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Structural design via form finding: Comparing Frei Otto, Heinz Isler and Sergio Musmeci

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ABSTRACT: Form finding is an effective approach for the conceptual design of structures. In the 1950s and 1960s, various form finding techniques flourished to create geometries that could not be realized with analytical models or graphical methods alone. The development of contemporary form finding owes much to the seminal work of a number of structural designers of the period, notably Frei Otto, Heinz Isler and Sergio Musmeci. The scientific cultures to which they belonged led to differentiated results in their research and design. This paper examines the approaches to the form finding of Otto, Isler and Musmeci, looking in particular at the inspirations, methods and visions of these protagonists in the history of structural design.

German architect Frei Otto (1925–2015), Swiss engineer Heinz Isler (1926–2009) and Italian engineer Sergio Musmeci (1926–1981) are structural designers who made form finding their main operative approach. Their education is rooted in the engineering culture of their time and their methods are informed by their individual backgrounds and scientific cultures. Although they all advanced experimental approaches to the discipline of structural design, they represent different perspectives on the subject of form finding. Therefore, a comparative study on their design approaches, as well as their written contributions, supports and enhances a broader understanding of their role within the history of engineering. This paper aims to compare the viewpoints of Otto, Isler and Musmeci on form finding by looking back at their writings and original documents in relation to their inspirations, methods and visions.

1 INTRODUCTION

Form finding is the design process, both physical and digital, that leads to the definition of the form of a structure in static equilibrium under given loads and boundary conditions. This term emphasizes that the form of the structure is the output of the design process: a "form-active structure" (Veenendaal & Block 2012) that expresses a "figure of equilibrium" (Linkwitz 1999) in compliance with the external and internal forces. It can also be considered as the result of an iterative procedure based on an experimental approach (Bletzinger & Ramm 2014; Ramm 2004) and subject to the law of causality (Carpo 2015). In the "initial equilibrium problem" (Haber & Abel 1982), other parameters besides structure must be considered, such as constructability and architectural aspects (Isler 1968). From this perspective, form finding goes beyond mere structural optimization to achieve minimal material use (Bubner 1972; Musmeci 1971) while obtaining "elegant forms" (Isler 1979a; Musmeci 1979a; Otto 1984a).

The study of specific physical phenomena to determine the form of structures under given loads and boundary conditions has its roots in the use of scale-independent physical models (Addis 2014). Early examples include Hooke's catenary curve (Hooke 1676) with St. Paul's Cathedral by Christopher Wren (1632–1723) as one of its first applications to architecture (Addis 2014). Further developments are due to Friedrich Gösling (1837–1899) and Antoni Gaudì (1852–1926). In particular, the latter is considered the original master of form finding with his investigation on combinations of catenary curves (Graefe 2020; Tomlow 2011). The exploration of structures under tension is rooted in the Euler and Plateau studies on soap-film membranes (Burkhardt 2020), with relevant applications in architecture, such as the pre-stressed cable-net membranes and shells by Otto, Isler and Musmeci.

Both Otto and Isler use the term "to shape" to describe the process of finding a form under given loads and boundary conditions (Isler 1959; Otto 1954). Musmeci also defines such a process as a "new philosophy of design" in which the form of the structure - and not its inner stresses - is the actual unknown (Musmeci 1979b). The projects for the German Pavilion in Montreal (1967) and the Olympic

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Stadium in Munich (1972), with their worldwide resonances, undoubtedly accelerated the interest in form finding among the structural engineering community.

The development of digital form finding procedures is strongly connected to the original physical methods (Tomlow 2016). The use of the first computational tools paves the way for the "Force Density Method" by Schek (Schek 1974) and the studies by Argyris on the extension of the "Finite Element Method" to membrane structures (Argyris et al. 1978). Their experiences form the basis for the further development of contemporary digital approaches to form finding, such as the "Dynamic Relaxation Method" (Barnes 1999), "Particle Spring System" (Kilian & Ochsendorf 2005), "Thrust Network Analysis" (Block 2009; Rippmann 2016) and "Combinatorial Equilibrium Modelling" (Ohlbrock & D'Acunto, 2020).

2 INSPIRATIONS

The form finding approaches of Otto, Isler and Musmeci draw their major inspiration from physical phenomena that belong to the natural world, albeit from different perspectives (Neri 2014). For example, Otto studies "nature" as a biological process and works in close collaboration with German natural scientists. In contrast, Isler's interest in the natural world suggests a more formal reference to its materialized physical principles. Musmeci studies the mathematical laws of mechanics in the context of recent developments in the natural sciences.

