MODEL-BASED FORMFINDING PROCESSES: FREE FORMS IN STRUCTURAL AND ARCHITECTURAL DESIGN

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***Abstract**.- The problem of form generation and of the transmission of production instructions is discussed, introducing the concept of "form process". Examples for the use of physical models in form-finding with structural motivation and for architectural motivations are presented.*
In structural design, physical models have been used to determine the figure of equilibrium for structures resistant by form, such as tents, tensile structures or shell structures. For structural design as well as for architectural design not concerning structure, some examples for the application of artistic working methods are discussed, and it is shown how it has become possible to realize the outcome of the form-finding process in industrial production.

One can find "free forms" in buildings for structural or for designing reasons. In the latter case, the designer of a building decided to give a particular form to the building, motivated by his conception of the project and perhaps his sculptural ambitions. Structures that are resistant by form, on the other hand, often present complex forms, forms that in many cases cannot be defined by elementary geometrical concepts, due to the interrelation between form and forces which is essential for these structures.

For realizing free forms in buildings, two fundamental tasks must be pursued: first comes the generation of the form to be built, and second comes the realization of the building in the desired form.

The incidence of the second task becomes very evident in the example of Günther Domenig's bank 'Zentralsparkasse Favoritenstrasse' in Vienna: To have his sculptural architecture realized, the architect was personally present on the site, telling the workers how to realize his ideas, and even working with them: the famous hand in the main hall ("the architect's hand") was modeled actually by the architect's hands. To overcome the problem of information transfer between form generation and building, Domenig blurred the division between planning and execution, between architect and craftsmen, unifying the whole building process under his personal control.

A more efficient solution in building realization is to find and to apply information procedures that can provide a sufficiently precise description of the form for its realization. To accomplish this, we have to adopt a description language for forms. Such a description language is Euclidean geometry, which is used by builders since the antiquity: it allows to describe forms precisely and unequivocally using a few parameters only. Any form that can be described by this language can thus be codified and reproduced with absolute fidelity.
However, this is true only for those forms that can actually be described by a given descriptive language. Principally, in any description language, only a limited gamut of forms can be codified. Many forms to be found "in the wild", most of the natural forms, for instance, cannot be described with the vocabulary of elementary Euclidean geometry. And even where more powerful, mathematical descriptive languages are applied, capable to describe a much larger gamut of forms (for instance, differential geometry), the principal problem remains.
The descriptive language necessary for the transmission of production information limits the architect's possibilities; however, a profound knowledge of its specialized "vocabulary", extraordinary in the case of Guarino Guarini, extends his capability of realizing complex forms in buildings.

The simple example, to build a masonry arch may illustrate this “information transfer problem”. For the realization of a semicircular arch, the working directions may be rather simple: the form of this arch can be described, with the vocabulary of Euclidean geometry, namely by the position of the center and the radius of the semicircular intrados. By means of a nail and a rope, the mason can easily reproduce this form on the construction site. The geometric descriptive language used helps to transmit the necessary information with a small amount of data.

The situation is quite different when we decide to build the arch in the form of a catenary - i.e., the figure of equilibrium of an arch under its own weight. Now, the form of the catenary cannot be generated by elementary geometrical procedures; it is defined by a system of two mathematical, implicit equations, which can be solved iteratively. If we want to give exact working instructions, we can transmit to the construction site a number of points given by their coordinates, as a result of some computation, together with directives on how the line between the points should be interpolated. The more information we transmit, the better will be the result of this approximation - in any case, the instructions that we have to transmit will be much more complex than in the case of the semicircular arch. We can also try to adopt a descriptive language that is more apt to describe this form, than Euclidean geometry - for instance, a spline curve.

Another possibility would be to generate the form directly on the building site by hanging up a rope and trying to turn the curve upside-down - by doing this, we would return to the personal union of planner and executioner.

