# *Collaborative Design Procedures*
## for Architects and Engineers

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# 1. Introduction

***This thesis argues for novel strategies to integrate structural design procedures and analysis data into an architectural design process. The overall performance of an architectural project follows from negotiating and balancing a complex network of multifaceted, interrelated requirements. Considering structure as an integral part of architecture implies that appropriate design proposals cannot be generated through single parameter optimization.***

The structural design discipline developed many procedures to tackle well-defined problems. Physical, digital and mathematical models are used to approximate material properties and determine their behavior. The reliability of those design procedures ensures that similar starting conditions always yield similar results.

Architectural design recently experienced the migration of algorithmic procedures through scripting and programming into the computer-aided design (CAD) environment. In contrast to the collaborating engineers, architects use those formal procedures for design exploration on the search for novelty.

The thesis seeks to interface both approaches by the means of digital tools. Architectural design is predominately conducted as a negotiation process of various factors but often lacks rigor and data structures to link it to quantitative procedures. Numerical structural design on the other hand could act as a role model for handling data and robust optimization but it often lacks the complexity of architectural design, the goal is to bring together robust methods from structural design and complex dependency networks from architectural design processes. Well known structural design procedures used to find or optimize form are confronted with architectural methods which do not necessarily rely on mere quantitative aspects.

## 1.1 Thesis statement

Design strategies of architects and engineers obviously differ. One major reason is seen in the different nature of problems both disciplines have to deal with.

While engineering problems can be approached with scientific rigor, predefined methods and procedures architects have to incorporate many aspects which are not only non-quantifiable but furthermore their quality depends on subjective criteria. While one discipline is carefully engaged in providing security and determinability by relying on established procedures the other urges for design exploration, novelty generation, artistic expression and sometimes personal style.

To a certain extent this polarizing statement is a cliché which ignores the numerous examples of engineers and architects who do not embody this stereotypes. Nevertheless the historical development of both disciplines and their current educational agendas explain and reveal the different understanding and approaching of design tasks. One major gap between both realms emerged in the 16th century. At that time scientific procedures were developed which still define occidental thinking and the way we conduct research today.

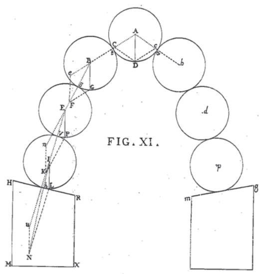



Figure 1.1: The theory of the thrust line. Poleni, 1748.

Engineering science is affecting the way structural design is conducted.

Central figures of science sought to explain the world as a deterministic and mechanistic system which could be reduced to masses and movements in abstract space and time. Insight was gained by the combination of empirical observation and intellectual explanation. The new scientific paradigm of observing a phenomenon, suggesting a hypothesis as an explanation, and the successive testing of the hypothesis became a crucial cornerstone of occidental thinking and research. Master builders at that time based their design on experience, trail-and-error, scale models, geometry, and harmonics. However, with a certain delay the scientific approach towards mechanics, as exemplified by Galileo, Newton and others, migrated into the practice of designing technical artifacts and structures and led to the emergence of engineering as a new discipline. Engineering benefited from the new insights in physics and mathematics that provided methods to formalize design procedures and to determine behavior of structural systems and materials.

System theory, cybernetics, and the radical constructivism challenged the scientific way of thinking in the 20th century. Cybernetics arises in circular systems where effectors are connected to sensors which act with its signals upon the effectors. The linearity of cause and effect was replaced by a concept of circularity. Furthermore second-order cybernetics repudiated the scientific paradigm of objectivity, which demands the separation of the observer from the observed. Instead the observer became part of the system. The Newtonian laws of cause and effect focus on potential energy of objects. Cybernetics however conceives objects as systems comprised of interacting and information-exchanging elements. These theories, meta-disciplinary research, and philosophies provide conceptual and explanatory models for design and planning procedures that deal with complex tasks.

Cybernetic research forms the basis of algorithms which are currently migrating into the field of architecture almost 20 years after Computer-Aided Design (CAD) started to establish in the discipline. Computer-numerically controlled fabrication and scripting languages paved the way not only for digital continuity within the planning process but also for using evolutionary algorithm, agent systems, and adaptive or non-periodic meshing strategies. Those formal systems carry the potential to yield novelty from well-defined starting conditions. The initial conditions of the system do not necessarily imply the predictability of the outcome.