2.1 *Reproducing biological processes*

Otto's understanding of "nature" is very broad. Considering all the disciplines that belong to the natural sciences (Otto 1995), his goal is to reactivate the role of research in architecture and find a scientifically based connection between natural and artificial domains. In Otto's view, biology provides a model of study for architecture. His research group "Biologie und Bauen" (Otto 1984b), founded in 1961, makes extensive studies on biological processes, exploring, in particular, the physical and mechanical activities of self-formation and self-organization. Otto's form finding approach stands as a methodology based on direct observation and the replication of natural processes. Every element, both animate and inanimate, develops a form that results from an adaptation process and can be expressed by a combination of compressive, tensile and bending forces (Figure 1).

Otto promotes the reproduction of biological phenomena in terms of forms and methods: from his perspective, the form is not the result of the designer's intention (Otto 1971). His interest in natural processes is multifaceted and multiscale: with the same research attitude, he studies diatoms (Otto 1985), radiolaria (Otto 1990a), bubbles (Otto 1988), bones (Otto 1984c), spider webs (Otto 1992a) and territorial networks (Otto 2008). From this perspective, even the city

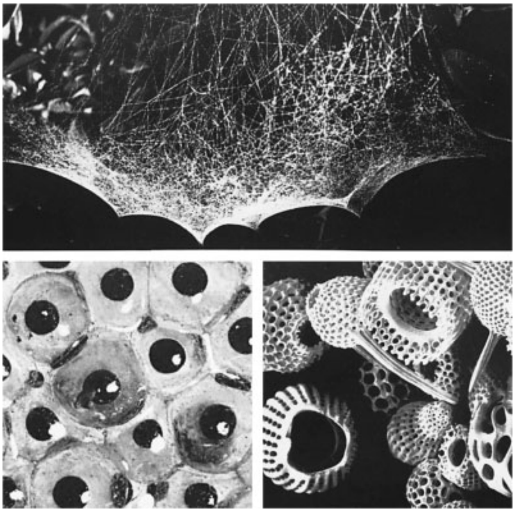

Figure 1. Studies on biological processes (Otto 1982: 15,19,20).

can be studied as an organism (Otto 1984d): as in biological processes, it adapts according to its boundary conditions (Otto 1975a, 1992b).

Otto's best-known experiments are those on soap films (Burkhardt 2020; Otto 1969, 1973). They follow the physical laws of minimal surface between given boundaries, characterized by constant stresses, and thus optimal distribution of material (Burkhardt 2020; Otto 1988). Exploring natural phenomena through physical experiments for the design of spatial cable-nets enables him to devise forms not yet realized in the artificial world and that go beyond the traditional structural typologies.

2.2 *Observing nature*

According to Isler, the natural world is a source of inspiration for the designer's own imagination (Isler 1992). Originally intending to become a painter (Chilton 2000), his early watercolors are probably his very first formal studies of the natural world. The elements belonging to it - insects, plants, fruits, soil - reveal principles and forms resulting from physical necessities. Their formal clarity provides a reference image (Isler 1983) for the definition of effective structural forms. Since optimal shapes follow natural processes, they are necessarily beautiful according to Isler (Isler 1980) (Figure 2).

Isler's design goal is to recreate "natural" shell shapes through a process of physical form finding. Although the designer is responsible for the experiment's set-up (boundary conditions and selection of materials), the process evolves naturally. Isler's experiments are thus similar to those of Otto but differ in their objectives. If Otto is concerned with studying the process evolution, Isler achieves a particular form thanks to his static intuition. The pneumatic membrane refers to the physical concept of a surface under pressure, whereas the form achieved through the hanging

Figure 2. Isler's photograph of a natural shell, 1963 (gta Archives, ETH Zürich).

membrane is based on the extension of the catenary curve into space.

In his work, biological objects also represent powerful images to promote his design approach. Due to the formal similarity of his shell structures with the natural shells, the communication of his form finding method is possible on different levels and easily reaches the broader public.

