(Digital) Form-finding

Chapter · September 2014

1 author:

Alberto Pugnale
University of Melbourne

ARTURO TEDESCHI

AAD_ ALGORITHMS-AIDED DESIGN

PARAMETRIC STRATEGIES USING GRASSHOPPER®

Foreword by Fulvio Wirz

LE PENSEUR PUBLISHER

AAD_Algorithms-Aided Design

Parametric Strategies using Grasshopper®

Arturo Tedeschi

with contributions by Stefano Andreani, Antonella Buono, Maurizio Degni, Lawrence Friesen, Andrea Galli, Francesco Lipari, Davide Lombardi, Ludovico Lombardi, Arthur Mamou-Mani, Alberto Pugnale, Antonio Turiello, Brian Vesely, Lorenzo Vianello, Fulvio Wirz.

Text revision by Brian Vesely

Each author bears responsibility exclusively for the contents he wrote and might dissent from contents of other authors featured in this book.

ISBN 978-88-95315-30-0

First edition 2014

Printed in Italy (september 2014)

Via Montecalvario 40/3 - 85050 Brienza (Potenza) – ITALY

http://www.lepenseur.it/books-and-training/en/

This book mentions several projects and buildings not necessarily designed using the algorithm editor Grasshopper®, but whose complexity was suitable for illustrating the potentials of the algorithmic modeling.

Sergio Musmeci, Bridge over Basento River (1967 - 1969).

(Digital) Form-finding

Alberto Pugnale
Lecturer in Architectural design at the University of Melbourne

In architecture and structural engineering, 'form-finding' identifies the process of designing optimal structural shapes by using experimental tools and strategies, i.e. physical models[1], to simulate a specific mechanical behavior. The reverse hanging method is the oldest and probably most diffused form-finding technique for arches, vaults and shells – a physical model, made with elastic cables or membranes with no rotational stiffness, is first subject to gravitational forces to obtain a structural state of pure tension; such a form, which is called "funicular", is then inverted to identify the mechanical compression-only situation. This principle was first mentioned in a publication by Robert Hooke in 1675[2]. With a Latin anagram, only solved in 1701, he proposed to reverse the curve which was generated by a hanging chain, under self-weight and supported only at its ends, in order to define the optimal structural form of an arch (figure 1). Such a curve is called "catenary" when the chain presents a constant distribution of weight[3]. Initially confused with a parabola by Galileo Galilei, the catenary was then mathematically described by David Gregory in 1697[4].

1. A detailed description on the use of small-scale physical models for structural design can be found in: Addis B., *'Toys that save millions' – A history of using physical models in structural design*, in "The Structural Engineer", April 2013, pp.12-27.
2. See: Hooke R., "A description of helioscopes and some other instruments made by Robert Hooke, Fellow of the Royal Society", London: T.R. for John Martyn, 1676, p.31.
3. See: Adriaenssens S., Block P., Veenendaal D., Williams C. (Eds.), "Shell Structures for Architecture", Routledge, 2014, pp. 7-8.
4. See: Kurrer K., "The history of the theory of structures: from arch analysis to computational mechanics", Berlin: Ernst &Sohn, 2008, pp. 213-216.

FIGURE 1
A catenary arch and its inverted shape.

Infinite ideal forms of a compression-only arch can be generated by varying two boundary conditions: (1) the applied loading; and (2) the span/rise ratio. Figure 2 shows how these parameters affect the final geometry individually.