The thesis thus argues that second-order cybernetics offers an explanatory model for the differences between design procedures of engineering and architecture. Furthermore the author expects a certain potential in computational concepts such as discrete information description, data processing and the above mentioned higher-level concepts to further integrate both disciplines.This hypothesis will be explored in detail by case studies that seek to integrate engineering procedures into the architectural design process.

The thesis explores the shifting methodology that comes along with collaborative design approaches by analyzing contemporary and precedent examples and strategies of various disciplines. Case studies of collaborative tools are developed to exemplify, analyze and evaluate the proposed work flow. Three case studies seek to incorporate structural aspects like deformations, stresses and forces as well as established procedures developed in the field of structural engineering into an architectural design context.

## 1.2 Personal motivation, background

The author is educated as an architect and the thesis is approached from an architectural perspective. During studies in the second half of the 1990s the author was confronted with novel digital tools and several leading figures of the new field in architecture like Mark Burry, Mark Goulthorpe, Lars Spuybroek and Bernhard Franken. The application of digital tools was discussed and explored in form-generation fostered by Spuybroek and Goulthorpe. At the same time it was conceived as a means to build those complex forms. Historical buildings like the Temple Expiatori de la Sagrada Família, still today the objective of Marc Burry's work benefited from computer-aided manufacturing (CAM) . The same applies for the temporary stands for several automobile fairs by Bernhard Franken. The broad range of applications indicated already the need for continuous digital production chains from design exploration to production.

The succeeding experience in the architecture office Coop Himmelb(l)au in Mexico and Vienna introduced an interesting approach of interdisciplinary practice to the author. In a series of projects ranging from competition entries to commissioned projects the architects cultivated a close collaboration with the engineers from Bollinger + Grohmann. Structural aspects became a design driver from very early project phases and the teams shared a common office and sometimes even common desks. The engineers did not hesitate to repurpose their analytical tools for design exploration and the architects, well-known for a specific formal language, delegated design competence to their collaborators.

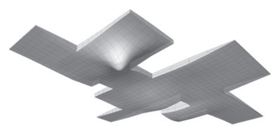


Figure 1.2: Roof of the JVC Urabn Entertainment Center, Guadalajara, Mexico by Coop Himmelb(l)au in collaboration with Bollinger + Grohmann

The large span roof covering a shopping mall in Guadalajara/Mexico, for instance, was exposed to gravitational loads in a simulation and the succeeding deformation became an architectural expression of the ceiling surface. Optimization in a structural sense was not the aim of this procedure but rather a novel explorative procedure. The project is not realized yet but the procedure was carried on in the design of the BMW Welt in Munich which opened in 2007. The author

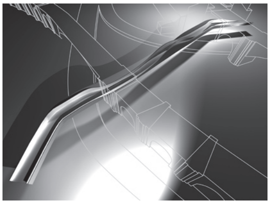


Figure 1.3: skyWALK competition entry for a pedestrian bridge in Vienna, Austria by Oliver Tessmann, Mirco Becker, and Asko Fromm.

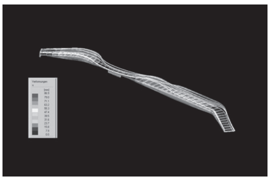


Figure 1.4: Continuously changing structural heights derived from different span distances are balanced with desired vistas.

was inspired by this collaborative approach and at the same time experienced cumbersome data exchange procedures when being in charge of the 3D model in the office.

The conceptual framework was carried on by the author in a series of architectural competitions conducted in collaboration with Mirco Becker. Again the input from structural analysis of conceptual architectural concepts was fed into the architectural design process of a pedestrian bridge and a landmark tower. Asko Fromm and Gregor Zimmermann contributed their engineering expertise and served as important counterparts in many discussions.