Form resulting from squeezing clay by hand, realized in gypsum at increased scale (Student's work at the University of Stuttgart, IDG2, Prof. Traub, Siegfried Albrecht)

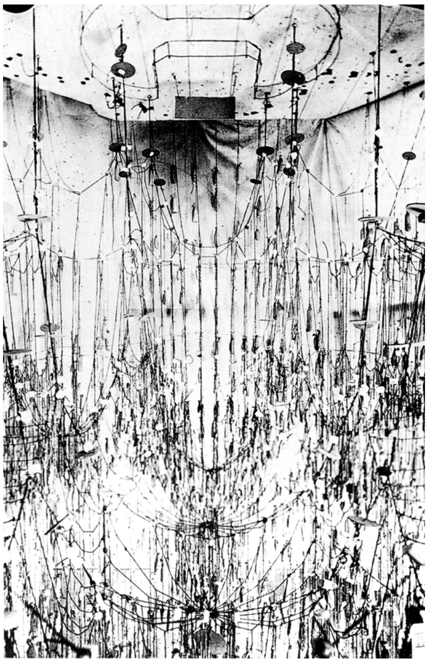
Many of the forms present in natural objects, as mentioned above, remain beyond the current possibilities of geometrical description: nevertheless, we are literally surrounded by these “natural forms”. In some cases, these forms are highly complex, in other cases they appear “simple”, but not deriving from simple geometric objects. Often they can be described much more easily and successfully by the “process” of their formation.

Such formation processes can be, for instance, processes of growth, swelling, or erosion, fraction, splitting apart, deformations by external actions, equilibration of external and internal action (also temporary), etc.. Several processes can interact on the same object: for instance, the form of a fossil found in a river is generated by a growth process, then by deformation due to high pressure, and finally by erosion due to the flowing water. In some cases, such processes are performed by human beings, as artificial processes, in the interaction with material, like in the work of a sculptor: gestic traces, impact of hands and tools, deformation of geometrically generated objects.

Describing forms in dependence on their generation processes can be extremely helpful for form generation: in fact, in many cases forms can easily be generated by the use of such processes. Therefore, forms that remain beyond geometrical description, in many cases can be generated on a physical model, or at least, can be developed to a high degree of approximation.

Such physical models, besides of their capability to generate a far richer gamut of forms contrary to geometrical procedures, also allow the intuitive control of the project on behalf of the designer. But, for the realization in a building, the information transfer problem mentioned above still needs to be overcome.

Structures resistant by form



Gaudí's hanging model for the Colonia Güell church [Tomlow 1989, 65]

Antoni Gaudí probably has been the first who has adopted a self-generating process performed on a physical model to determine the form of the complete structure for a whole building. In his project for the church of the Colonia Güell, near to Barcelona, he used a three-dimensional funicular model, about 6 m long and 4 m high (corresponding to a scale of about 1:10), made of threads; the loading was simulated by small weight sacks containing lead shots [TOMLOW 1989, p. 43]. This model served to create an equilibrium figure that determines a structure resistant by form, to be realized as a complex masonry structure with columns, ribs and arches, all rigorously loaded by axial pressure loading under deadload.

The hanging model simulates the flow of forces in the linear elements such as columns and ribs, presenting only tension in the strings. Thus, by turning upside-down the configuration of the model, a structure is obtained that, under its own weight, is subject only to axial compression load in every element, without bending moments.

Gaudí transposes the principle of the catenary, well-known in its application to the form-finding of masonry arches or symmetric domes, to a complex spatial structure: The entire building, consisting of the crypt, the main stairway serving as pronaos to the crypt, the nave with its gallery, the branched main columns carrying domical vaults crowned by towers, is described by the stable figure generated in the funicular model.

During the long working process on the model, Gaudí captured its outside and inside views in photographs, sometimes simulating the surfaces of walls and vaults with pieces of cloth hung between the threads. He then painted over the photographic plates, developing the sections and prospects of the building directly from the survey of the model.

The building has remained unfinished - only the crypt and the entrance terrace have been built. The model was destroyed during the Spanish Civil War, only a set of photographs survives; in 1982, a reconstruction in slightly reduced dimensions was carried out at the Institute of Lightweight Structures (IL) at the University of Stuttgart by Jos Tomlow et al. [TOMLOW 1989].

On one hand, this procedure is apt to bring statical knowledge to highly convincing architectonic solutions – besides that, it is a highly experimental working method, extremely refined, compared with traditional architectural planning manners. In this case, in fact, the architect will not determine directly the shape of the building: giving up his role of forming directly the shape of the building, "giving form" in a voluntaristic manner, the architect is submitting himself to the "behavior" of the model, acting only on the boundary conditions. That means that any intervention to the form of the building has to follow the rules of the funicular model, for instance, by changing the length of threads, or adding or removing some weight in the small lead-shot filled sacks. The procedure is rather complicated, because every local intervention has an effect on extended portions or even on the entire structure.