2.3 *Exploring natural laws*

Unlike Otto and Isler, Musmeci looks at physical phenomena through an analytical mindset aiming to grasp the universal laws behind them. Like Otto, Musmeci is fascinated by the ever-changing physical and mechanical processes and their dynamic interactions. From his perspective, "nature" represents a collection of diverse entities that are interrelated (Musmeci 1979a). He is not interested in studying individual events: their structural organization is of greater importance. As the temporal synthesis of an unfinished process, form represents the organization of objects in space (Musmeci 1979a). Thanks to a vivid curiosity towards any mathematical theory, he investigates this concept of form and space in various fields, such as astronomy, but most importantly, architecture and structural design (Musmeci 1971). His search for new forms explores the potential correlation between scientific theories and their physical translations into design concepts (Figure 3).

For Musmeci, each element's original nature reveals the geometric and structural principles that contribute to its form. In his structural design conception, the optimal design solution expresses the force flow within the structure through its form. In this way, the form shows the variation of the inner stresses in accordance with its material properties (Musmeci 1960). As "natural" (Musmeci 1979b), the found form is the optimal shape because it manifests explicitly the concept of static equilibrium in the way it materializes.

3 METHODS

The different approaches to form finding by Otto, Isler and Musmeci reflect their diverse backgrounds.

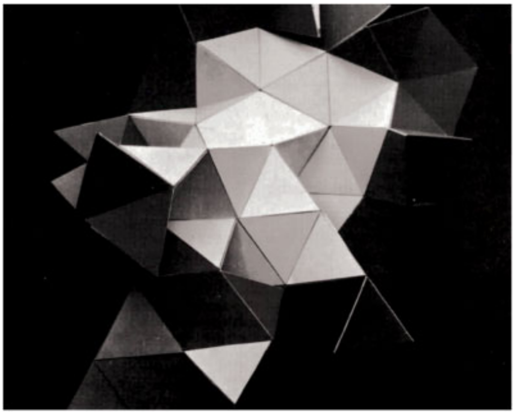

Figure 3. Sergio Musmeci, Studies on Polyhedra (Musmeci 1979c: 15).

Interestingly, both Otto and Musmeci had experience in aeronautics, although the former graduated in architecture and the latter in engineering. Among the three, Isler is the only structural designer who has a solely civil engineering education. Although with different objectives, they all establish relations with public and private institutions. Otto's projects represent not only the test field for his theoretical research but more importantly, the best occasions to promote new German technologies at globally important events. Isler's collaboration with a variety of Swiss private industries creates a constellation of fruitful alliances that fosters the development of Switzerland as a modern country. Musmeci explores new design and construction methods, also thanks to his collaboration with the construction company Italcementi (Musmeci 1980). In different ways, their works push the established building industry to envision new structures for new materials.

3.1 *A scientific approach to form finding*

Otto's research group at the Institute for Lightweight Structures in Stuttgart challenges the conventional approach to architectural design. The relation between biology and building becomes the key research objective and reproducing scientifically self-forming processes provides the operative approach (Otto 1971). Design creativity emerges from a synthetizing action (Otto 1990b). Otto's Institute promotes several research projects on long-span and adaptable buildings, all of which related to lightweight construction (Otto 1984a): "with the knowledge of the "principle of lightweight", one can begin to consider the objects of living nature from a technical point of view" (Otto 1982: 8).

Unlike Isler and Musmeci, Otto's design approach results from strong collective research that brings together several disciplines at the University of Stuttgart, including biology, botany, paleontology, zoology, biophysics, photography. For example, within the research collaboration at Otto's Institute, the nature photographer Andreas Feininger (1906–1999) develops innovative photographic techniques to further study natural objects (Burkhardt 1969). At the same time, the design experiences on cable-net structures help the biologist Ernst Kullmann (1931–1996) develop his research on spider webs (Otto 1984b).

Like Isler, Otto considers the physical experiment as the primary source of knowledge. It is the "methodical basis" (Otto 1990b) in every research project. It helps a process of abstraction, from the contingent event to its reproduction under specific conditions. That is, the physical model is the "medium to materialize the idea" (Weber 2020), which helps to test the theoretical assumptions developed by the research team. Among the three protagonists of structural form finding, Otto is probably the one who explores the most, with every material type and principle: sand cones (Schanz 1995), tensile nets (Otto 1954, 1975b), pneumatic membranes (Otto 1975a, 1975c, 1977, 1984c) and soap-film models (Otto 1969).

While Isler follows the same methodology to produce his physical models that is then implemented in all his projects, Otto continues exploring new possibilities throughout his career. His experiments require the development of high-tech instruments at various stages of design. For example, his "soap-film machine" (Figure 4) keeps the soap-film model in a climatic chamber with high humidity, which extends its lifespan and allows studying its geometry using parallel light and a camera (Fabricius 2013).

