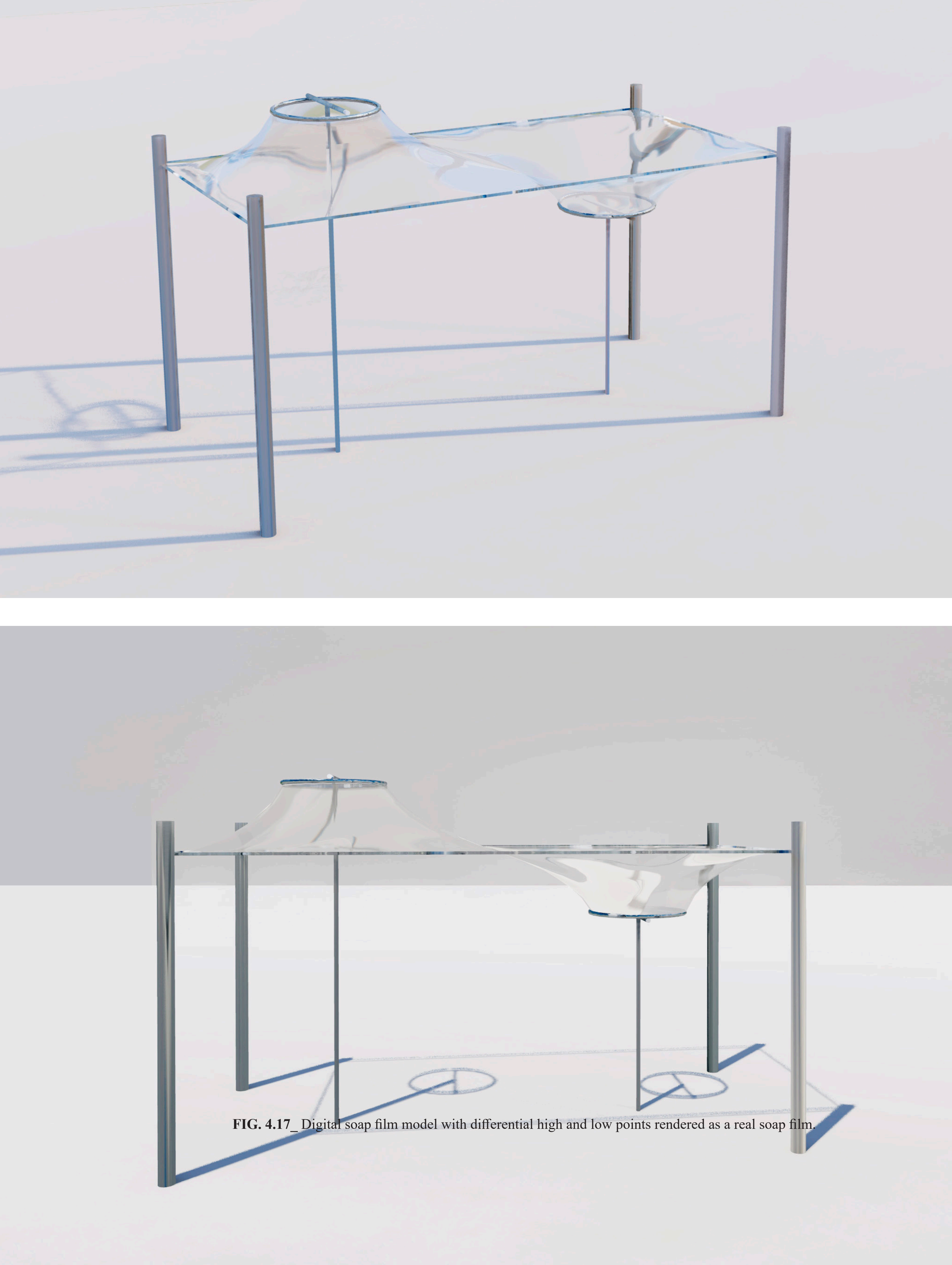


FIG. 4.17_ Digital soap film model with differential high and low points rendered as a real soap film.

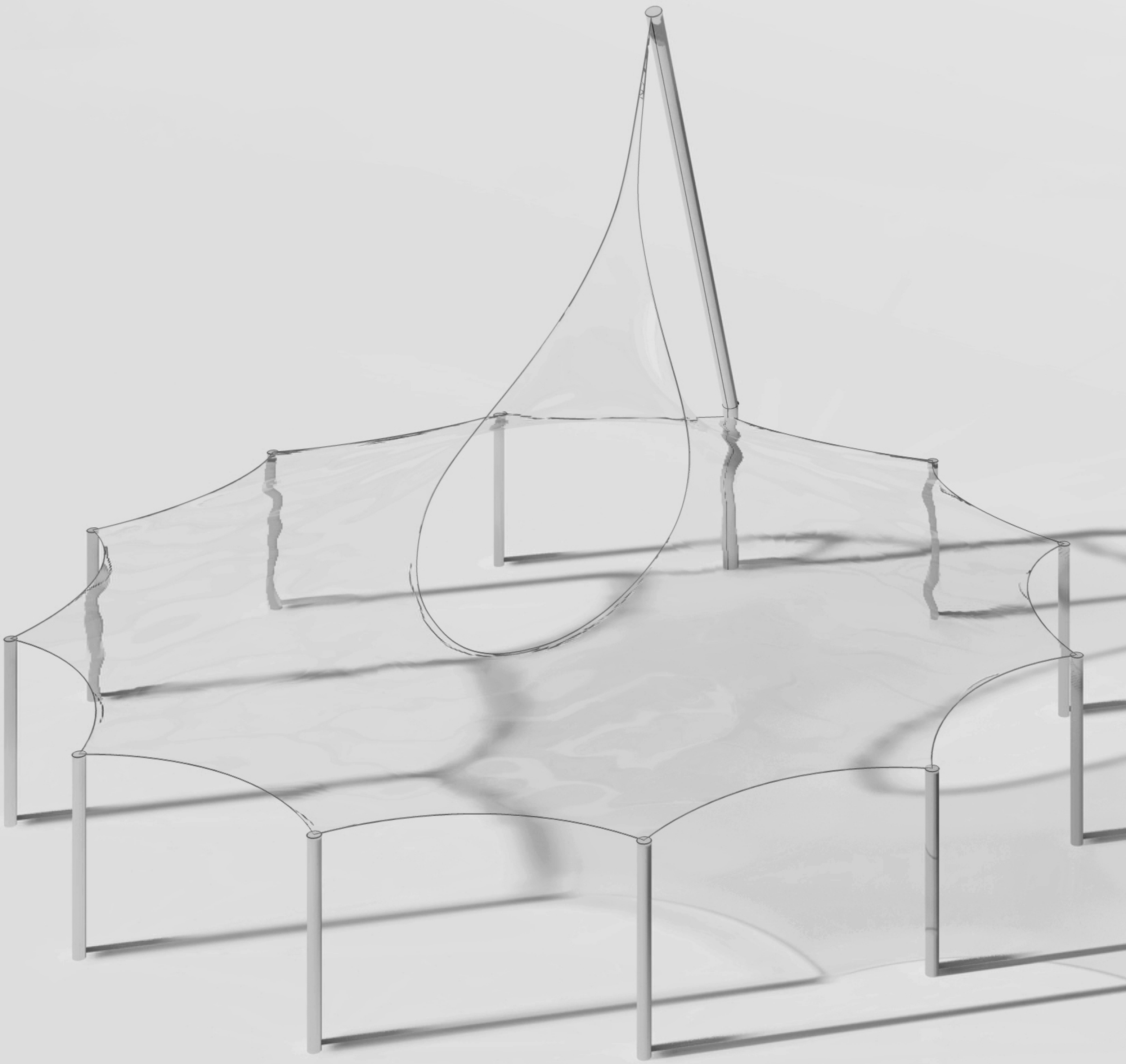


FIG. 4.18_ Digital soap film model of the IL Pavilion at the University of Stuttgart using Grashopper3D.