This thesis and the work with students and colleagues at the University of Kassel offered a chance to investigate and advance those interdisciplinary efforts on a methodological and technical level. Besides the explorative potential for form-generation the research revealed integration as another important aspect. The modernist architectural approach tends to decompose complex problems into parts and solve them individually and isolated from each other while ignoring the interaction between those components. Optimization often pursues a similar agenda but most architectural challenges cannot be approached in this way. An integrative approach, in contrast, seeks to negotiate diverging or even conflicting aspects to yield a solution which incorporates all aspects. The author sought to develop methods that integrate and balance architectural and structural aspects within one collaborative design procedure.

The research is approached from an architectural viewpoint. The aim is not to substitute engineering work by automated procedures. In contrast the critical evaluation from a structural design point of view even gains importance. Furthermore the quantitative data from analysis is treated in a qualitative or sometimes even ornamental fashion, best exemplified in the third case study.

## 1.3 Key terms and concepts of the thesis

The following paragraphs describe several terms and concepts the thesis successively relies on.

### 1.3.1 Design procedures

The term design procedure is used to describe the formalized part of a design process. After envisioning a design proposal techniques and tools are necessary to depict, communicate, document, justify, and refine the initial idea. Design procedures are comprised of methods and tools. Thus they allow repeating the process while generating similar results or conducting it as a third-person.

The term covers a broad variety of processes ranging from highly formalized systems like calculation procedures for sizing structural elements to less rigorous architectural form-generating procedures. A 3D modeling environment for instance is a tool and a certain way to use it a technique or method. Other examples for design procedures are processes that derive form from the self-organization of material systems like hanging models, wool threads or soap films in design exploration. In structural design a design procedure is for instance used to derive element dimensions or determine the behavior of a structural system.

Design procedures can be found in every period of building history. They embody contemporary cultural heritage and previously gained scientific insights. The author claims that structural design procedures and the resulting projects reveal how scientific knowledge and methods migrated into practice and that this process broadened the gap between architecture and engineering.

### 1.3.2 Formal systems

A formal system consists of a formal languages and a set of inference rules. Those elements form a deductive system which can be used to derive new expressions from existing expressions. The rule-based manipulation of symbols is separated from its meaning and is based on four elements:

- A finite set or alphabet of symbols (operands)
- A grammar (operators) which define how well-formed formulas are constructed out of symbols
- A set of axioms
- A set of inference rules

A formal system is self-contained which means that everything outside the system is irrelevant including any kind of meaning. Truth of expressions is depicted and proven by well-formed formulas. Thus new insights can be gained from known expressions by a mechanistic application of rules (Haugeland, 1985). Calculus is an example of a formal system but also games like chess are based on the above described elements. Formal systems abstract, formalize and mechanize epistemological processes which helps to convert individual insights into public knowledge and procedures. Structural design benefited from those mechanized insights gained in science. At the same time formal systems prescribe a framework which will not be exceeded. When formal systems migrated from science to engineering practice they became design procedures. What will be designed then is limited to what is possible to calculate.

### 1.3.3 Form-finding

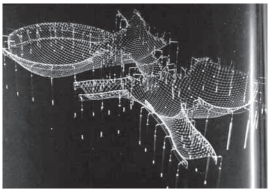


Figure 1.5: Form-finding model Multihalle Mannheim, Frei Otto. A wire mesh is fixed along a predefined boundary and then exposed to gravitational forces

Form-finding is a design procedure which exposes a physical model to extrinsic forces. The model is expected to change its form to establish an equilibrium of internal and external forces.

Form emerges depending on the material properties, the behavior of the model, and the magnitude and direction of the impacting force. Antonino Gaudi, Frei Otto, and Heinz Isler are famous representatives for the exploration of form-finding as a design procedure. Furthermore several of their projects embody forms generated through those processes. Form-finding can achieve a high level of integration. Heinz Isler's shells for instance coalesce structure, skin, and overall from into one single layer. Nevertheless the fact that exclusively structural forces generate the overall from is, in this thesis, conceived as conceptual flaw of the procedure. Those structurally idealized forms dismiss additional requirements which are not related to structural issues. Therefore the most successful realized projects are those that did not needed to integrate further architectural requirements like large roofs of industrial buildings or sport arenas etc.

### 1.3.4 Optimization

Optimization approaches a design problem from the opposite direction. It comes into operation when a form already exists but needs to be improved regarding certain aspects. Optimization requires a well-defined problem, quantifiable criteria and a specific goal the process is steering toward. Structural rather then architectural design problems suit these requirements. Therefore optimization procedures are more common in engineering.