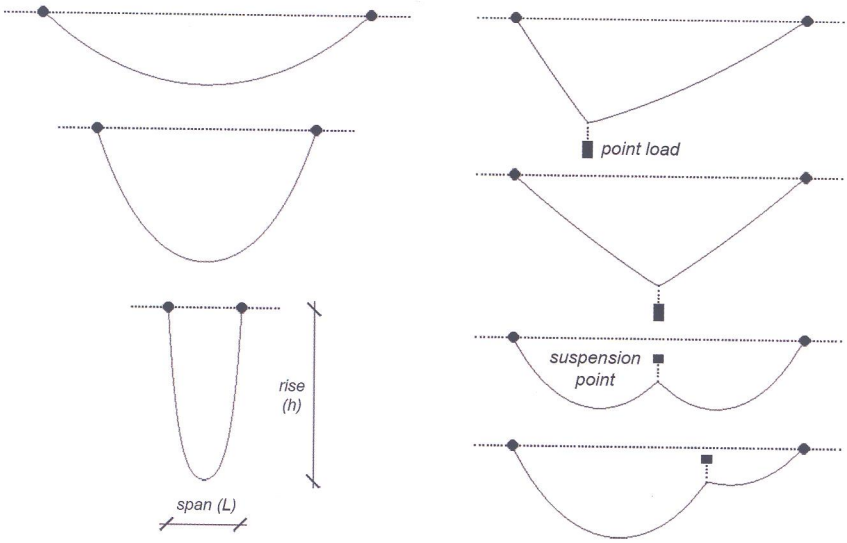

FIGURE 2
Variations of the boundary conditions and respective hanging chains.

The same principle can be extended to the three-dimensions in order to find structural form of Reinforced Concrete or masonry vaults and shells, as well as of steel or timber gridshells. Roughly, three model constructing methods can be distinguished. The first is based on the use of strings, with the function of discretizing either barrel vaults, if placed in parallel, or domes, when disposed in a radial way. Bags of sand are then added to control the distribution of weight. Antoni Gaudí designed several buildings with the aid of this procedure. Rather known is the model he realized for the Church of Colonia Güell, in which two hierarchical orders of strings were used – the first defined the geometry of columns, main arches and supported the second, which established, indeed, the form of walls and vaults. In 1982/83, the Institute for Lightweight Structures in Stuttgart performed a reconstruction of the original Gaudí's model, demonstrating that its preparation is highly time-consuming and precision becomes a key aspect of the simulation in order to get accurate results[5]. The second model making technique takes advantage of non-rigid nets, realized either with chains or elements, in order to find structural form for gridshells[6]. The Multihalle in Mannheim (1973-74) is the biggest and probably most relevant building which was designed with this method. A 1:300 wire-mesh model was initially built by Frei Otto and his research group in Stuttgart to establish the basic geometry – two main halls connected by a tunnel, of which the larger spans about 60 meters. A 1:98.9 scale model was then prepared to refine the shape of the gridshell and determine the precise position of the boundary supports (Figure 3). A rather sophisticated design phase that followed was the survey of the model through photogrammetry – geometrical data were then transferred into constructing drawings and other analytical models for further calculations[7].

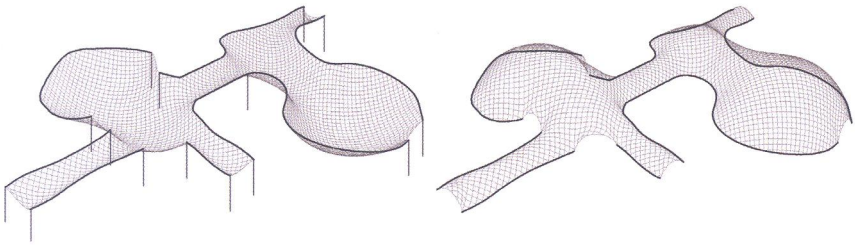

FIGURE 3
Schemes of the second form-finding model of the Multihalle in Mannheim, which represents every third lath of the real structure.

5. See: Tomlow J. (Ed.), "IL 34. The model: Antoni Gaudi's hanging model and its reconstruction – New light on the design of the church of Colonia Güell", Stuttgart: Institute for Lightweight Structures (IL), 1989.
6. See: Hennicke J. et al., "Il 10. Grid Shells", Stuttgart: Institute for Lightweight Structures (IL), 1974.
7. See: Burkhardt B. et al., "IL 13. Multihalle Mannheim", Stuttgart: Institute for Lightweight Structures (IL), 1978, pp. 33-55.

The third method of making hanging models was developed by Heinz Isler in 1955, and it was specific for the form-finding of RC shells which are a continuous type of structures. Such a characteristic was simulated through suspension of wet pieces of fabric or membrane - the derived forms were then frozen and finally inverted[8]. Very different results can be obtained by varying the type of fabric used, i.e. the properties of the model material play an important role in the process.
Amongst the shells Isler designed throughout his career, the ones of the Deitingen service station, built in 1968 on the Bern-Zurich motorway, and the roof of the open-air theatre in Grötzingen, dated 1977 and with a thickness of only 11cm, are the most representative of the structural lightness this form-finding technique can lead to.