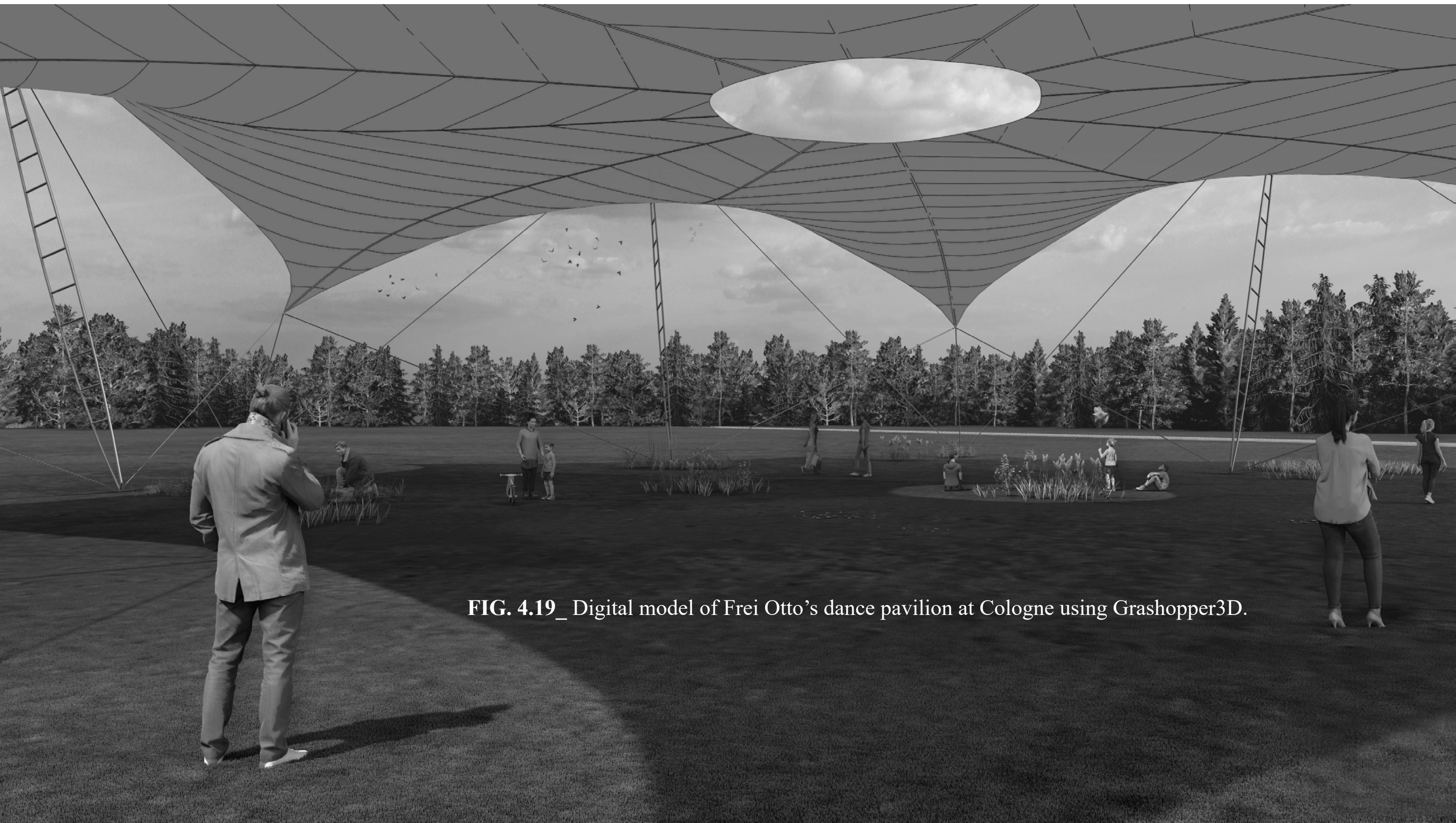


FIG. 4.19_ Digital model of Frei Otto's dance pavilion at Cologne using Grashopper3D.

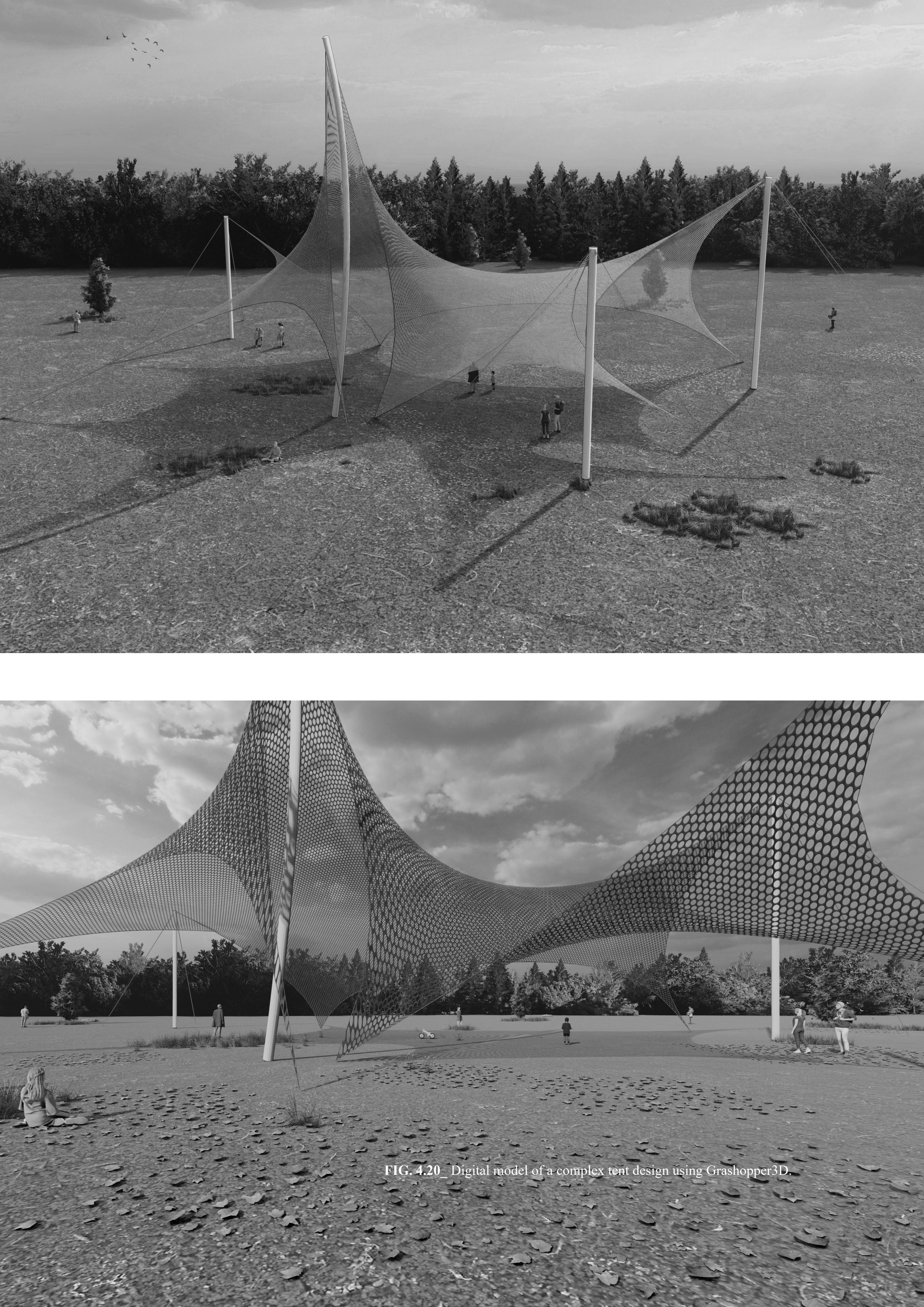


FIG. 4.20_ Digital model of a complex tent design using Grashopper3D.

4.3. CONCLUSIONS

Unlike analog models, in this case, prior operational knowledge about the modeling program (Grasshopper3D in this case) used is necessary. Recreating the simple gesture of dipping a closed wire frame in a soap solution digitally so that a minimal surface is formed can be a very complex task if you do not have this knowledge. But once you figure out how to make minimal surfaces digitally, it is very easy to change from one geometry to another, even more complex ones.

In this case, understanding the process of forming the shape with the most basic perimeters is not the main concern, as changing the given boundary is as far as three clicks. The main aspect to consider is the logic to follow to create these surfaces. One of the disadvantages of parametric modelling is the difficulty of modifying the design logic at the end of the design process. If the relationship between two or more parameters has to change, it will affect the whole model and therefore will be hard to accomplish. So it is important that the logic is well designed from the beginning and that it can be adapted to the greatest number of cases and scenarios.

When working with digital design tools, the fragility and ephemeral qualities of soap films are eliminated, speeding up the design process and allowing to work with more complex shapes. The designer or architect can focus on the architectural purpose of the form without the concern of obtaining a sufficiently stable surface to be analyzed that can burst at any time.

The problem of taking the obtained form to the plans that the analog models had is clearly solved with digital tools. The forced order of the procedure with analog models that consists of finding the shape, measuring it, building other models to make structural analysis and, if everything works, being able to work with that shape in a deeper way disappears in this case. With digital models, structural analysis and shape modifications can be done at any point in the process as you always work with the same model and there is no need to build another one. Although the precision of the shape can be adjusted, if you want a very detailed result, you will need to work with powerful computers to have a smooth workflow.

5. RESULTS AND CONCLUSIONS

5.1. RESULTS

Although the steps to follow to find the minimum surface with an analog and digital method are very different, I have chosen some of the main aspects of the work process to compare them and see in which aspect which method stands out over the other. In the following graph you can see the comparison of these aspects evaluating them according to how high or low they are on each method.

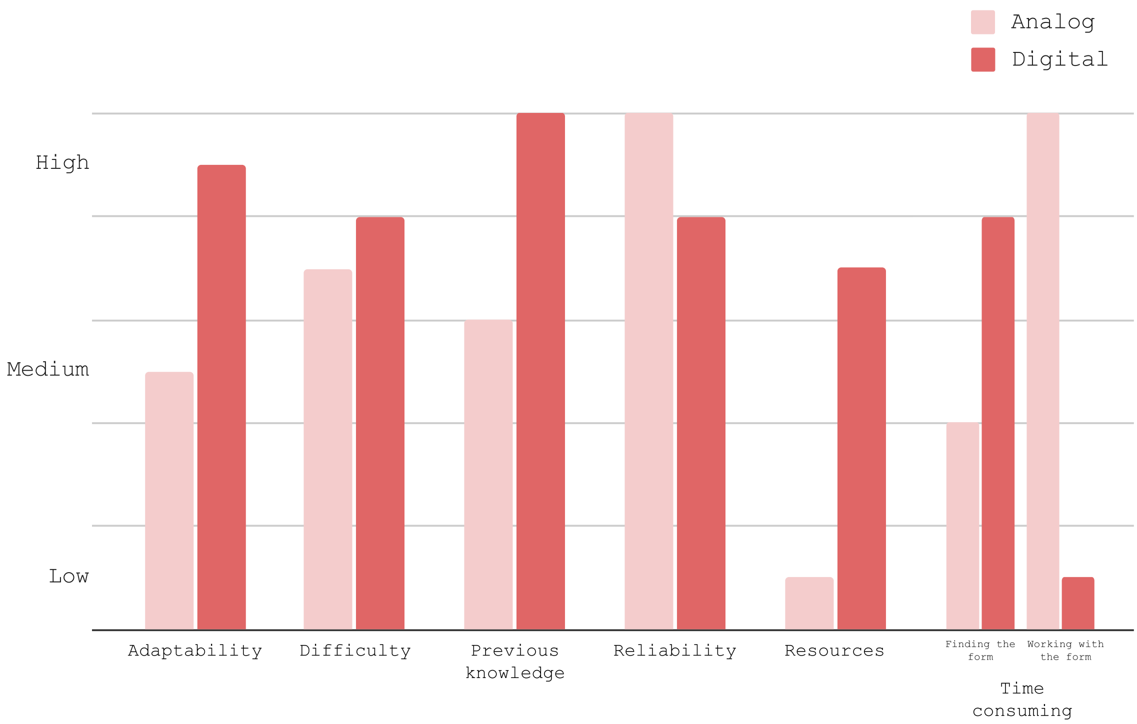


FIG. 5.1_ Comparative graph between the analog and digital method.