Crypt of the Colonia Güell church, near Barcelona

It is due to his refined working method, characterized as open process of self-generation, that Gaudí, although departing from a fully traditional and current typological scheme, arrives at a result that is new, innovative, highly complex and convincing by the coherence of its spatial development.
On the other hand, this process guarantees the achievement of a stable form for the structure, as long as the manipulations on the model, e.g. the changing of the weights, is correctly translated to the real building.

In one way, Gaudí has been "punished" for abandoning the simple Euclidean geometrical concepts, deducting the configuration of the principal construction elements from the funicular model: Working on the building was possible only while the architect was personally present on site. Whenever he was not able to be present, the workers interrupted the construction works. This is the consequence of not having any descriptive language available for codifying the working instructions for the execution in a sufficient manner.

Heinz Isler, who has built hundreds of concrete shell structures since the 50's, is systematically using physical models for form-finding - the shapes of his shells are developed upon stable forms generated by mechanical, physical models, namely funicular forms (hanging cloth hardened with polyester or frozen water), pneumatic forms and floating forms [RAMM et al. 1989; ISLER 1959, etc.]. Unlike many sometimes prominent shells with shapes derived from simple Euclidean geometric objects, his free-form shells have excellent structural behavior. In many cases, like the gasoline station in Deitingen (1968), his shells have free edges, without any support by edge-beams or structural elements in the facade - this is due to the optimized shape of these shells.

Concrete shell roof of the gasoline station at Deitingen, Switzerland (Heinz Isler)

This "structural clarity" is only one aspect of the high aesthetic quality of Isler's shells. However, the design process that leads to this structural and formal quality is essentially different from the "traditional" architectural designing methods: self-sustaining forms like membrane or funicular shapes, in fact, cannot be found by classical, elementary geometric procedures, due to the intrinsic relationship between forces and form typical for structures resistant by form [LINKWITZ]. Like in Gaudí's project for the Colonia Güell church, every intervention on the building form can be taken on only by modifying the boundary conditions of the construction and the concert of forces, leaving the immediate determination of the shape to the physical process.

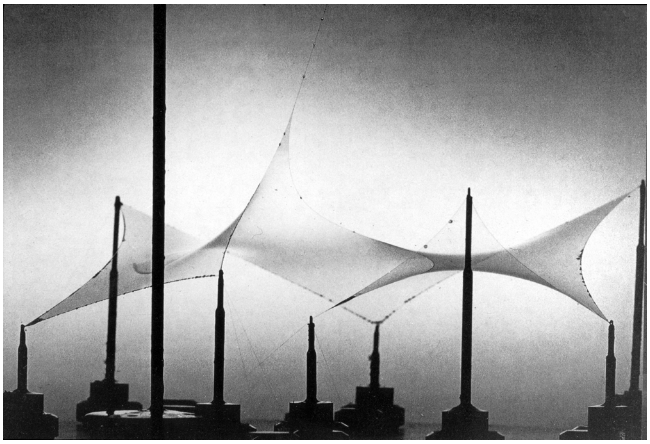
This shows how the design of shell structures, even if aiming only to meet aesthetic criteria like the "clarity" mentioned above, calls for different planning methods in contrast to those that architects normally are used to - a different way of thinking, perhaps less voluntaristic: abandoning the role of "creator" and "descending" to the role of a participant playing within the rules of an experimental process.

A similar, radical non-voluntaristic approach to building design, has been propagated by Frei Otto. Otto derives his structures from simulation models, and he has systematically developed strategies based on self-generating processes performed on physical models. This is true for his prominent projects, like the numerous tents, the wide-spanned tensile structures, e.g. the roofs of the German

Munich, cable net roof of the olympic installations

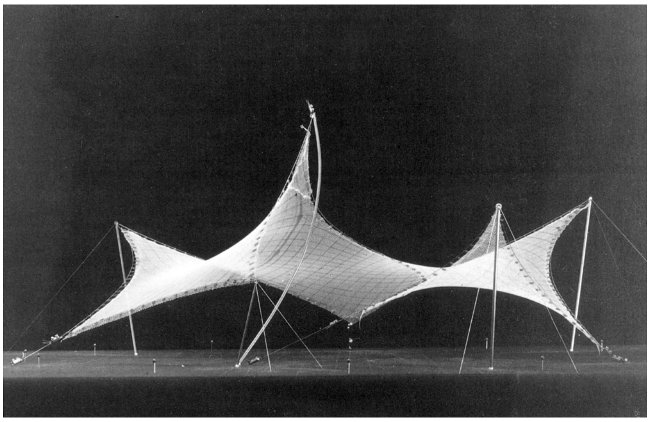
Pavilion in Montreal (1967), of the Olympic Park in Munich (1972) and the Conference Center in Mecca (1974), his light grid-shell structures like the Multihalle in Mannheim (1975), his branched structures and his project for pneumatic structures. These self-shaping processes determine the design of structures, they are assumed to be useful for elaborating a typology of structural design, and they are also performed in the attempt to explain the structures to be found in nature, subject of extended studies taken on by Frei Otto himself and others in his surrounding for many years.