A typical optimization problem is to find a shape with a minimal consumption of material while satisfying all given constraints. The notion of balancing different constraints makes optimization interesting for collaborative design approaches. In this thesis it is sought to negotiate quantifiable architectural aspects with structural criteria in order to achieve equilibrium of multiple design criteria.

A multitude of optimization procedures are known. In the thesis an Evolutionary Algorithm is used to search a solution space and yield a proposal which converges towards the most balanced solution. Those algorithms are based on mimicry of the process of evolution. These evolutionary strategies depend on the fitness ranking, as selection constitutes the only control mechanism to direct the development. In nature individual fitness is evaluated on the phenotypic level as the likeliness for further reproduction (Mayr, 2001). Likewise, in digital processes each individual structure needs to be fully defined and modeled in order to be evaluated. Each evolved structure is based on the genetic information of a previous generation and has undergone further adaptation.

### 1.3.5 Differentiation

The notion of differentiation changed through the use of digital procedures in architectural design. Post-modern approaches used the collage to organize a multitude of objects all different in kind together forming a composition. Novel digital tools are able to describe relations between elements. The collage is now accompanied by associative geometry implying hierarchy, inheritance and relations. Dimensions are rather driven by variable parameters than fixed values. Parametric components do not differ in kind but rather in dimensions and digital procedures can generate a lot of them. Computer-numerically controlled fabrication can tackle this differentiation in dimensions as long as the constraints defined by material and machine properties are not exceeded. Continuous digital chains from design to production enabled Mass Customization in the field of product design and contributed to the realization of complex shaped buildings. Mass Customization in product design spreads its differentiated products when selling them to customers. Differentiation of architectural components in contrast can be apparent in one single building. This kind of self-similar differentiation is often camouflaged to achieve the reverse. The courtyard roof of the British Museum by Fosters and Partners and Buro Happold embodies a high level of homogeneity of member length achieved by dynamic relaxation algorithms which could only be achieved by the differentiation of every single node between the elements. The author regards self-similar differentiation as a creative means worth unfolding and displaying. One case study of this thesis seeks to drive this architectural approach by data derived from structural analysis.

Figure 1.6: Courtyard roof of the British Museum by Foster and Partners and Buro Happold. Only highly differentiated nodes enable homogeneous member length.

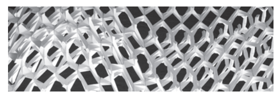


Figure 1.7: Expressive differentiation as a creative means. Student project at the University of Kassel.

## 1.4 The Case Studies

### 1.4.1 Form-finding within a network of multiple constraints

Well known physical form-finding strategies are transferred into the digital realm and applied to architecturally designed shapes to initialize a negotiation of architectural and structural demands. An initial NURBS-surface is translated into one or more meshes, which then are exposed to their dead load in the structural analysis software. The resulting deflections are fed back into an algorithm that steers the appropriate reactions towards the local stresses and deformations: The geometry of the initial mesh is slightly altered to reduce bending, while still embodying the initial architectural proposal. Unlike in sequentially organised form-finding procedures, this process negotiates the form-driving ‘forces’ of both realms, the structural and the architectural.

### 1.4.2 Negotiation of conflicting parameters through evolutionary algorithms

In this case study space frames become the objective of multi-dimensional negotiations. A parametric space frame model allows externally driven variation to achieve a solution space instead of a single solution.

An adequate means to generate and navigate such a solution space is an Evolutionary Algorithm (EA). Those algorithms are based on mimicry of the process of evolution, which leads to the effect, that through the accumulation of small improvements over time the maintained solutions gradually converge towards the defined criteria. Each space frame individual is evaluated and ranked by a set of fitness functions. The strength of EA's is the ability to balance different or even conflicting requirements. This potential is exploited by defining not only structural but also architectural fitness functions. A solution cannot be achieved by the implementation of a generic structural system but has to be adapted to the specific project criteria.

### 1.4.3 Parametric components driven by architectural and structural data

In recent years geometric models became increasingly augmented through requirements of computer-numerically-controlled fabrication techniques. By integrating constraints like geometric complexity (flat panels, single-curvature, etc.), material properties (bending radius, machinability) and panel sizes the design process is pre-rationalized.