In the case of physical models with solid plaster casts, a 3D measuring machine surveys the form using an electrical measuring system especially developed at Otto's Institute. In both cases, photogrammetry and geodesy are used to extract geometric information that forms the basis for further project development. In this process of analysis and synthesis, the Institute of Applications of Geodesy to Engineering directed by Klaus Linkwitz (1927–2017) plays a significant role, as in the case of the project development for the curved roof geometry of the Olympic Stadium in Munich (Tomlow 2016; Weber 2020).

3.2 *Form finding through craftmanship*

In contrast to Otto and Musmeci, who experimented with several structural systems, Isler devotes his work to studying a specific typology: the reinforced concrete shell. His "new shapes for shells" (Isler 1959) are free-form shapes that use physical models - in particular hanging and pneumatic models - as the main design tool. Indeed, Isler's approach to shell design is highly experimental, from exploring multiple design variations in the conceptual design phase to measurement models before shell construction (Isler 1993). His prolific activity confirms his unique perspective on structural design as an engineer (Isler 1979b). Isler is influenced by his engineering education under the Chair of Prof. Pierre Lardy (1903–1958) at ETH Zürich (Billington 2003; Chilton 2000). Moreover, his experimental methodology is embedded within the Swiss engineering culture, considering that the Swiss codes accept the use of physical models instead of analytical calculations (Lardy 1955) to prove the structural soundness of buildings.

During his "research activity after office hours" (Isler 1979c), Isler works alone in his garden to observe natural processes in their original setting (Isler 1979d, 1992). This formal inspiration is then translated into his form finding models developed in his office. Model makers Anton Friedli and Hans Glanzmann support him in the construction of his gypsum models. However, the final design decision is left to Isler, who enters into a private dialogue with his objects, following a procedure that has been defined "Fingerstatik" (Glanzmann 2019).

In his form finding explorations, Isler acts as a craftsman and follows a rigorous methodology. The initial structural forms are generated by implementing basic principles: air pressure is used to produce pneumatic membrane forms and gravitational forces to define hanging membrane forms. At the same time, the materials employed in these models are simple: rubber membranes cut according to the initial starting shapes and anchored to timber frames (Boller & Chilton 2020). To further study the form, Isler makes use of solid plaster casts. (Figure 5)

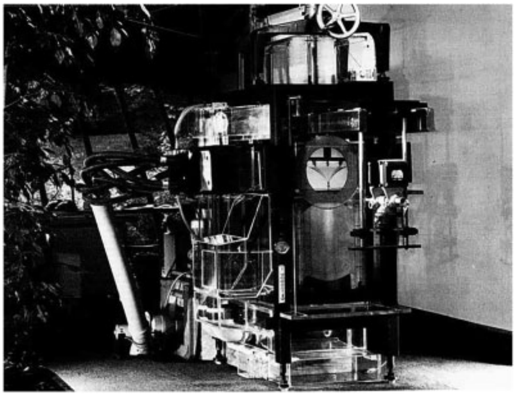

Figure 4. Soap-film machine at the IL (Schanz 1995: 58).

Figure 5. Heinz Isler, Studies on the form finding model of the Sicli project, 1968 (gta Archives, ETH Zürich).

Since this approach is simple, economical and fast, it enables Isler to test several design variations in the form of gypsum models until the shape is found that best fulfils the given structural and architectural constraints (Isler 1959). The structural behavior of this form is then studied in more detail. At first, the chosen gypsum model is measured with a measuring machine to extract its shape in x, y and z coordinates. Afterwards, a wooden mold translates the geometric data into a fiber-reinforced polyester model. A set of hanging timber masses is used to test the structural behavior under different load types through electrical strain-gauges. Whereas the form finding models are the output of Isler's craftmanship and experience, the form-validating models belong to a more established practice within the engineering discipline (Hossdorf 1971; Müller 1971). The translation from the small-scale physical model to the full-scale building is possible if similarity, precision, the quality of the materials used and cleanness of execution are respected (Isler 1979b, 1993, 1994).