Frei Otto claims that his structures are “natural structures”; this term, however, is never interpreted in the sense of formal analogy to nature - the physical self-generating process itself is considered essentially to be “natural”, as these optimization processes can be stated as being determinant for the shape of animals and plants, their constructions (e.g. spider webs, shells, even the structure of animal settlements), such as the forms of non-living nature like hills, etc. - attempting to trace back all form in nature to fibers, membranes and pneumatic structures [OTTO 1982; 1988; 1995]. In these terms, there is obviously no room for the idea of “giving shape” on behalf of a subjective will or the expression of individual creativity; the shape of the building is not subject to the will of the architect, but is justified by the self-shaping process. Consequently, when the design of the building becomes subject of polemics, the architect would rather defend the process, than the building itself. The building can thus be conceived as "state" or "condition" (*Zustand*), in terms of an open structure in time and space, rather than a closed, determined object.



Form-finding for a small tent, by generating minimal surfaces with a soap film (IL-Archiv [GAß 1990, 7.7])

The first approximation for the design of tents and wire-net tensile structures, like the roofs in Montreal, consisted in generating minimal surfaces with soap-films. Minimal surfaces are in fact the "natural" shapes of membrane structures: a pre-stressed membrane with uniform stress will always assume the form of a minimal surface. A soap-film, within a given boundary, will always form some so-called "minimal surface"; this surface will be the surface with the smallest area possible locally - the load-bearing property is obvious: any deformation by external forces augments the area of the membrane, thus provoking tensile stress



Form-finding model in larger scale, made of tulle (IL-Archiv [GAß 1990, 7.9]) reactions. The anticlastic double curvature, mathematically speaking, vanishing mean curvature, typical for minimal surfaces, assures the stability of the structure, its resistance to "disturbing" loads: in one direction, the curvature of the surface is concave, in the other direction, orthogonal to the first, the curvature is convex, the radii of the two curvatures having the same value - this corresponds to the "hanging" and the "standing" chain in other pre-stressed cable structures.

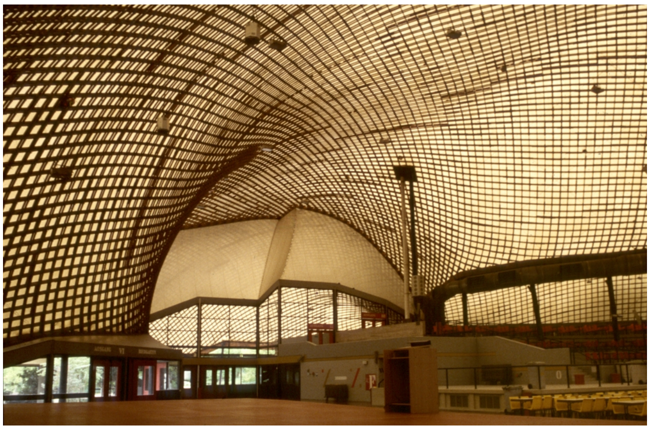
These minimal surfaces can be generated by solving the minimal surface equations numerically [NITSCHE 1975], e.g. by the force-density method developed by Klaus Linkwitz [LINKWITZ 1994; 1996]; they can also be generated in physical models - this is due to the intrinsic interrelation between force and form they present.

In consequence of the observation that the form of a pre-stressed membrane construction corresponds exactly to the minimal surface generated with soap-films, a special device for generating and measuring soap films was constructed at the Institute of Lightweight Structures, at the University of Stuttgart [BACH ET AL. 1988, p. 326]. The result of the measurements on the soap-films can then be used to build simulating models in larger scale, in tulle, with the possibility to perform fine adjustments to the disposition of the membrane, and then wire-models in even larger scale, where tests on the load-bearing behavior can lead to further improvements of the structure.