As the previous concepts are deeper than a simple title, now I will explain what each of them refers to and why they obtained this score.

Although the soap film models should be considered as dynamic objects since they can be modified and adapted to new perimeters (for example, in the study of high and low points), these perimeters cannot undergo major changes since: either the soap film will not support the change in tensions or the new desired perimeter has nothing to do with the existing one. In the case of digital models, the same definition of Grashopper3D can be applied for different perimeters, as long as the way in which the minimum surface is obtained has the same logic of relationships between parameters. Very simple or very complex surfaces can be obtained with the same or very similar definitions. For example, if we take the digital model of the Dance Pavilion in Cologne as a base, the number of sides (FIG. 5.2-3), the height, the strength of the cables, its diameter, etc. can easily be changed.

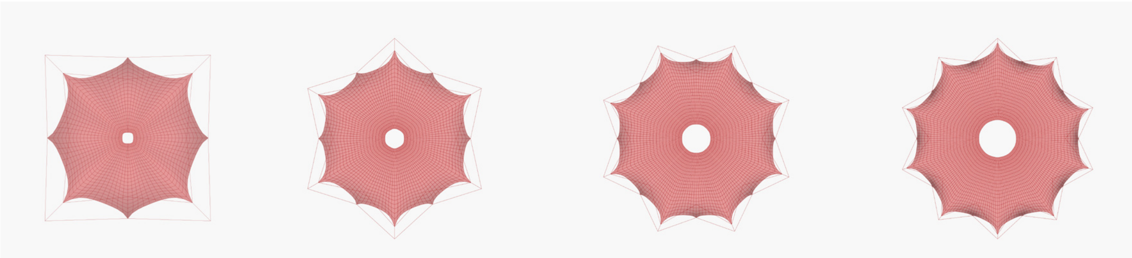


FIG. 5.2_ Top view of the Dance Pavilion modeled with Grasshopper3D with different number of sides.

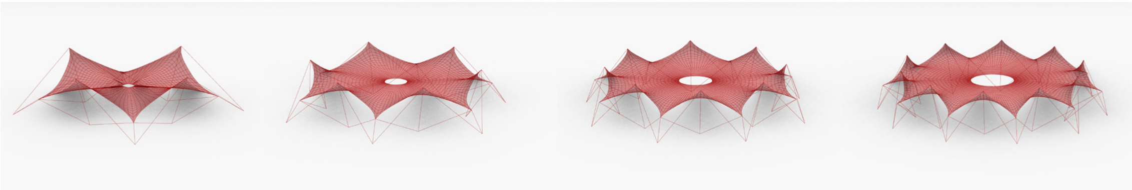


FIG. 5.3_ Axo view of the Dance Pavilion modeled with Grasshopper3D with different number of sides.

As stated before, creating a minimal surface analogically is as simple as dipping a closed perimeter in a solution of soap and water. The main difficulty lies in the process of transferring the forms obtained in the paper. If you don't have the necessary tools to do it, it can seem like an impossible task. Also, when working with complex shapes it can be very tedious to get the soap film to form. Its difficulty is linked to the previous knowledge necessary to be able to design forms and structures with an architectural application. The more knowledge you have about the behavior of the material, the easier it will be to design suitable forms. The difficulty in finding minimal surfaces digitally lies in finding the most suitable parametric logic for the shape you are looking for. When working with complex computer programs, they require a great deal of prior knowledge of how it works. Modeling the simplest minimum surface can be a very complicated task if you do not have a knowledge of using the software.

As the form finding methodology responds to the internal behavior of the material and its physical characteristics, the models obtained through an analog process are very reliable. The most sensitive part and where there could be an error is when analyzing this form and transferring it to paper. Although when working digitally, the material factor disappears, its characteristics and internal behavior can be recreated. That is why the reliability of the form obtained is very high, although for this the parametric definition must not have errors.

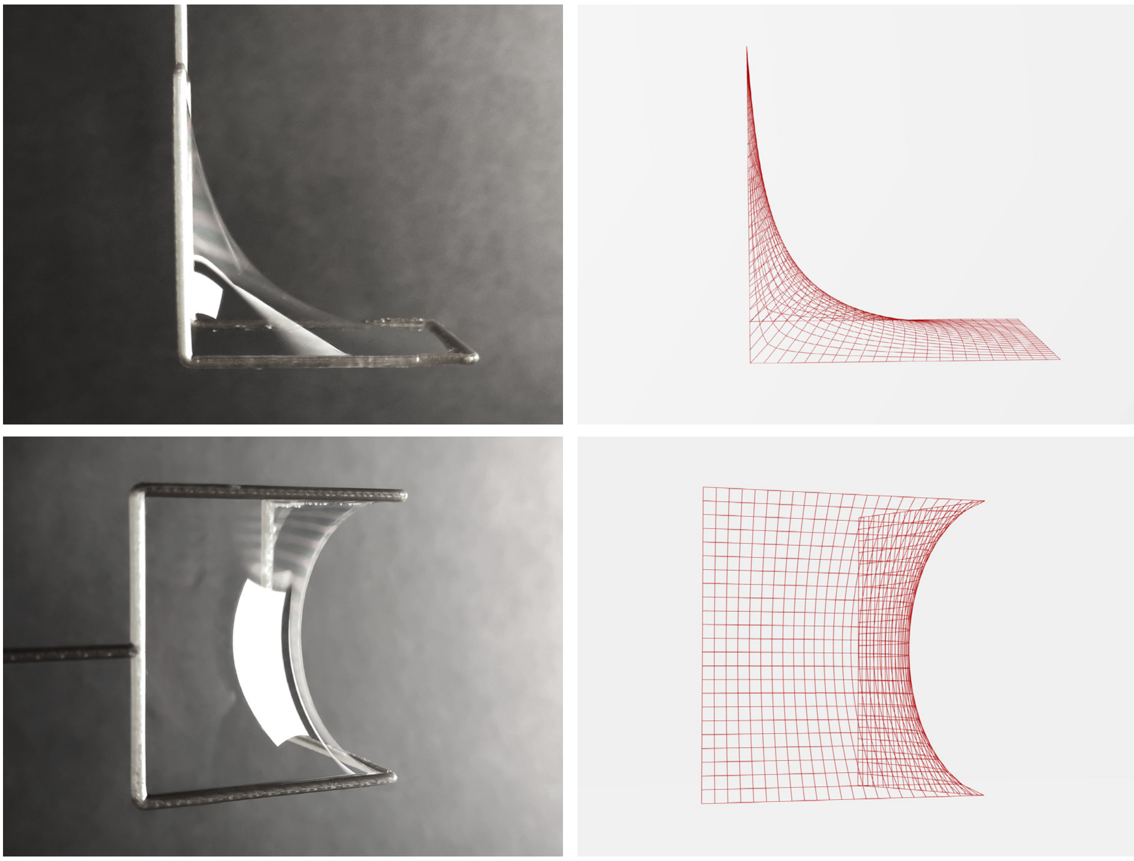


FIG. 5.4_ Comparison of the same form obtained from an analog and digital method.

The resources to make this type of models are minimal, water, soap and wire. It is true that Frei Otto built a very sophisticated machine to systemize the process, but it is by no means necessary to carry them out. On the other hand, to perform them digitally, a sufficiently powerful computer is needed to be able to work with digital parametric tools.

When we talk about the modeling time of each of the methods, I think it is important that we differentiate between the time it takes to find the shape and the time it takes to be able to work with that shape. When working with analog models, there is a direct relationship between modeling time and shape complexity. The more complex the shape, the longer it takes to find it. On the other hand, when working with digital models, the modeling time depends more on the elements involved and not on the complexity of the shape itself. It also depends on the designer's operational knowledge of the program. Very simple shapes can take a long time to model. Being able to work with the form obtained from analog models is a time-consuming task, especially if you don't have the necessary tools. On the other hand, with digital models you can work on the model at any time during the design process.

5.2. CONCLUSIONS

Frei Otto was one of the pioneers in applying the form finding methodology to architecture. He systematized an entire work process in order to apply this methodology to architecture in the most optimal way. As shown in this research work, this process can be further investigated and improved with the help of computational design tools.

As Frei Otto's research goes back before the appearance of digital parametric tools, he based all his studies on analog models such as the previously seen soap film, hanging chains or tensile fabric models. His models began as a very basic element and, from the systemization of the process, they became very sophisticated analysis elements. The essence of finding the shape through analog modeling is the intrinsic relationship between the material used and the shape obtained and at the same time with the type of structure to which it refers (soap film for membrane structures, hanging chains for compressive arch and shell structures...).

When working with digital design tools, the material dimension disappears, although its properties such as weight, resistance, strength... can be defined as parameters. The resulting shapes are based on a series of calculations from these given parameters. That is why the architect or designer could be attributed the characteristics of a computer programmer since he is the one who defines these algorithms and parameters. These softwares are not only able to create the forms, but also analyze them.

To find the shape with analog models is a lengthy procedure, hours or days are needed, on the other hand, with digital parametric models, very complex shapes can be achieved in a few minutes. I think that the factor of time is the most decisive when it comes to choosing one methodology or the other. Nowadays, clients demand tighter delivery dates, thus limiting the time in the design process. The problem, I think, with designing only with a computer and calculating everything with a computer is doing things without fully understanding them. To be able to design with analog models it is very necessary to understand the internal behavior of materials, even when working with very simple shapes.