This case study aims to integrate a further crucial aspect of architectural design: the structural performance of building components as design driver from early on. In collaborative design processes of architects and engineers structural design is thus becoming an integrated node within a network of multiple requirements which have to be balanced. While one discipline is carefully engaged in providing security and determinability by relying on established procedures the other urges for the generation of novelty in processes, procedures and products. One promising way to blur the realm of quantitative data with qualitative approaches is seen in the use of macro-scripting and programming. Those techniques give designers a handle on numeric control to feed into the steering of aesthetic results

In a design studio students went through a one week drill of RhinoScript and subsequently designed and implemented their own module. Additionally they were given a custom-made tool that not only populates the modules but also interfaces the 3D model with structural analysis software. The propagation of modules is twofold: In the first iteration a centre line model of the structure is generated and transferred to a structural analysis program.  In the second iteration the actual modules are generated driven by the guiding geometry and the cross-section forces derived from the preceding analysis. Finally the laser cutter which was chosen to fabricate the module required flat or developable elements.

Besides questions of pre-rationalization the research explored the potential of building components that blur architectural and structural aspects. While maintaining similar topology the module changes in geometry and functionality – from space generating to space limiting to structural element.

## 1.5 Introduction to the chapters

### 1.5.1 Chapter two

In the second chapter the notion of the design procedure, as it is conceived in this thesis, is defined. The development of design procedures in structural design is presented and set into relation to procedures which evolved in mechanical and engineering science. It is argued that those scientific methods and concepts, like the Newtonian notion of a linear connection of cause and effect, migrated into the engineering practice which contributed to the emerging gap between architecture and engineering.

### 1.5.2 Chapter three

Chapter three presents cybernetics as a concept emerging in the twentieth century which challenges the rationalist tradition and its way of thinking. Circularity is proposed as an alternative concept to the linear causality of cause and effect. The consequences of this novel approach for the use of formalized systems in architectural and engineering design are discussed. The distinction of well-defined and ill-defined problems is drawn and set into relation to the tasks of both disciplines. Furthermore second-order cybernetics serves as an explanatory model for design processes which cannot exclude the designer from the system he or she is working with.

### 1.5.3 Chapter four

In case design problems cannot be tackled with existing procedures the designer has to design a procedure before approaching the actual design problem. Chapter four presents examples of precedent engineers and architects who developed their own procedures either for design exploration or as a reaction to envisioned proposals which could not be approached using existing methods.

### 1.5.4 Chapter five

Chapter five consists of the three case studies conducted by the author. All three experiments seek to develop collaborative design procedures which integrate engineering approaches or analysis data into architectural design processes. Case study one confronts digitally simulated form-finding with shapes already informed by architectural aspects. The second case study uses an evolutionary algorithm to balance architectural and engineering requirements while designing space frame structures. The last case study establishes an interface between a 3D modeling program and an analysis application to use the quantitative data derived from analysis as a design driver during the proliferation of parametric components.

### 1.5.5 Chapter six

The last chapter draws a conclusion of the thesis under consideration of the case studies and their results. The author perceives a great potential in embracing structural design procedures and feeding analysis data into the architectural design process. The integrative approach manages to embed a certain structural rationalization but even more important is the use of structural aspect as a design driver instead of a limitation in design freedom. A need of further research is seen is the development of design procedures which are able to exceed their own framework. Those methods of higher order are explored in the field of genetic programming and would be able to yield solutions beyond the solution space initially defined by the designer.

# 2. Design Procedures

The very act of creation or conception, which takes place in our minds, is highly based on individual aspects like the body of knowledge of a person, one's education, personal experiences etc. Most designers have difficulties to express how they come up with new ideas and concepts. To analyze this process from outside is even harder and will most likely not lead to any results. Thus at a certain stage of the process it becomes necessary to formalize the design in drawings, linguistic concepts, calculations etc. so that other people can grasp the idea. Furthermore things become more complex during design development thereby making successive consequences harder to anticipate if the idea remains a concept of thoughts.