3.3 *A mathematical perspective on form finding*

Musmeci's education as a structural engineer is deeply rooted in the Italian scientific culture of his time. His unconventional approach to form finding stems from the analytical approach to structures typical of the Italian school of engineering in which the mathematical perspective on structures is dominant. Musmeci belongs to the "second generation of Italian engineers" (Iori and Poretti 2018). In this context, he envisions a novel approach towards structural design regarding the search for new structural forms as one of its pillars (Musmeci 1971). While the traditional theory of structures considers geometry as a given input, with the assessment and verification of the inner stresses as the ultimate goal of the analytical procedure, Musmeci highlights that in the process of structural design, the form should instead be regarded as the real unknown (Musmeci 1979b). This intuition represents a paradigmatic shift that opens new perspectives in structural design. Thus, the analytical methods become design tools to control the form of the structure and the use of the material (D'Acunto & Ingold 2016). In line with the work of Maxwell (Maxwell 1870) and Michell (Michell 1904), Musmeci defines the notion of "static action" (Musmeci 1967), which is the signed product of the force acting in a structural member (positive for tension and negative for compression) and the length of that member. The algebraic sum of the "static actions" extended to an entire structure in static equilibrium – "total static action" – is an intrinsic characteristic of the system of external forces applied to the structure, and it is independent of the specific structural configuration (Musmeci 1967). This new perspective on structures leads to Musmeci's explorations of different structural typologies, based on accurate consistency between the shape and its corresponding force flow: from continuous surfaces towards spatial lattice structures (Musmeci 1979c). The search for those forms that minimize the amount of material required to resist a given load represents Musmeci's main design objective: it is about the essentiality that achieves the maximum synthesis (Musmeci 1968a).

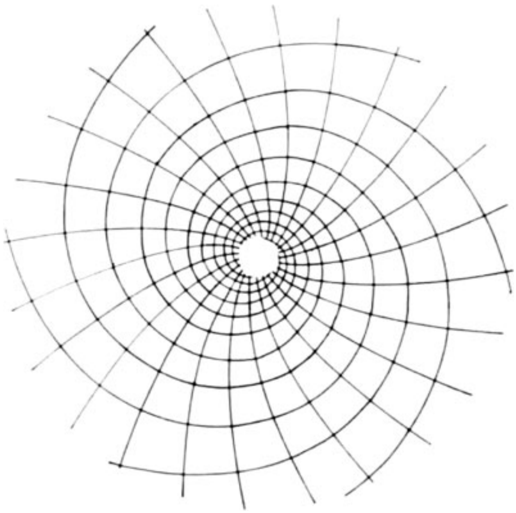

Figure 6. Equiangular spirals that satisfy the equation of the "structural minimum" (Musmeci 1968a: 411).

Unlike Otto and Isler, who use physical models as the primary design tools, Musmeci's physical models are rather instruments to visualize the mathematical theory underlying the design (Ingold 2020) (Figure 6). Musmeci often produces physical models at different scales for the advanced design phase and uses various materials to approximate the form and structural behavior gradually. These include, for example, the 1:100 methacrylate model and the 1:10 micro concrete model for the Basento Bridge (Musmeci 1977), the latter constructed at the national testing center (ISMES) founded by Arturo Danusso (1880–1968).

Musmeci believes in the concept of "static thinking" (Musmeci 1960) as the main starting point for any design exploration. If in the past intuition and experience are the main design factors that do not help envision new structural possibilities (Musmeci 1979b), his research supports a creative approach to structural design that minimizes the use of material. The form results from a precise static choice and should highlight its structural features by explicitly showing the variation of the internal stresses within the material (Musmeci 1979a).

4 VISIONS

Otto, Isler and Musmeci are the representatives of a generation shift between the physical and digital methods of form finding. Their visions of the future of the discipline are crucial at the turning point towards the new century. Otto and Musmeci saw the recently introduced computers as essential tools opening up new design possibilities. On the contrary, Isler found the new computational tools a potential threat to a proper understanding of his form finding methodology based exclusively on the use of physical models and supported by practical experience.

4.1 *Between analog and digital models*

Thanks to its strong network of collaborations, Otto's research group was able to take advantage of emergent electronic tools to support its activities. Since the methodology behind a complex research project requires many iterations, Otto considered the combination of physical and computational methods as an excellent opportunity to reduce the effort required in the design process. Unlike Isler, he managed to find a balance between analog and digital models. In the early phases, he worked mainly with physical models. In fact, Otto argued that mathematical models require a lot of time and energy in the form finding process (Otto 1990b). On the contrary, physical experiments like those with soap-film models are quicker to produce and therefore enable multiple design possibilities to be easily explored. The roof design for the Olympic Stadium in Munich was the first project where the form of the physical model was compared with that generated with early digital tools (Linkwitz 1999). It is no coincidence that Otto's collaborator on this project, Ewald Bubner (1932-), wrote one of the first dissertations on early digital form finding methods (Bubner 1972). Linkwitz, together with Hans-Jörg Schek (1940-), developed a computational approach to control the geometry of the complex cable-net structure (Linkwitz & Schek 1972) and to compare it with the photogrammetric measuring method on Otto's physical model. Similarly, even the calculation phase was the result of a collaboration between the analytical approach of Fritz Leonhardt (1909–1999) and the early digital methods based on the "Finite Element Method" developed by John Argyris (1913–2004) (Argyris et al. 1978).