Although before carrying out this research work, my opinion was that analog models were obsolete compared to digital processes, especially in the use of the form finding methodology, now I firmly believe that analog models are a key element to find the form from natural processes. The advantages of digital tools over analog ones are very clear. The first ones allow to speed up the process in a very considerable way as well as allowing to work with much more complex shapes. But in order to work with a form finding methodology to its maximum potential, it is essential to understand the internal process of materials that contributes to the design of natural forms, no matter how complex they may be. In my opinion, this understanding of the self-formation process is achieved through free experimentation.

This is why I bet on an approach that combines the two methods. Not only work the form finding methodology from a solely digital perspective, but gain experience from free experimentation with analog models before starting to work with more complex forms. Although most of the work can be done digitally, I recommend accompanying the digital models with very simple analog models. The analog ones allow a closer approximation to reality and allow detecting the problems that may arise. They do not need to be very complex or detailed, even the simplest ones allow you to quickly see if something is doable or not. This hybrid approach is way quicker than the full analog approach that Otto had without losing the qualities of the analog models.

Responding to Frei Otto's statement at the beginning of the work on finding the form with computational tools, these have evolved in such a way in recent years that they are capable of recreating the characteristics of materials and their internal behavior, so I believe that it is possible to find the form through a computer. Despite the great potential of parametric tools has not yet been embraced, the ability to work with complex geometries far exceeds the ability of analog models.

During the realization of this research work, one of the main problems that I have realized in relation to the design with parametric tools is that the great complexity with which it is possible to work, sometimes, leads to a design process that is very focused on what can be designed, instead of what should be designed, resulting in buildings with excessively complex geometry. Although the following statement by Frei Otto does not explicitly refer to digital tools, I think it reflects very well the problem discussed above.

> *"Why should we build very large spaces when they are not necessary? We can design halls spanning several kilometres and covering a whole city, but we have to ask, what does it really make? What does society really need?"* [10]

This social aspect of design and architecture was also an important aspect of Frei Otto's research. He attached great importance to the relationship between structures and the people who used them.

10 Frei Otto, interview with Icon magazine, 2005.

Although this work has focused only on geometric parameters for the form finding methodology from an analog and digital method, I would like to end this research work with a concern about the potential of digital parametric tools that emerged during the investigation. Is it possible, within the great potential that parametric digital tools have, to treat aspects as complex as human behavior, history, culture, collective memory, etc. as parameters? Even though these concepts are far from the objectives of this work, I think it would be an interesting research topic for a future work taking this one as a starting point.

6. FIGURES REFERENCE

7. REFERENCES

7.1. BIBLIOGRAPHY

Addis, Bill. Karl-Eugen Kurrer and Werner Lorenz. 2020. *Physical Models: Their historical and current use in civil and building engineering design.* Edition Bautechnikgeschichte / Construction History

Dierkes, Ulrich, Stefan Hildebrandt, and Anthony J Tromba. 2010. *Regularity of Minimal Surfaces*. Book. 2. Aufl. Vol. 340. Grundlehren der mathematischen Wissenschaften. Berlin, Heidelberg: Springer-Verlag.

Drew, Philip. 1976. *Frei Otto : form und Konstruktion.* Book. Stuttgart: Hatje.

Glaeser, Ludwig. 1978. *The Work of Frei Otto and His Teams, 1955-1976 : IL Special Issue Devoted to the Exhibition Organized in 1971 by the Museum of Modern Art, New York*. Stuttgart : Institut für Leichte Flächentragwerke.

Meissner, Irene, Frei Otto, and Eberhard Möller. 2015. *Frei Otto : Forschen, Bauen, Inspirieren = a Life of Research, Construction and Inspiration*. München : Ed. Detail.

Otto, Frei. 1996. *Frei Otto, Artengo, Menis, Pastrana : Firenze 1996.* Book. Edited by Frei Otto. Firenze: Accademia delle arti del disegno.

Otto, Frei. 1988. *Form : Ein Vorschlag zur Entwicklung einer Methode zur Ordnung und Beschreibung von Formen = a proposal for developing a method of classifying and describing forms*. Book. Edited by Klaus Bach. Mitteilungen des Instituts für leichte Flächentragwerke ; 22. Stuttgart: Institut für leichte Flächentragwerke IL.

Otto, Frei, 1925-2015. 2008. *Frei Otto : Conversación Con Juan María Songel*. Barcelona : Gustavo Gili.

Otto, Frei, 1925-2015. 1979. *Arquitectura Adaptable / Frei Otto ... [et Al.]*. Barcelona : G. Gili.

Otto, Frei, 1925-2015. 2005. *Frei Otto : Complete Works : Lightweight Construction Natural Design / Edited by Winfried Nerdinger in Collaboration with Irene Meissner, Eberhard Möller, Mirjana Grdanjski*. Basel [etc.] : Birkhäuser.

Otto, Frei, Ludwig. Glaeser, and N.Y. Museum of Modern Art, New York. 1972. *The Work of Frei Otto*. New York : Museum of Modern Art.

Roland, Conrad. 1973. *Frei Otto : Estructuras : Estudios y Trabajos Sobre La Construcción Ligera / Por Conrad Roland ; Versión Castellana de Francesc Albardané ; Prólogo de Félix Candela*. Barcelona : Gustavo Gili.

Tedeschi, Arturo. 2014. *AAD_Algorithms-Aided Design : Parametric Strategies Using Grasshopper.* Book. Brienza: Le Penseur.

Vrachliotis, Georg, Joachim Kleinmanns, Martin Kunz, Philip Kurz, Irene Meissner, Cornelia Escher, Holger Hanselka, et al. 2017. *Frei Otto : Thinking by Modeling*. Leipzig : Spector Books.

Werkbund Bayern., Frei, 1925-2015, and Museum Villa Stuck. 1995. *Frei Otto, Bodo Rasch : Finding Form : Towards an Architecture of the Minimal : The Werkbund Shows Frei Otto, Frei Otto Shows Bodo Rasch : Exhibition in the Villa Stuck, Munich, on the Occasion of the Award of the 1992 Deutscher Werkbund Bayern Prize to F*. Stuttgart : Axel Menges.

_ Fabricius, Daniela. 2017. Material models, photography, and the threshold of calculation.

_ Gaß, Siegfried. 2016. Physical analog models in architectural design. International Journal of Space Structures.

_ García Pino, Fernando. 2015. Centro Multiusos en Mannheim. Frei Otto. Doblando la malla hasta hacer una concha.

_ Laso Jimeno, Sol. 2018. Experimento y simulación en el trabajo de Frei Otto, Heinz Isler y Antonio Gaudí.

_ Songel, Juan María. 2008. Frei otto y el debate sobre la génesis de la forma arquitectónica.

7.2. FILMOGRAPHY

_ Alan Schoen: ‘Shapes of Soap Films’: Triply-Periodic Minimal Surfaces

_ Alan Schoen: Soap Films and Minimal Surfaces

_ Frei Otto - AA School of Architecture Lecture

_ Frei Otto’s Arbeitsmethoden, Vortrag von Christine Otto-Kanstinger

_ Frei Otto. Light structures inspired by nature

_ Frei Otto. Premio Pritzker. Homenaje

_ Frei Otto: Spanning The Future

_ Frei Otto - The Work of Frei Otto: Architecture and Natural Sciences

_ Matt Parker: An Attempt to Visualise Minimal Surfaces and Maximum Dimensions

7.3. WEBGRAPHY

_https://www.archdaily.com/799988/frei-ottos-drawings-and-models-showcased-with-exhibition-design-by-far-frohn-and-rojas 'Frei Otto's Drawings and Models Showcased'

_https://www.plataformaarquitectura.cl/cl/763573/video-frei-otto-experimentando-con-pompas-de-jabon 'Frei Otto, experimentando con pompas de jabón'

_https://www.plataformaarquitectura.cl/cl/763636/pritzker-2015-frei-otto-y-la-importancia-de-la-experimentacion-en-la-arquitectura 'Pritzker 2015: Frei Otto y la importancia de la experimentación en la arquitectura'

_ https://www.plataformaarquitectura.cl/cl/767750/en-perspectiva-frei-otto 'En perspectiva: Frei Otto'

_https://www.archdaily.com/610531/frei-otto-and-the-importance-of-experimentation-in-architecture 'Frei Otto and the Importance of Experimentation in Architecture'

_ https://researchlm.wordpress.com/2016/04/03/frei-otto/ 'The Structure of Vagueness'

_ http://ferminblanco.com/web/?page_id=4931&lang=en 'Form Finding. Frei Otto, a free man'

_ https://www.metalocus.es/en/news/frei-otto-video-modeling-soap-films 'Frei Otto. Modeling with soap films'

_ https://www.saai.kit.edu/veranstaltungen/otto-denken-in-modellen.php 'Frei Otto - Denken in Modellen'

_https://www.plataformaarquitectura.cl/cl/914377/tensoestructuras-como-funcionan-y-que-tipos-existen 'Tensoestructuras: ¿cómo funcionan y qué tipos existen?'