A fine example of the method developed by Frei Otto and his teams for the design of tensile structures is a students' group project for a small tent, performed at the Institute of Lightweight Structures, as presented in [GAß, pp. 7.6 sqq.]. First, the general layout of the tent is developed in a model of tulle with hexagonal mesh; the formal appearance and functional parameters, like the height of passage areas, are determined. Next, the boundary conditions of the project are transferred to a soap-film model. The first minimal surfaces generated on these boundary conditions are not satisfactory: the position and the heights of the masts and the anchoring points are modified until the minimal surface corresponds to the intentions visualized in the first model. Based on the boundary conditions developed in the soap-film machine, a model in scale 1:20 is built in tulle with square mesh: the membrane is fixed to the boundary cables by springs, all anchoring points can be modified. Thus, the uniform distribution of the tensions in the membrane and the smoothness of the minimal surface can be improved by tightening or loosening the anchorings etc., i.e. by modifying slightly the boundary conditions. In conclusion, even for the determination of the cutting patterns a model-based method is performed.

The case of the "Multihalle Mannheim"

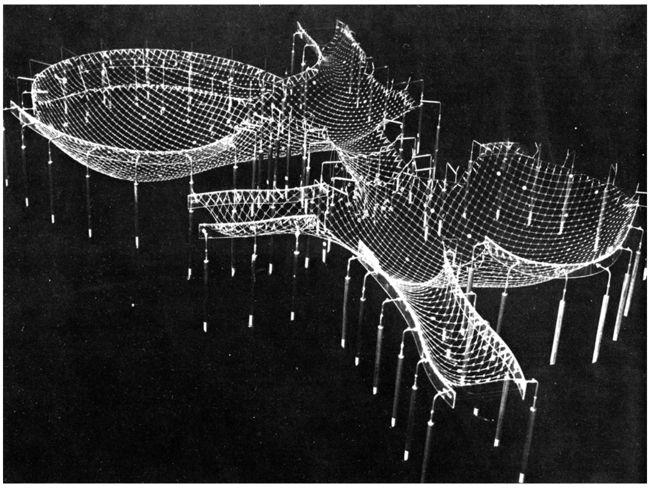
A wide-spanned structure loaded by compression designed by Frei Otto using physical models, is the roof of the multi-purpose hall “Multihalle” for the Federal Garden Exhibition in Mannheim in 1975.



Mannheim, Multihalle

The structure, consisting of two shells with a curved, “organic” configuration in the ground plan, connected by a covered passage-way, is a grid-shell made of a double mesh of wooden laths (5x5 cm), covered by a polyester membrane; covering 7400 m^2 with maximum spans of up to 60 m and height of 20 m, its weight is only about 14 kg/m^2 [IL10; IL13]. The structure was planned to exist only temporarily and therefore doesn't meet normal load-bearing and security standards; however, it lasted till today and recently has been declared a monumental building.

It was built by extending the laths on the ground, connecting them to a square mesh but not yet blocking the bolts. The mesh was then slowly pushed up with the help of scaffolding towers lifted by forklift trucks. The synclastic double curvature of the initially plain mesh could be obtained by bending the laths and by turning the connections between them, transforming the square mesh to a rhomboid mesh. Once the final position of the grid was reached, the bolts were blocked and the boundaries were fixed. For satisfactory buckling safety, a diagonal cable-net was introduced, and finally the structure was covered with a membrane.

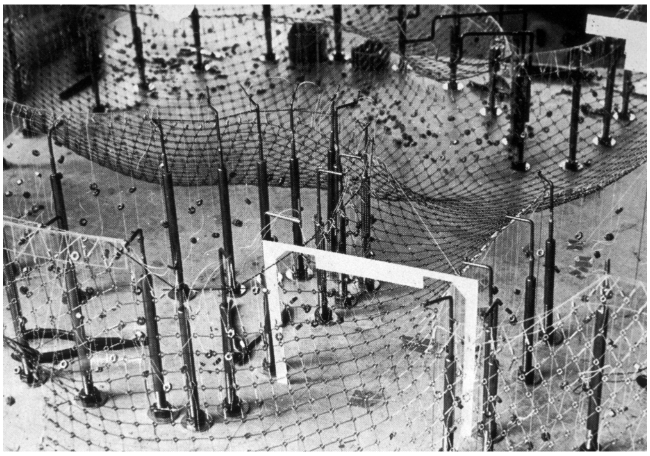

Form-finding Model for the 'Multihalle', in scale 1/100 ca. [IL 13]