4.2 *Creativity and the use of digital tools*

Isler's long experience with physical models made him question the potential use of new tools in the design phase (Isler 1998). This aspect became evident in one of his last commissioned works: Stuttgart 21 (1997-). In collaboration with Otto and the British engineering office Buro Happold, he was involved in the form-refining phase (Boller & Schwartz 2020). To recreate the chalice-shaped column proposed by the team winning the architectural competition, Isler made one of his most complex form finding models based on the hanging membrane principle (Isler 1997a). His physical results – two gypsum models - were then compared with the outcomes of the digital form finding method developed by Buro Happold. From Isler's point of view, the outcome of the digital approach was not accurate enough because the definition of the algorithm required too many simplifications. The physical approach refers to the "genuine hanging process" (Isler 1997b) and, therefore, was more reliable than the digitally found shape. He believed that the form finding process needs experience and intuition to achieve a trustworthy result: the apparent simplicity of the process can lead to arbitrary outcomes (Isler 1986), especially when implemented within digital tools.

Isler believed that inventive work needs human minds, and cannot be replaced by automatic processes (Isler 1997c). Contrary to Musmeci, he considered computers were unable to provide creative results (Isler 1992, 1997d) as physical models did.

4.3 *The computer and its new design possibilities*

According to Musmeci, electronic tools within the disciplines of architecture and engineering represented an important step towards a more integrated design approach. He appreciated the scope for accelerating structural calculations in the structural analysis phase (Musmeci 1972). At the same time, like Otto, he anticipated the development of a computationally-driven methodology for rational data analysis that combined knowledge from several disciplines (Musmeci 1979a).

From his viewpoint, "structural design" was to deal with the problem of form optimization to achieve the solution that best approximated the "structural minimum" (Musmeci 1968b). In this respect, computers could be extremely powerful tools. Unlike Otto and Isler, Musmeci foresaw the cooperation between humans and machines to enhance creativity in structural design: "I think that one day, perhaps not very far away, this will be the way a creative structural engineer designs" (Musmeci 1972: 159–160). Indeed, digital methods would then help in both quantitative and qualitative aspects of the design process (Musmeci 1972). If electronic tools could be implemented in the conceptual design phase, this might lead to new shapes. The designer's task was to choose from among all the eventual solutions, that which best met the architectural and structural requirements, taking full advantage of the possibilities offered by new materials (Musmeci 1980). Thanks to digital tools, he foresaw the possibility of controlling a greater number of parameters to study the most complete and diversified structural possibilities. Unfortunately, his premature death in 1981 did not allow him to fully exploit this new digital world and experience the outcomes of his intuitions.

5 CONCLUSION

Frei Otto, Heinz Isler and Sergio Musmeci opened up new ways to form finding. Their broad curiosity in multiple fields and their innovative approaches contributed to changing the perspective on the discipline of structural engineering. The wide-ranging fascination with natural phenomena formed the starting point for the development of their design methods. Otto's biological processes, Isler's natural references and Musmeci's studies of the mathematical laws behind them were reflected in their practical production. For example, Otto became head of a research group at the University of Stuttgart, where experimental activities led to the creation of real projects. Isler established his engineering office to promote his innovative shell design that encapsulated to nature. As an intermediate figure between Otto and Isler, Musmeci balanced his professional collaborations as an engineer with his theoretical studies on structural design. The methods they developed are the basis for today's digital form finding tools. Indeed, the principles behind them translate their approaches in the digital world. The computer enhances the possibility to explore multiple design possibilities following specific protocols without losing the combination of creativity and scientific thinking that are the two main characteristics of Isler, Otto and Musmeci's practices. For this reason, their works rank among the most relevant references for today's structural designers. Even though the design tools have changed, as Isler stated, "What is the best form, or even the correct form? This will remain the crucial question" (Isler 1997e).

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