_https://www.plataformaarquitectura.cl/cl/895618/reinventando-la-multihalle-de-frei-otto-como-una-enorme-caparazon-de-madera-temporal-se-vuelve-permanente 'Reinventando el 'Multihalle' de Frei Otto: cómo una enorme caparazón de madera temporal se vuelve permanente'

_ https://discourse.mcneel.com/t/soap-film-from-boundery/110777

_ http://antoniomacia.com/publications/all-in-one-conferences-bubble-facades/ ‘Bubble façades’

_ https://journals.openedition.org/lha/1575 ‘De la maquette à la modélisation. La recherche architecturale de Frei Otto’

_https://www.quantamagazine.org/math-duo-maps-the-infinite-terrain-of-minimal-surfaces-20190312/ ‘Math Duo Maps the Infinite Terrain of Minimal Surfaces’

_https://www.wintess.com/es/project/revision-estructural-al-pabellon-aleman-expo-67-montreal/ ‘Revisión Estructural Al Pabellón Alemán, Expo ’67, Montreal’

_ https://wewanttolearn.wordpress.com/category/resources/inspiration/frei-otto/ ‘The Nature of Gridshell Form Finding’

_ https://www.saai.kit.edu/551.php ‘Frei Otto (1925-2015)’

_ https://www.grasshopper3d.com/forum/topics/frei-otto-bubbles ‘Frei Otto Bubbles’

_ https://www.albertopugnale.com/2018/03/27/integrating-form-structure-and-acoustics-a-computational-reinterpretation-of-frei-ottos-design-method-and-vision/ ‘ntegrating form, structure and acoustics: A computational reinterpretation of Frei Otto’s design method and vision’

_ http://mkmra2.blogspot.com/2018/11/kangaroo-2.html ‘Kangaroo Physics in Rhino 6’

_ https://discourse.mcneel.com/t/live-soap-film/93103/2 ‘Live Soap Film’

_https://www.behance.net/gallery/40189735/Conditional-form-Tensile-structures-%282015%29?tracking_source=search_projects_recommended%7CFREI%20OTTO ‘Conditional Forms and Algorithmic Architecture’

_ https://www.alessandrobuffi.com/form-finding ‘Minimal patterns’

_ https://www.ladybug.tools/butterfly.html

8. ANNEXES

8.1. ANNEX.i

In this annex section there are some complementary images of the buildings resulting from Frei Otto's experiments with soap films. They are in an annex section since they are not the objective of the study, but they are important to complement the work.

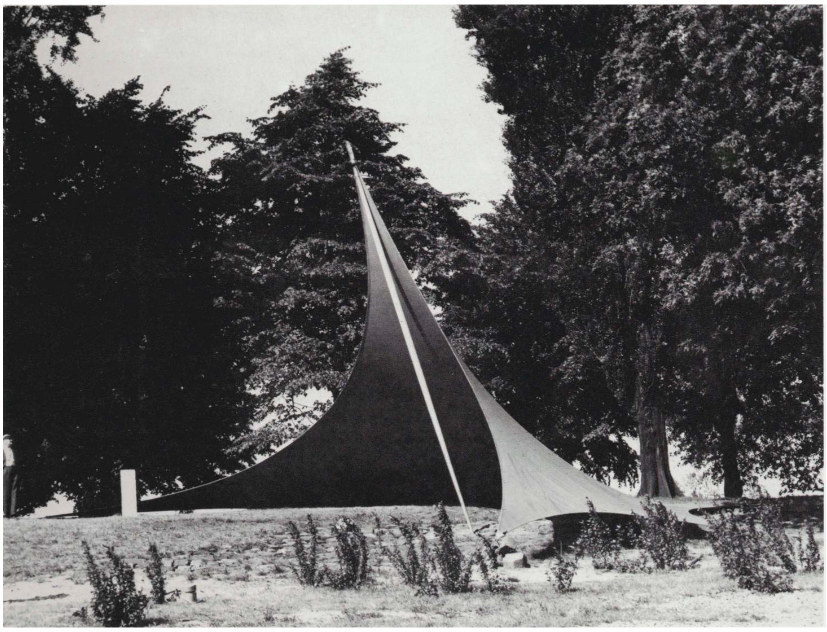


FIG. A.1_ Shelter Pavilion, Cologne. 1957.

FIG. A.2_ Exhibition Pavilions, Lausanne. 1964.

FIG. A.3_ Humped Pavilion, Cologne. 1957.

FIG. A.4_ Hangar Tents, 1957.

FIG. A.5_ Wave Hall, Hamburg. 1963.

FIG. A.6_ Wave Hall, Hamburg. 1963.

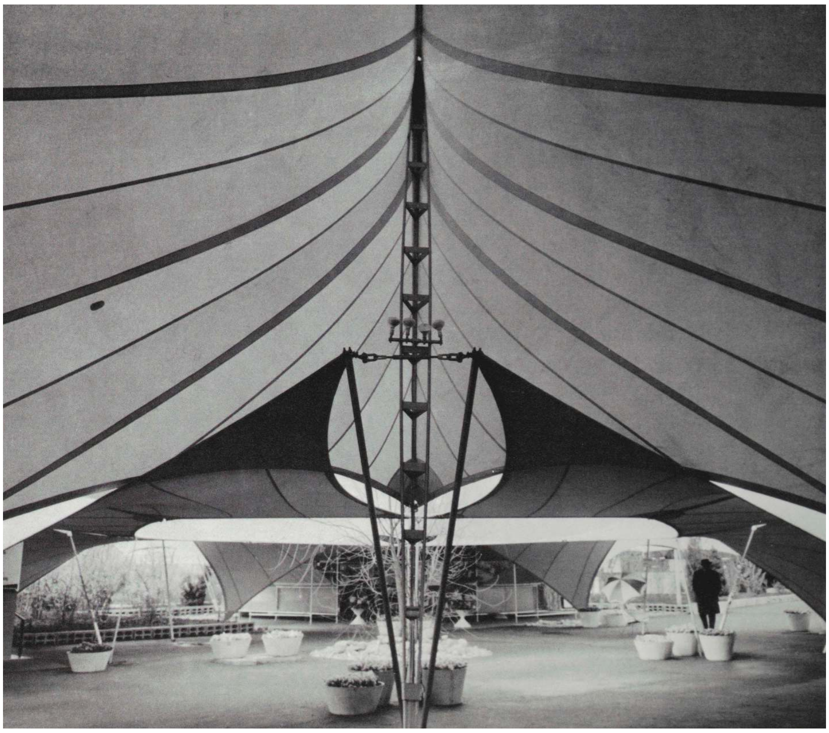


FIG. A.7_ Small Pavilions, Hamburg. 1963.

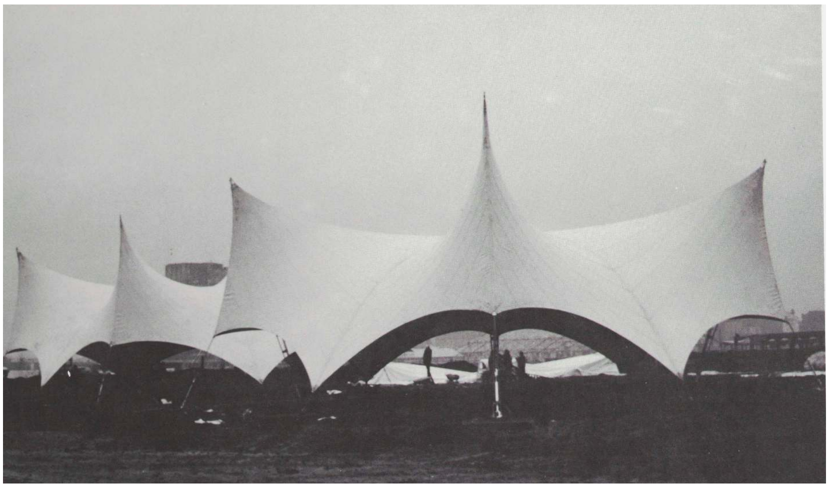


FIG. A.8_ Small Pavilions, Hamburg. 1963.

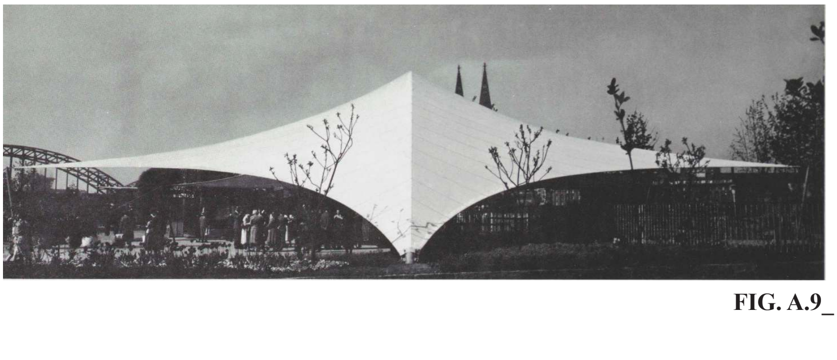


FIG. A.9_ Entrance Arch, Cologne. 1957.

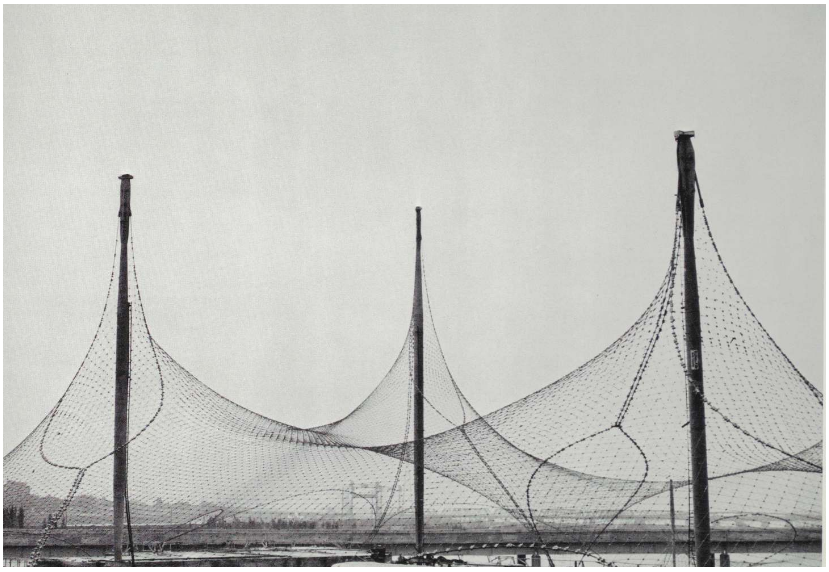


FIG. A.10_ German Pavilion, Montreal. 1967.

FIG. A.11_ German Pavilion, Montreal. 1967.

FIG. A.12_ German Pavilion, Montreal. 1967.