The form of this shell structure is that of its stability figure - instead of using geometric procedures or even creating a double-curved Euclidean shell, its funicular shape was developed partly in a physical model, partly by means of the so-called analytic form-finding. This was done so even though the proportion of the proper weight was very small compared to the “disturbing” loads which do not derive from the dead-load pattern (e.g. wind loads, uneven distribution of snow masses), given the extreme low weight of the structure itself (pre-stressing would not lead to a stabilization for this type of construction), and though the realization of such a complex shape could be expected to be more complicated, mainly in the anchoring of the shell to its foundations.

After roughly laying out the project in a wire mesh model, the development of the shell has been taken on in a funicular model in scale 1:100, made of wire elements representing three elements of the real mesh each; the boundaries were made of plexiglass. The hanging model obviously represented the shell upside-down, so that virtually the data for constructing the grid-shell could be obtained by measuring the model.

In this model, the curvature of the laths could be controlled - excessively low radii of curvature would cause breaking of the laths, but sufficiently large synclastic double-curvatures were needed to make the shell resistant to the “disturbing loads”. The mesh's evenness and its degree of curvature were step by step improved, modifying the fixing at the boundaries. The interventions on the form had to be performed by changing the geometrical and mechanical boundary conditions, i.e. by changing the position of the boundary or by changing the length or the tension of the mesh's elements. Functional criteria, like the sufficient height of the roof in the passage-ways, could also be checked on this model.

The final definition of the structure's shape was then performed by Klaus Linkwitz and his team, departing from a stereo-photographic measuring of the model; the result was a precise plan of the entire grid, with the exact altitude of every node, and the real dimensions of every element - essential for producing the laths and mounting the grid, for the design of the boundary details, for performing the lifting process, and, of course, for the calculation and verification of the shell's structural behavior.


Detail of the form-finding model [IL 13]

Given the impossibility to transport the data from the measurement of the scaled model directly to the definition of the final structure (every error would have been amplified 100 times, according to the scale of the model), these measuring data had to be corrected; also, the node's coordinates not represented in the model had to be interpolated, the curvature had to be smoothened, and the whole shape had to be approximated to the stability figure as far as possible, i.e. the inverted funicular shape with homogeneous force distribution and grid curvatures. Therefore, the force-density method, mentioned above, was applied [LINKWITZ 1996; IL 13, p. 41; HANGLEITNER 1990]. In consequence, the physical model used for the initial design process, respect to the whole procedure, remains only the first iteration of a computational analytic form-finding process.

Here, strictly from a point of view of structural optimization, one could state that form-finding on physical models will come to an end - computational methods are becoming powerful enough to be able to perform analytic form-finding without needing physical models - even as first iteration.
This would be true, however, only if the architect's activity - or better, the designing process in the whole - were limited to the problem of pure optimization. Instead, as long as the optimization problem remains only one aspect of the design of a building, the conclusion might be different - as a closer view to the grid-shell at Mannheim might show.

Mannheim, Multihalle: Passage-way connecting the two shells

To the visitor, the “Multihalle” offers extraordinary formal and spatial qualities. The whole building, with its “amorphous” plan, lies within the surrounding vegetation like a giant ameba. But the inside is far more impressive: When entering the building, one experiences a space that gives a notion of wideness and organicy - a somehow “fluid” space, that seems to breath, sometimes expanding, sometimes contracting, without ever forcing its movement. Moving through the main halls and the connecting passage-ways, the sequence of spatial situations and qualities is of extraordinary variation and richness. This sensation is caused mainly by the variations of size and - obviously -, of curvature, and the ever changing inclination of the shell at its boundary; there are even areas where the shell, approaching its boundary beam, is turning inward, or, so to say, overhanging to the outside. This “richness”, the high quality of architecture that this building presents, seems to be owed to the design process - very similar to the Colonia Güell church by Gaudí. If we accept to conceive artistic working techniques in expanded manner, we can state that the development of this project is based on a sculptural process: an open process, subject to his intrinsic rules and not to individual will, allowing to develop, understand and “find” the shape of the building. Otherwise, how can something like this be invented?