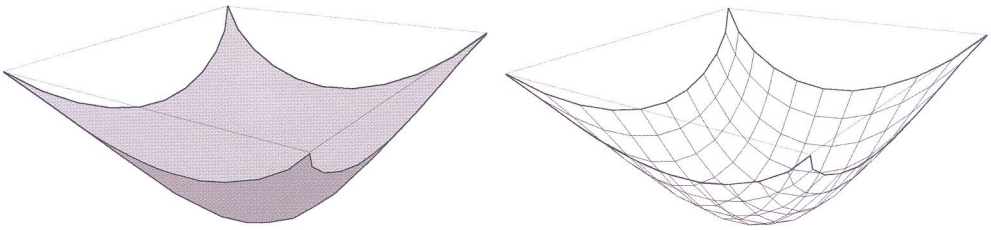

FIGURE 4
Simulation of a hanging membrane model and its corresponding cable net one.

Apart from the reverse hanging method, a few other experimental ways of finding structural form through physical models have been developed. The first is based on stretching cables or elastic membranes across different edge frames – this simulates the pre-stress state typical of cable nets or tensile structures and generates, consequently, their geometry. The shape of small scale tensile structures can also be found dipping closed frames, made for instance of thin wire, into a membrane-forming liquid[9]. This procedure forms soap films, which are mathematically defined as "minimal surfaces"[10]. Frei Otto has been a pioneer in this field. Together with his research group of the Institute for Lightweight Structures in Stuttgart, he defined an extensive set of rules for the generation of soap films. They classified such minimal surfaces according to the number of closed frames they needed to generate them. For instance, saddle shapes can be obtained from a single

8. See: Isler H., *New Shapes for Shells – Twenty Years After*, in "Bulletin of the International Association for Shell Structures", no.71/72, 1980, pp. 9-26. See also: Isler H., *New Shapes for Shells*, in "Bullettin of the IASS, no.8, 1961; and: Isler H., *Concrete Shells Derived from Experimental Shapes*, in "Structural Engineering International, Vol.3, 1994, pp. 142-147.
9. See: Otto F., Rasch B., "Finding Form: Towards an Architecture of the Minimal", Axel Menges, 1996, pp. 58-59.
10. Several examples of minimal surfaces can be found in: Gray A., Abbena E., Salamon S., "Modern Differential Geometry of Curves and Surfaces with Mathematica", 3rd ed., Boca Raton: CRC, 2006 (1993).

closed edge. Two ring frames are necessary to form a catenoid, which is the surface of revolution of the catenary curve, and infinite other different soap films can then be found if further two-dimensional inner edges are added[11].

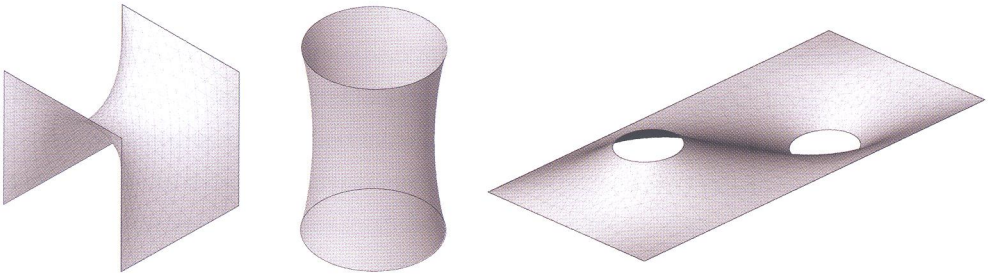

FIGURE 5
Generation of soap films from one (left), two (middle) and several closed frames (right).

Two projects by Frei Otto are worth to be mentioned: the Tanzbrunnen tensile structure in Cologne, dated 1957, and the large roofs built in 1972 for the Olympic Games in Munich. Minimal surfaces have also been used for the form-finding of compression-only structures. A rather interesting example is provided by the RC bridge designed by Sergio Musmeci over the Basento River in Italy (1967-69)[12].