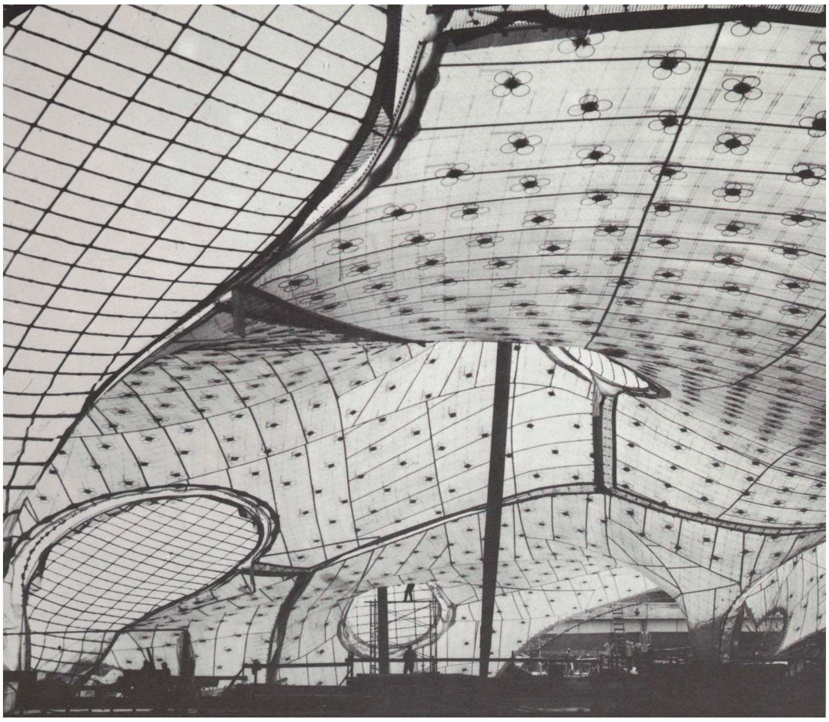


FIG. A.13_ German Pavilion, Montreal. 1967.

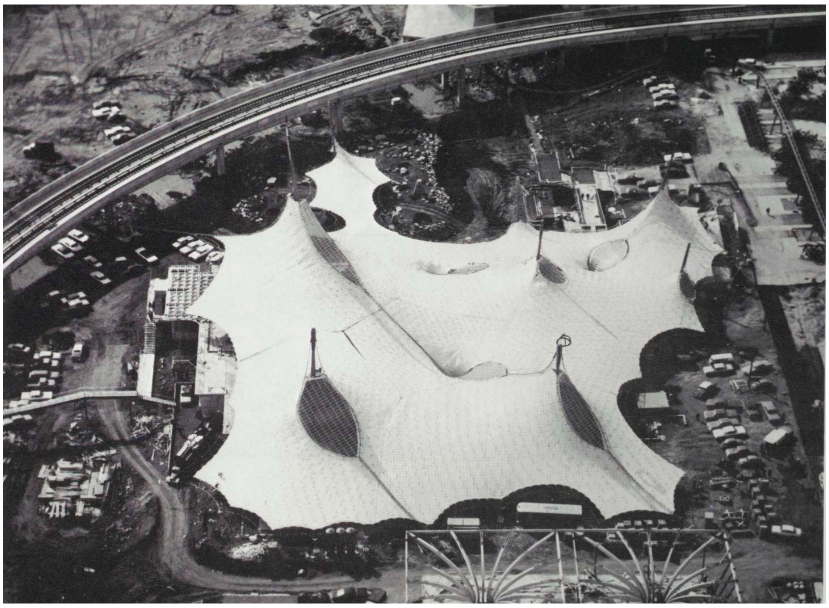


FIG. A.14_ German Pavilion, Montreal. 1967.

FIG. A.15_ German Pavilion, Montreal. 1967.

8.2. ANNEX.ii

In this annex section there are some of the current architectural examples that use the form finding methodology.

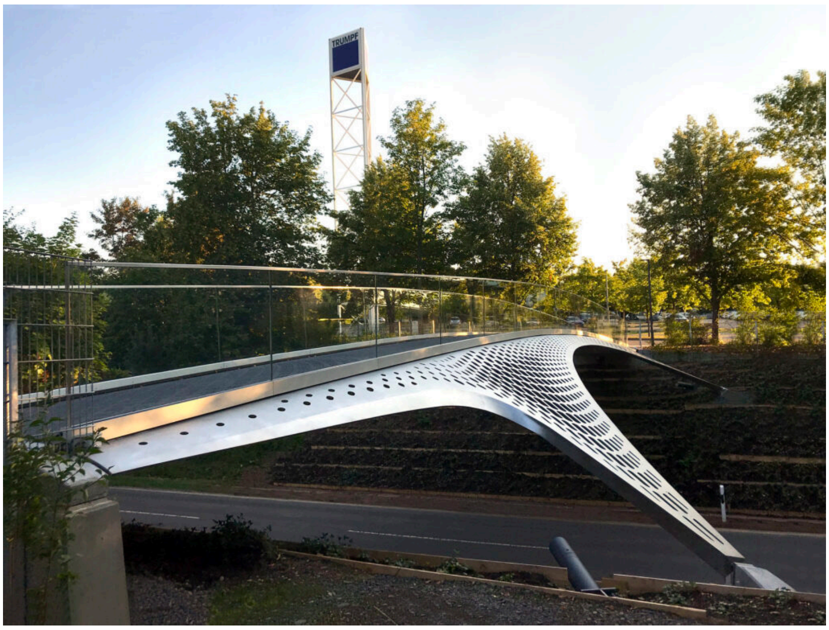


FIG. A.16_ Trumpf footbridge, Schlaich Bergermann Partner. 2018.

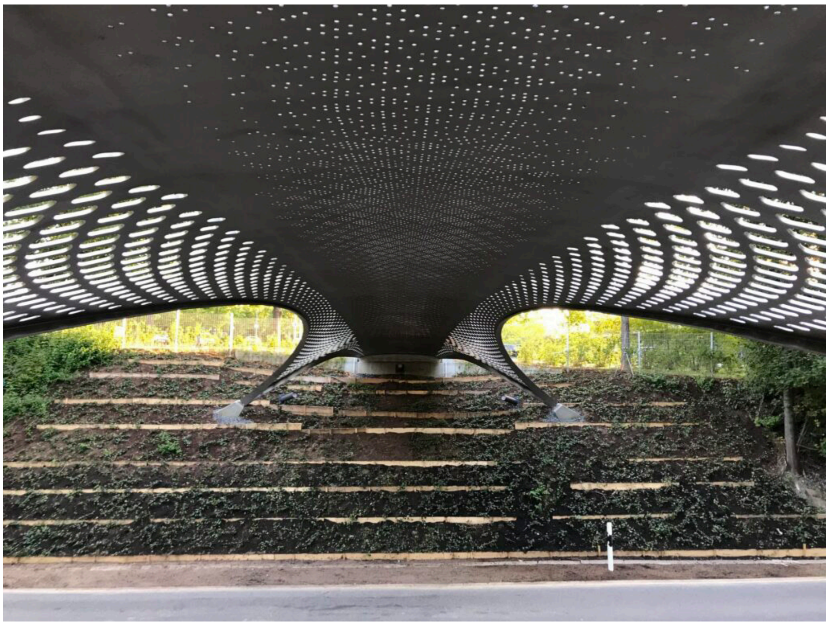


FIG. A.17_ Trumpf footbridge, Schlaich Bergermann Partner. 2018.

FIG. A.18_ Schierker Feuerstein Arena, Schlaich Bergermann Partner. 2017.

FIG. A.19_ Schierker Feuerstein Arena, Schlaich Bergermann Partner. 2017.

FIG. A.20_ National Sports Complex Olimpiyskiy, Schlaich Bergermann Partner. 2012.

FIG. A.21_ National Sports Complex Olimpiyskiy, Schlaich Bergermann Partner. 2012.

FIG. A.22_ Pavilion for EXPO 2012, SL Rasch. 2012.

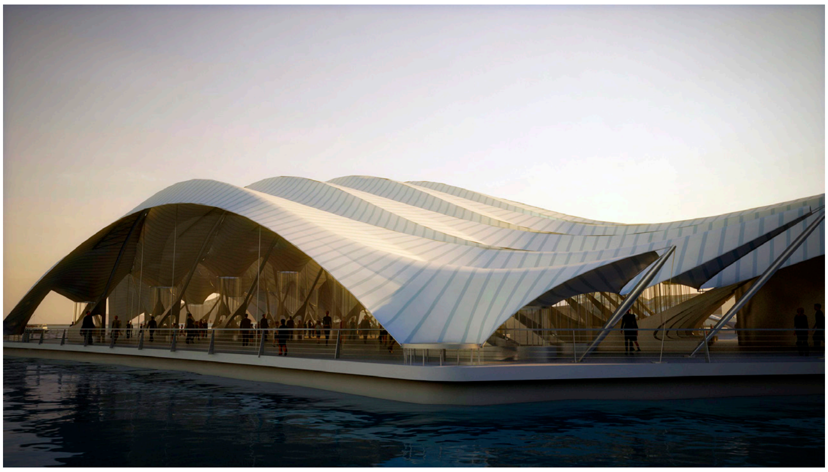


FIG. A.23_ Pavilion for EXPO 2012, SL Rasch. 2012.

FIG. A.24_ Convertible Aircraft Shading, SL Rasch. 2016.

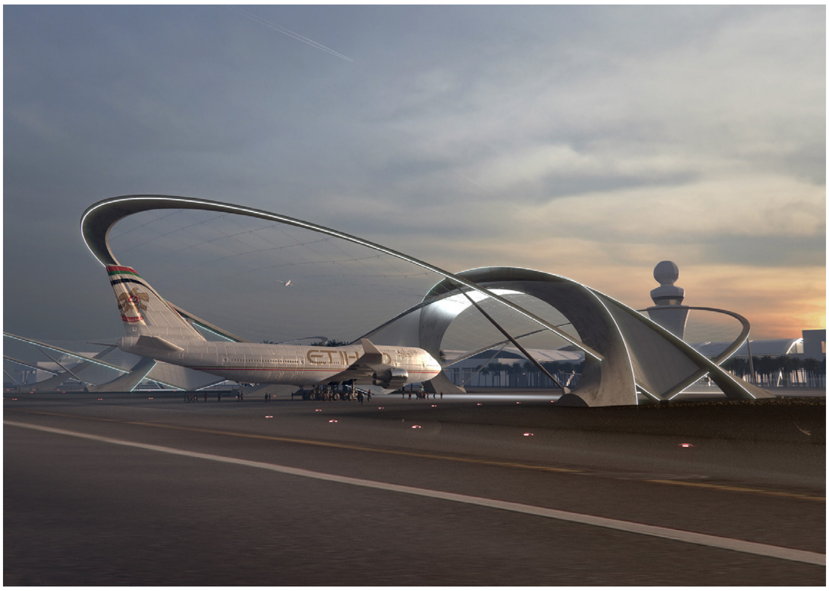


FIG. A.25_ Convertible Aircraft Shading, SL Rasch. 2016.