Hence a design procedure, comprised of a series of formalized steps, is required. Formalization describes the transformation of imaginations and procedures that only exist as individual thoughts into repeatable methods. The act of formalizing can be seen as the sedimentation of an ephemeral thought into language or procedures. The insight and understanding which were necessary to first imagine a novel procedure is not needed anymore when rules define the way one has to act to achieve a specific goal.  Thus formalization enables the creation of methods that guarantee the non-reflected repetition upon a growing body of prerequisites, which are always in play but not always updated (Blumenberg, 1999).

Depending on discipline and subject the degree of formalization varies. While the procedures and their results of artists might be recognizable they are nonetheless highly individual and not of any use for other persons. Structural design in contrast requires design procedures which provide a certain transparency of the process as well as repeatable and transferable actions. The structural performance of a building, bridge or tower has to be anticipated in advance since a failure would threaten the life of its users. Thus the use of approved design procedures and their outcomes improves the work of the engineering discipline.

## 2.1 Models of representation

Design procedures require a model as a representation of the physical world. The model is used to communicate and represent but also to anticipate and simulate effects and behavior of a design. The very nature of the models lies in a certain simplification, approximation, and appropriate assumption of an observed phenomenon or structural model. Only those aspects that seem to be of relevance are integrated into the model whereas others are ignored. Hence a model is not an objective representation of reality. Its changing character in history rather indicates the respective current stages of development of science, engineering, and architecture. The theory that was anticipated to explain the world in the most precise way was sooner or later formalized and integrated into the model of choice. The notion of the model can be found in any era of architectural history dressed up in more or less formal ways. The structural model, comprised of the structure itself, the chosen material and the impacting loads, is embodied as a physical, qualitative or mathematical (quantitative) representation (Addis, 1990).

While Greek and Gothic models relied on qualitative aspects like geometry, proportions and harmonics the last three hundred years yielded increasingly precise mathematical models that focus on the quantitative aspects of structural design. Those representations were based on a new approach towards science. In the 16th century central figures of science sought to explain the world as a deterministic and mechanistic system which could be reduced to masses and movements in abstract space and time. Insight was gained by the combination of empirical observation and intellectual explanation. The new scientific paradigm of observing a phenomenon, suggesting a hypothesis as an explanation, and the successive testing of the hypothesis became a crucial cornerstone of occidental thinking and researching. Observation and explanation of natural phenomenon thus led to mathematical models that later proved helpful in engineering. Abstraction, formalization, and mechanization were utilized to deduce models from phenomenon and decompose complex systems into comprehensible subsystems. With a certain delay those paradigms migrated from the field of science into the models and design procedures of engineers. Condensed and encapsulated knowledge of geometry, mathematics, statics, strength of material, and the theory of buckling or of shells is applied in the design process to exactly predict the stresses and strains in a structure and can furthermore be identified in the constructed outcomes. Like the availability of certain materials or new requirements like railway bridges, specific calculation methods had a significant impact on what was built and how it was built.

The notion of a 'design procedure' is borrowed from William Addis in his book 'Structural Engineering - the nature of theory and design' published in 1990. It carries the advantage that it is equally applicable to all times in history. The design procedure, as a statement of how a designer should tackle a certain task is not as such new, especially in the field of structural design. The historical development of structural models is characterized by cumulative gain of knowledge and gradual progress on one hand and radical questioning and revaluation of existing paradigms on the other hand (Addis, 1990). The following chapter describes the development and changes in the models and design procedures of master builders and engineers. The geometrical models responsible for Gothic cathedrals underwent a constant refinement until they were replaced more often by mathematical models that incorporated the properties of materials.

## 2.2 Design procedures driven by structural geometry

Gothic structures embody for the first time in architectural history an extensive use of the principle of economics and efficiency: With a minimum of material use a maximum of space was embraced. The techniques necessary to achieve this goal are described by Hans Straub as four major aspects:

- The differentiation of the wall in load-bearing columns and space-embracing surfaces.
- The use of an adaptive ogive.
- The decomposition of vaults in ribs and light cap-surfaces.

- The invention of the flying buttress that transmits the thrust of the vaults to a system of buttresses (Straub, 1992).