Subjective approaches to form

In many cases, structural issues are not the major concern in architectural design - it may be desirable to realize “free forms” independently of any structural purpose. Especially where the shape to be built cannot be conceived or developed within the restricted range of geometrical description, form-finding processes on physical models are used, enabling the architect to develop the shape of the building in terms of material interaction, or in terms of more refined sculptural processes - towards innovative artistic working techniques that go beyond unilateral individual expression.

In his projects for the "endless house" (1944-1965), Friedrich Kiesler worked to a great extent with models, some of them in large scale. In these models, he explored space for human living, literally elaborating this space by working form the human perspective. His idea of infinite interrelations of the elements within human living space ("correalism") leads him to the concept of space where "all ends meet", that has "strict boundaries according to the scale of our living. Its shape and form are determined by inherent life forces, not by building code standards or the vagaries of décor fads" [*Notes on Architecture as Sculpture*, 1966, cit. in BOGNER 1997, 140]. The Exploration of "inherent life forces" focuses on the possibilities of intuitive control offered by physical models, and alludes to the dimension of perceptual psychology.
This topic cannot be discussed within the limits of this paper, but it may be worth to point out that the evaluation of any instrument for designing formal and spatial structures should be based on our knowledge of perception of space, and perception of our surrounding.

One generation before Kiesler, Rudolph Steiner attempted to conceive a holistic approach of the human and his surrounding, the social interaction and interaction between individual and cosmos - the so-called "Anthroposophy", considering the consequences for the creation of our artificial ambient to be realized in the buildings.
However, in contrast to Kiesler, Steiner's "anthroposophical" approach is not based on contemporary scientific currents, but is essentially mythological - choosing as key reference texts by Goethe where scientific and cosmological ideas are drawn from observations of nature, conceived as an "alternative" approach to the classical scientific approach of Newton. Parallel to the well-known theory of colours, some kind of "form codex" appears to be derived from Goethe's "Plant Metamorphosis" (*Metamorphose der Pflanze*). The two major architectural works by Steiner are the first and second "Goetheanum" (1914 and 1922), the central assembly building of the anthroposophic community at Dornach, near Basel. After the first wooden building was destroyed by fire, the second "Goetheanum" was built in concrete. Both projects were developed on rather large-scale clay models; Steiner carefully modelled the shape by hand, exalting his individual inspiration.

To us, this sculptural process may appear to be less refined than other sculptural processes, like the self-shaping processes or the open form processes mentioned earlier. In any case, it becomes obvious that forms for buildings sometimes are not only not defined by geometrical objects, but also not defined by any systematical procedure at all. In those cases where the form to be built is subject of personal conviction, of a spiritual dimension, as in Steiner's case, or is, in the "simple" case, subject of a designer's "sculptural attitude" or the use of artistic working techniques, form-finding is usually performed on physical models. The generation of forms that can thus be only accepted as they are, but not justified, explained or re-enacted in mind, can be left to the inspiration of the designer working on the material. However, the "information transfer problem" of obtaining usable working directions remains, as, unlike to the stability figures in lightweight structures, it is extremely difficult to develop general objective criteria of how the data obtained from the model are to be treated when transformed to the full-scale building design.


Designing model for the "Hölderlin-Haus", Maulbronn, made of wood and gypsum in scale 1/20

An example of the realization of such a building design, in accordance to industrial criteria, is the wooden shell roof of the anthroposophical assembly hall in Maulbronn, near Stuttgart. It was built by the local anthroposophic community guided by Elisabeth Krauß; the definition of the form of the building and the elaboration of the data for its production were performed by Klaus Linkwitz [LINKWITZ 1995]. The development of the free-formed shape is mainly based on a spiritual creative process performed by the group, rather than on the anthroposophic

Maulbronn: Wooden shell roof of the "Hölderlin-Haus": the two double-curved main beams and the shell elements were prefabricated and then assembled on site.

"form codex" derived from Steiner's second "Goetheanum". The process started with modelling shapes in sand, and it finally resulted in a gypsum model in scale 1:20.