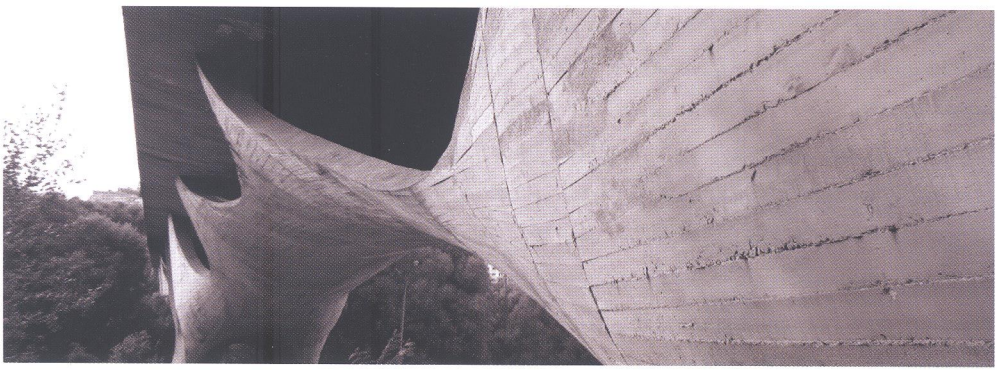

FIGURE 6
Bridge over the Basento River, Potenza (Italy).

11. See: Bach K., "IL 18. Forming bubbles", Stuttgart: Institute for Lightweight Structures (IL), 1988, pp.73-219.
12. No English sources have been published on the work by Musmeci. However, the Italian books are: Nicoletti M., *Sergio Musmeci: Organicità di forme e forze nello spazio*, Torino: Testo & Immagine, 1999, and Guccione M., *Il ponte e la città. Sergio Musmeci a Potenza*, Roma: Gangemi, 2003.

A second alternative to the use of hanging models is called "pneumatic or inflated hill method". The concept is rather intuitive: structural form is obtained through inflation of membranes and can be applied for the design of RC shells, as well as air-supported membrane halls. During the 60ies, Italian architect Dante Bini developed and patented a curious construction technique called "Binishell", which took advantage of this form-finding process in order to erect RC domes in a rapid way - concrete pouring was initially performed over a flat pneumatic preformed formwork, and then inflation allowed rising and roof completion within a couple of weeks[13]. Other alternative form-finding methods are based on flowing forms or on combinations the previous techniques. An extensive description of such experimental strategies can be found in the book: "Finding Form: Towards an Architecture of the Minimal" by Frei Otto and Bodo Rasch[14]. Analytical methods have been developed too. In this case, structural form is defined using analytically well-known geometries, such as cylinders, spheres, ellipsoids, or forms obtained through operations on them. Félix Candela designed several examples of this kind. The Church of Our Lady of the Miraculous Medal, completed in 1955 in Mexico City, and Los Manantiales Restaurant in Xochimilco, dated 1958, are two outstanding buildings resulting from geometrical operations on hyperbolic paraboloids. Through form-finding, design is always directed towards structural optimum. From the conceptual point of view, this cannot result in free-forms, which are 'freely' generated apart from any structural and construction principle. In other words, the representative component of architecture cannot be separated from its conformative core. Digital technologies are radically modifying this aspect. Numerical calculation techniques are replacing entirely experimental structural design and analysis methods - the way now is to use mathematical optimization which, on the basis of one or more chosen criteria, takes advantage of the computation power of the computer to interactively search for optimal solutions to a problem from among a series of possible candidates. This change is relevant, from the architectural design point of view, for at least three reasons. Unlike in classical form-finding, the topology of a structural system no longer needs to be fixed. It can therefore become the object itself of the optimization process, as in the case of the design of the new TAV station in Florence, which was developed by Isozaki and Sasaki on occasion of an international competition in 2003[15].