Gothic vaults anticipate the skeleton structures of following centuries, with the limitation that its components transmit exclusively compression forces. The pointed or ogive arch which became the defining characteristic of gothic architecture is probably the outcome of a structural evolution. Its shape approximates the inversed catenary unlike the semi-circular curved Roman vaults. The resulting vault-loads are directed in a more vertical direction significantly reducing horizontal thrust accompanied by ribbed vaults with intermediate cap-surfaces which represent a further means of weight reduction.

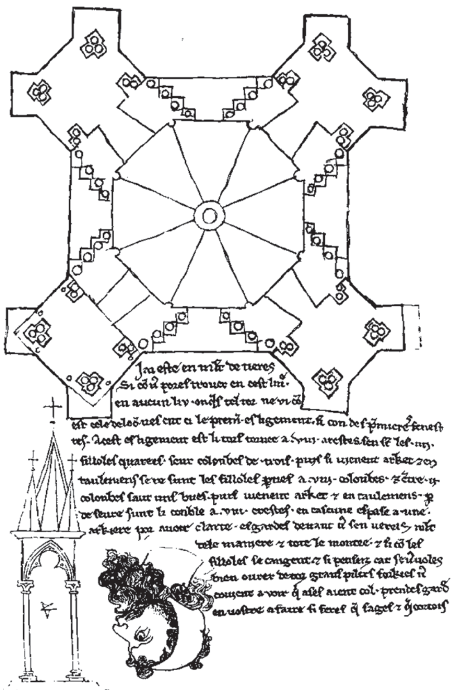
The most remarkable evidence of professional experience and intuition is the innovation of the buttress for bearing and transmitting forces from the high rising vaults. Shear forces are split in two components and are redirected towards a column or buttress and an angular flying buttress (Straub, 1992). To what extent this achievement was based on mathematical and analytic methods is not known today. The secrecy that surrounded the skills of the master masons obscure the knowledge of ancient design procedures since it was forbidden to share any information inside or outside the lodges (Addis, 1990).

Nevertheless building practice was not limited to pure intuition and experience gained from trial and error procedures. Scale models were not only used to conceptualize, visualize and communicate a design proposal but most probably also to evaluate its safety and stability. William Addis describes an example that gives evidence to this assumption: Antonio di Vincenzo who was commissioned to design the Basilica of San Petronio in Bologna in 1390 had built a scale model that was six meters in height, using similar materials as in the full scale structure after visiting comparable proposed and implemented examples in Milan and Florence. The reasons for building a model 19 meters in diameter are not entirely known but its construction and the use of brick and plaster makes it a reliable instance of the full scale design proposal since compression as the only force in gothic arches is dependent on relative proportions and not on scale, like bending and tension forces are.

Besides the mere empirical approaches of scale models, the ancient Greek knowledge of geometry and harmonics provided additional explanations of the medieval world. The use of geometry and the significance of results that could be drawn from its application gave way to extensive innovations in gothic architecture. Likewise, the structural performance relied on the geometric properties of the building components. The master builder embodied both the professions of architect and engineer. The same could be considered for his design procedure:

Geometric rules could be applied to architectural questions of proportions as well as for structural aspects of a building. The records of the German master builder Matthäus Roriczer (1435 – 1495) display procedures to design pinnacles using rules of proportions of √2. The algorithmic procedure is comprised of four steps:

- Draw a square
- Inscribe a smaller square with its corners are the midpoints of the first.
- Repeat the operation
- Rotate the second square 45° so that all three are parallel and concentric.