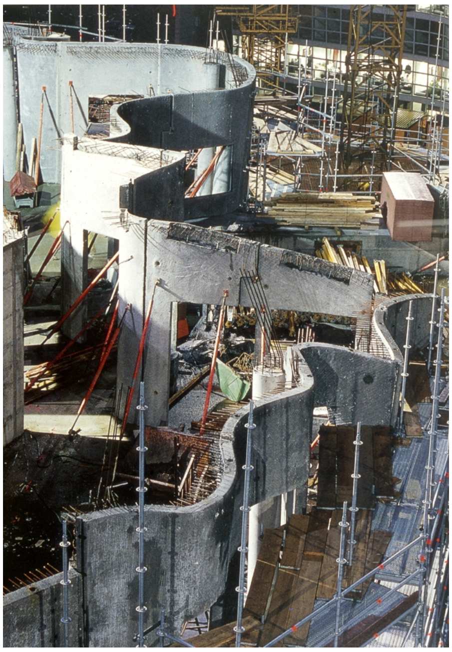
In order to realize the building, precise working directions had to be elaborated. A fundamental condition for any industrial production process, like the prefabrication of the wooden shell elements, is the establishment of a continuous information flow, and, therefore, of a digital model as source of the fabrication data. This digital model, however, could not be obtained by simply taking measures from the physical model - modeling and measuring errors, instead of being amplified to the full scale, had to be corrected. Therefore, on the base of the measuring data of the physical model, the shape was completely re-modelled, applying differential geometric methods - so-called "geometrical reverse engineering". The conformity of this new model, digital and - after all - in agreement with (complex) geometric concepts, could be guaranteed only by a close collaboration with the designers - the improvement of the project to realizability, in this case has been possible only by intensive communication.

In this case, the combination of material interaction on a physical model and geometric reverse engineering has proved to be very useful for realizing "free forms" in buildings: a realization of the forms aimed by the anthroposophic community would not be possible passing a priori through the formulation of geometric objects - the only way of generating "organic forms" within the logic of the authors of the project, was working by hand, interacting with the material. And the only chance for realization has been re-modeling the building shape, by representing the geometrical data by means of information technology and employing a continuous information flow from planning to the production process, like in industrial production.

In the past decade, some very prominent examples of free-formed, "sculptural" architecture have been planned and realized by Frank O. Gehry. He studied their complex spatial configurations on models. The projects could be realized in buildings by re-modeling, elaborating digital models under the architect's control, and adopting industrial production techniques. The working process on the models is essentially intuitive; the process is documented by polaroid-photographs, so that it can freely develop, although any earlier stage can be restored. For the Guggenheim Museum in Bilbao, this is well documented in [BRUGGEN 1997]. The traces of the sculptural process and the material interaction remain visible in the buildings: in the curved surfaces of the volumes, of course, but also in the somehow fragmentary character of the whole - instead of being closed "objects" with a beginning, a center and an end, Gehry's buildings are open structures.

The digital remodeling is done with a powerful CAD/CAM tool, capable to generate and handle free-form surfaces, and to transmit the data directly to automatic production machines. These features have been used, for instance, for the pre-cast concrete wall panels at the "Zollhof" in Düsseldorf (Germany, 1999), where the molds for the free-form panels have been cut in polystyrene with a CNC milling machine [ALBRECHT 1999; GEHRY 1999]. The production without drawings, directly from CAD data, is today standard in industrial production, however, not yet in building industry. The realization in buildings of these highly complex spatial configurations, acceptable by building investors, has become possible only because an industrial process chain could be established: The "Zollhof", for instance, is not a prestigious project free from financial limits, but a "normal" real estate investment project.

It is reasonable to simulate such form processes that can be captured by precise description by means of information technology - this may be the case e.g. for some figures of equilibrium; but it is equally reasonable to perform on physical models those form processes that remain beyond precise description, when we refer, for instance, to working processes based on material interaction and on spatial perception of individuals.
Both on the haptic level of material interaction, and on the visual level, the physical object positioned in the ambient is immediately caught by human perception, whereas, for instance, representations of reality by perspective projections are not [GIBSON 1979], and have to be translated and elaborated in the mind. Although the topic of perception psychology can not be discussed in this paper, it may be claimed that in many cases, form-finding techniques based on physical models will remain extremely important.



"Zollhof" at Düsseldorf: Assembly of the prefabricated concrete panels (photo Thomas Mayer [GEHRY 1999, 197])

The transfer from the project to building, as long as industrial production processes are intended, which are capable of reliably realizing complex structures, requires a digital model, that can be obtained by geometrical reverse engineering. This procedure is not trivial or mechanical, but usually interactive, as the essential qualities of the original form have to be preserved: the designer's intention has to "survive" this translation process. It may be necessary to bring back the digital model to the designer's control with the help of visualization techniques (e.g. renderings or rapid prototyping), that therefore become part of the designing process.

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