8.3. ANNEX.iii

In this annex section there are some of the Grashopper3D definitions of the digital models shown in the work.

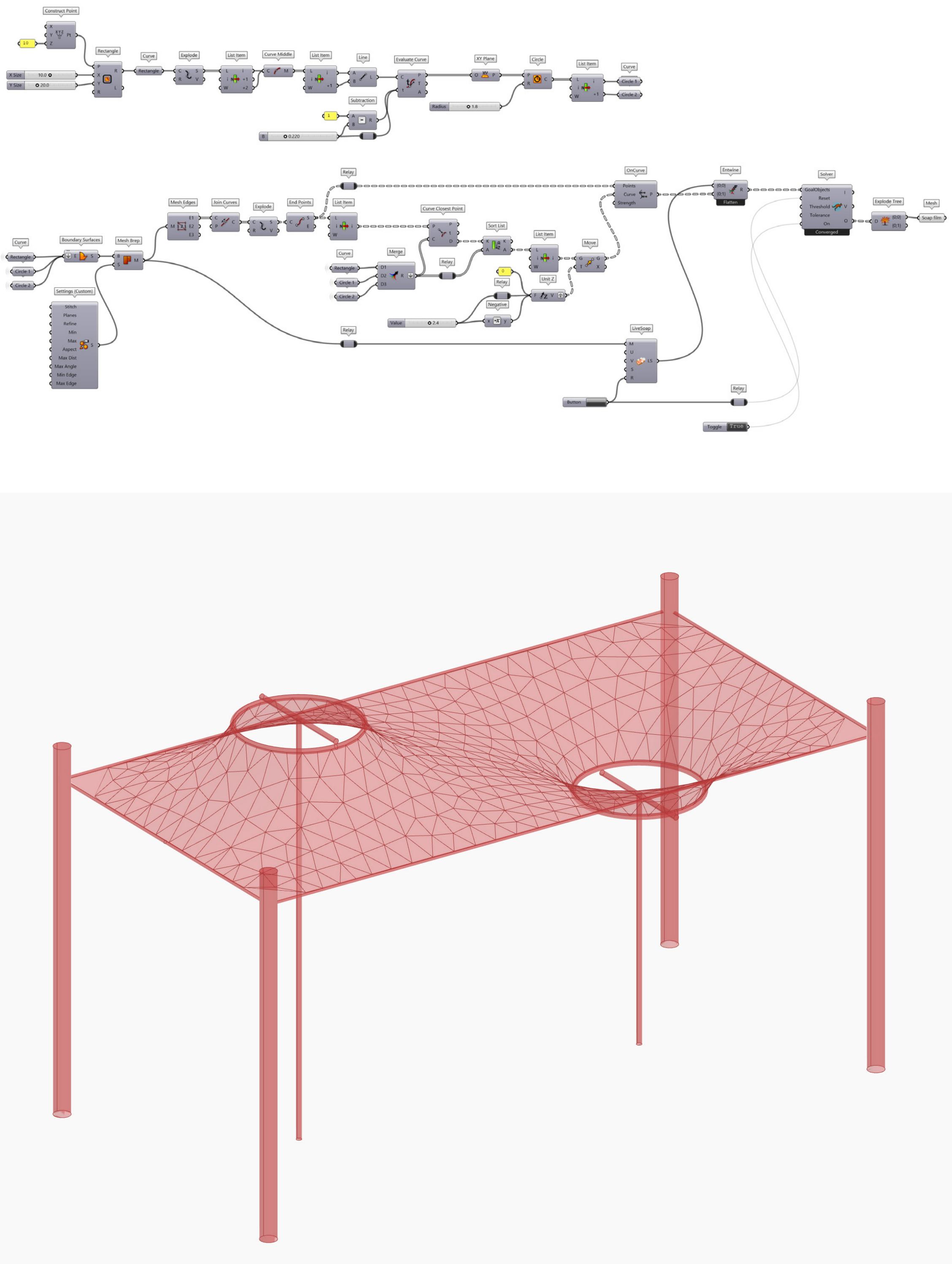


FIG. A.26_Grashopper3D definition of the digital soap film model with differential high and low points and its result.

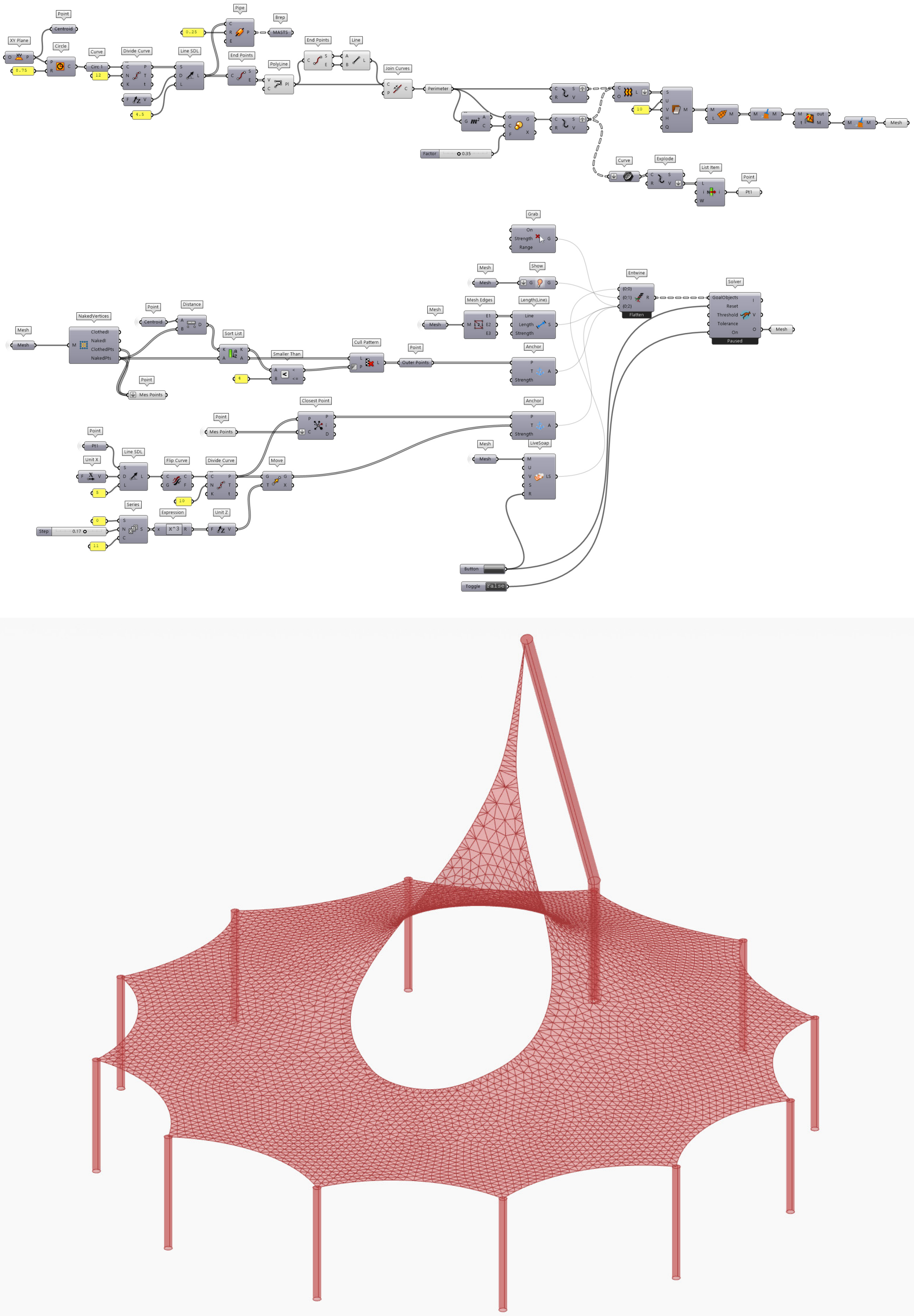


FIG. A.27_Grashopper3D definition of the digital model of the IL pavilion at University of Stuttgart and its result.