Compared to the projects by Heinz Isler and Frei Otto, optimization also allows the original form-finding concept, literally aimed at the search of the optimal form, to be changed into what can be

13. Bini D., "Building with air", London: Bibliotheque McLean, 2014.

14. See: Otto F., Rasch B., "Finding Form: Towards an Architecture of the Minimal", Axel Menges, 1996.

15. See: Cui C., Ohmori H., Sasaki M., Computational Morphogenesis of 3D Structures by Extended ESO Method, in "Journal of the International Association for Shell and Spatial Structures, Vol. 44, no. 141, 2003, pp. 51-61. The competition project for the new TAV station in Florence is also described in: Sasaki M., Flux Structure, TOTO, 2005.

defined as "form-improvement"[16] - this new process is instead aimed at improving the performances of an already existing spatial configuration, which does not necessarily mean reaching the structural optimum. For example, as far as the Kagamigahara crematorium is concerned, no physical model used to obtain the inverse of the tension-only hanging membrane would have been able to translate the idea of the architect Toyo Ito into a structure. Instead, through optimization, the floating RC roof, figuratively inspired by a cloud, was first freely modeled as if it were a sculpture and was then structurally honed through a Sensitivity Analysis (SA)[17].

The last fundamental aspect of optimization is that it is not just limited to resolving questions of a static nature, which instead is an intrinsic characteristic of form-finding based on physical models. Techniques like GAs can be used in all those cases in which an architectural performance can be formulated through a mathematical function, such as in the case of acoustics or light, and, technically speaking, it can therefore be "minimized".

From being a simple resolution instrument, optimization is becoming an efficient "form-exploration" tool to support conceptual design. It is forcing the limits of classical form-finding and defining several new research directions that redefine entirely the relationship between architecture and engineering.

Alberto Pugnale is a lecturer in Architectural design at the University of Melbourne, Australia. In 2007, he won the fifth edition of the IASS HANGAI Prize, related to the study of complex architectural/structural bodies. He has been an assistant professor at Aalborg University, Denmark (2010–2012), and an invited lecturer in France and Italy. At present, he is member of the International Association for Shell and Spatial Structures (IASS) and is a licensed architect in Europe. His research interests are in the computational morphogenesis of free-form structures, reciprocal structures and history of construction.

http://albertopugnale.wordpress.com/

16. The term "form-improvement" was coined by the author in March 2007 for a short online article.
17. The Sensitivity Analysis is explained briefly in: Sasaki M., Flux Structures, TOTO, 2005.

AAD_

ALGORITHMS-AIDED DESIGN

PARAMETRIC STRATEGIES USING GRASSHOPPER®

Main topics:

- Grasshopper environment and plug-in software
- Parametric modeling and advanced data management
- NURBS curves and surfaces
- Meshes and Subdivision Surfaces
- Digital fabrication techniques
- Recursions
- Form-finding strategies
- Particle-spring systems
- Topology Optimization
- Evolutionary solvers
- Environment-informed design

Algorithmic design is not simply the use of computer to design architecture and objects. Algorithms allow designers to overcome the limitations of traditional CAD software and 3D modelers, reaching a level of complexity and control which is beyond the human manual ability.

Algorithms-Aided Design presents design methods based on the use of Grasshopper®, a visual algorithm editor tightly integrated with Rhinoceros®, the 3D modeling software by McNeel & Associates allowing users to explore accurate freeform shapes. The book provides computational techniques to develop and control complex geometries, covering parametric modeling, digital fabrication techniques, form-finding strategies, environmental analysis and structural optimization. It also features case studies and contributions by researchers and designers from world's most influential universities and leading architecture firms.

Arturo Tedeschi is an architect and computational designer. Since 2004 he has complemented his professional career with an independent research on parametric design, focusing on relationships between architecture and digital design tools. He is the author of *Parametric Architecture with Grasshopper*, a best-selling book on parametric design, originally published in Italy and translated into English in 2012. He has taught at many universities, companies and institutions and from 2012 he is the co-director of the AA Rome Visiting School for the Architectural Association School (London). His work has been featured on a series of international magazines and exhibited in Rome, Milan, Venice, London and Paris. He has collaborated with leading architecture firms, including Zaha Hadid Architects, before setting up his consulting company A>T.

www.arturotedeschi.com

ISBN 978-88-95315-30-0

9 788895 315300

€ 40,00