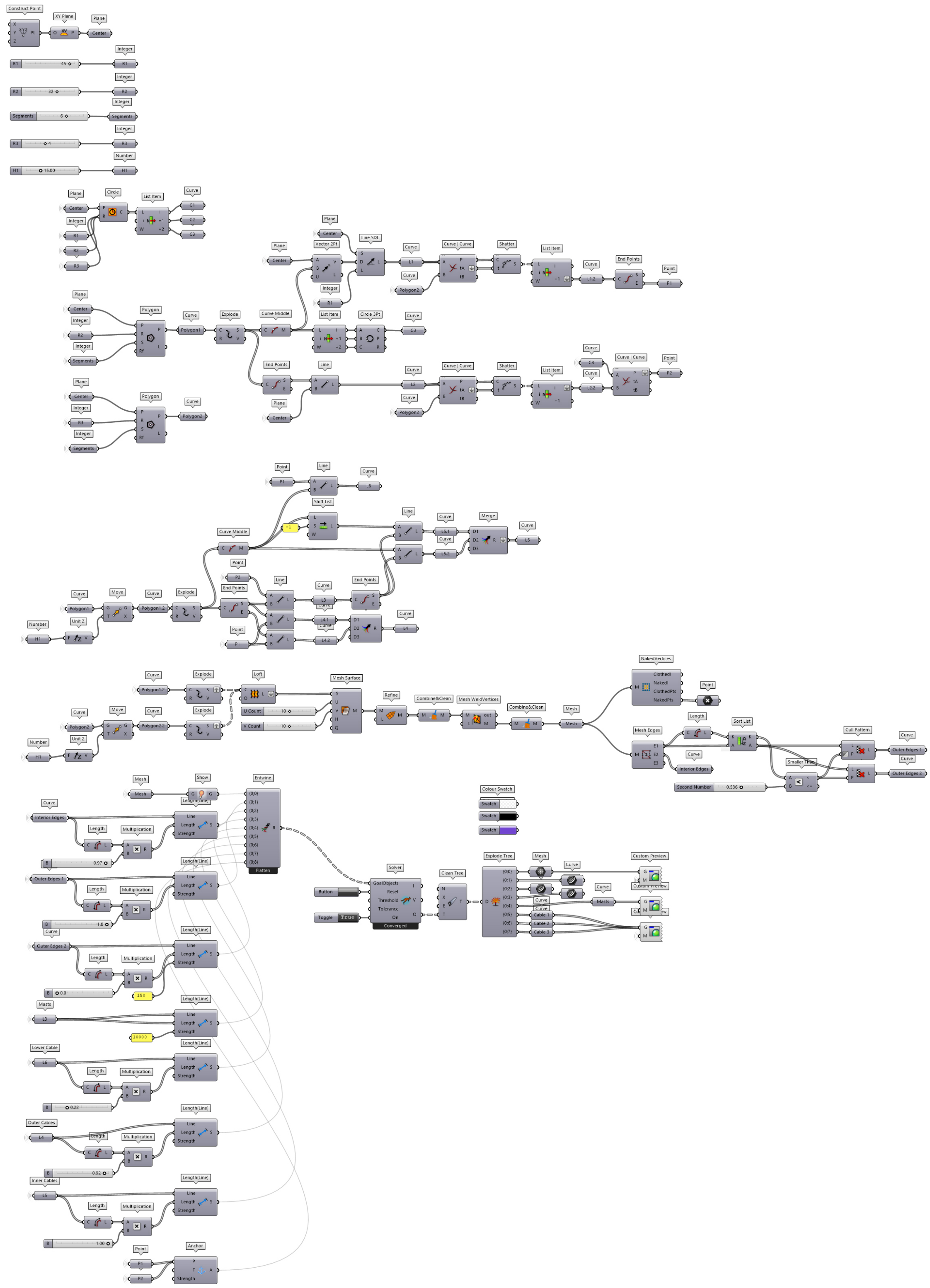
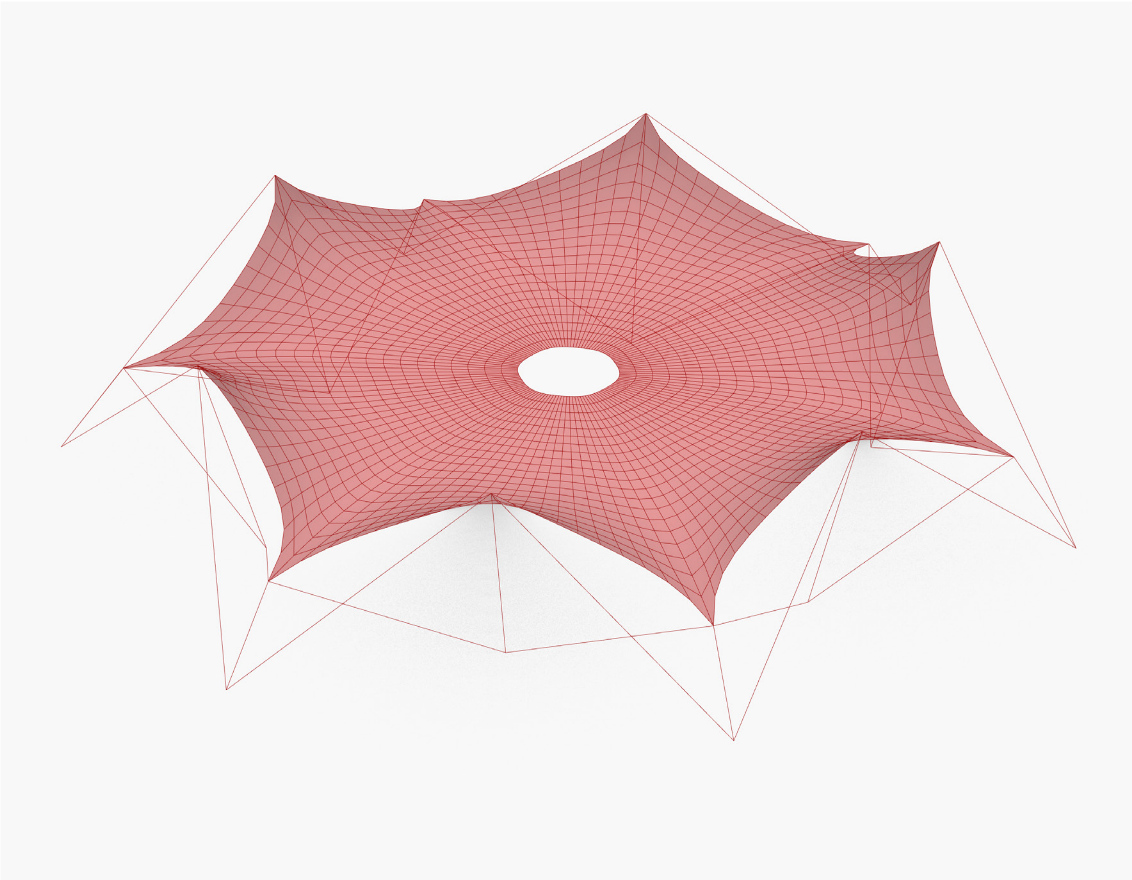


FIG. A.28_Grashopper3D definition of the digital model of Frei Otto's dance pavilion at Cologne and its result.



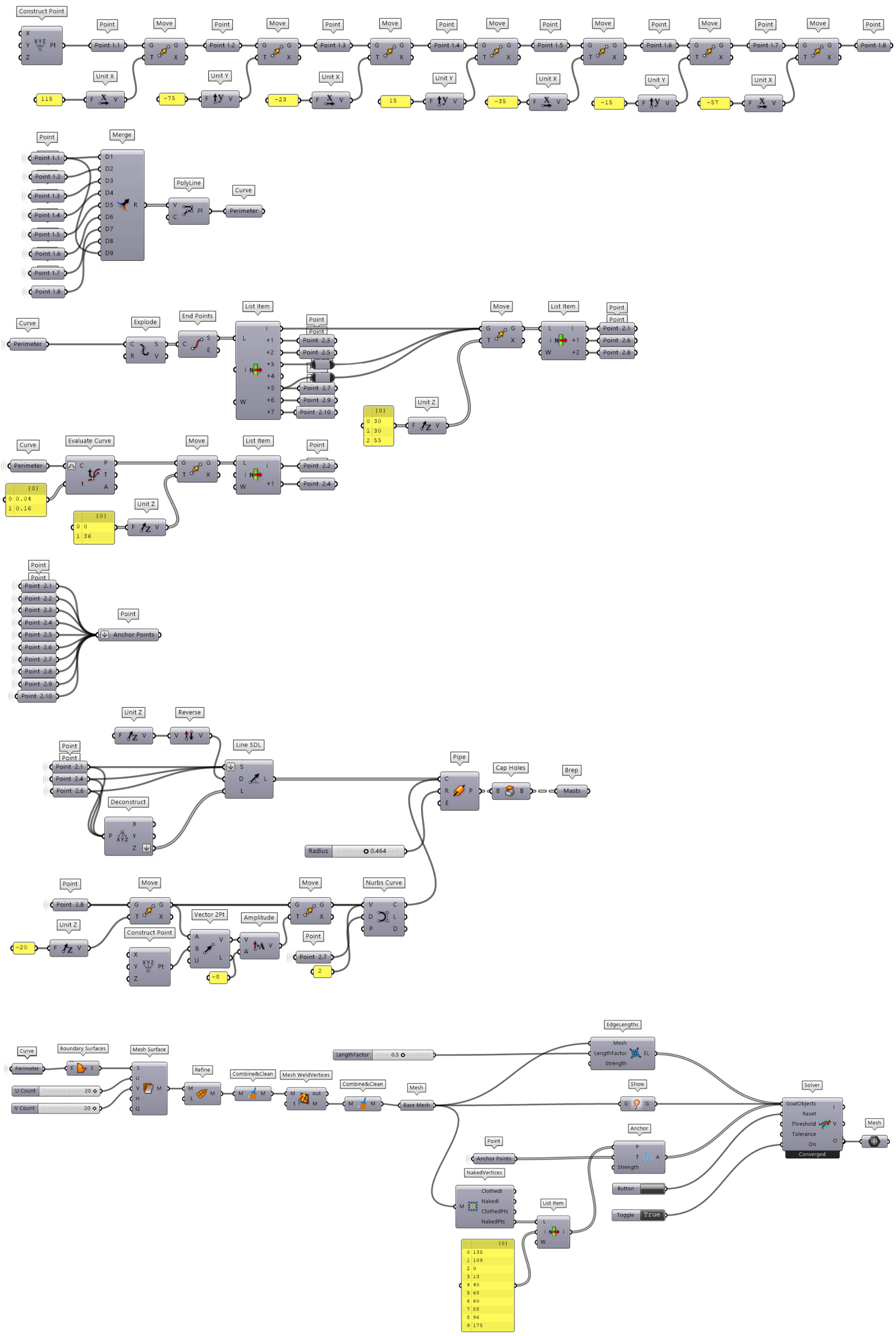


FIG. A.29_Grashopper3D definition of the digital model of a complex tent design and its result.