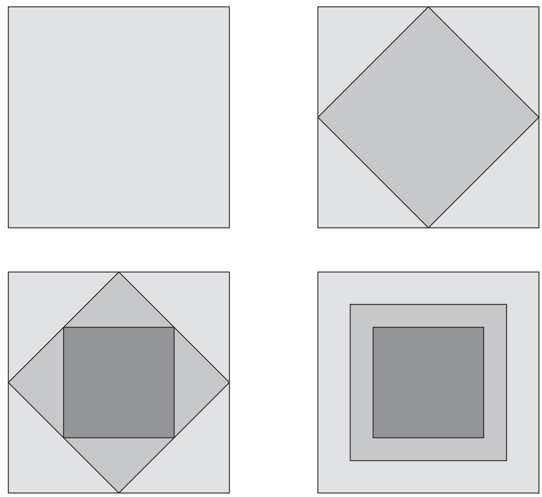
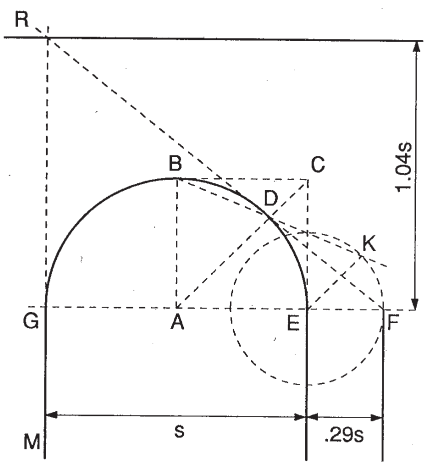


Figure 2.1: Villard de Honnecourt presents the plan of the tower of Laon cathedral which is derived from using a design procedure of diminished and rotated squares. The sketchbook of Villard de Honnecourt compiled about 1235, is one of the most prominent examples of documents that demonstrate gothic design rules based on geometry and proportions.

Figure 2.2: Sequence of digrams, depicting the underying procedure



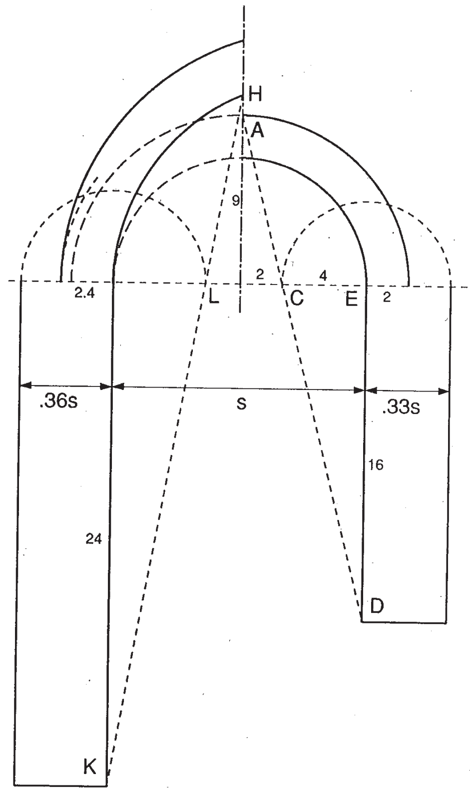




Figure 2.3 (left): Geometrical design procedure to determine the required thickness of abutment and height of the superimposed masonry an arch rib can carry.

Figure 2.4 (right): A second geometrical design procedure to determine the required thickness of an arch and the height and thickness of abutment for semi-circular and pointed arch ribs. Rodrigo Gil de Hontanon (1500 - 1577) proposes a rib thickness of one-sixth, and an abutment thickness of one-third of the span.

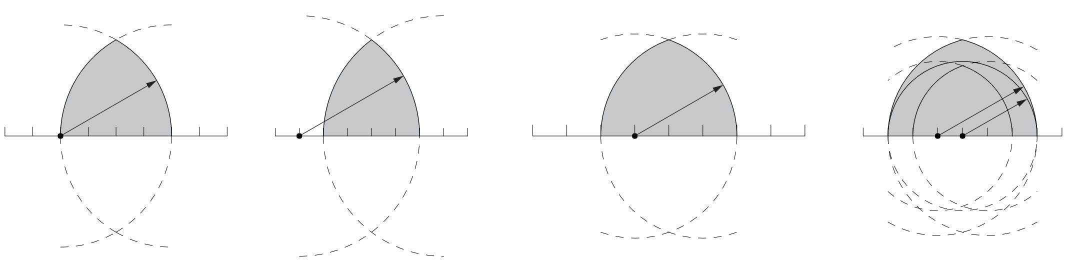


Figure 2.5: Design procedures for pointed arches yielding different span:rise ratios. The outermost right diagram shows a procedure to derive an arch rib thickness from arch geometry.

This fundamental Gothic design procedure is based on a method given by Vitruvius and reappears in the sketchbook of Villard de Honnecourt (Figure 2.1). Basic geometrical techniques were also used to create the gothic pointed arcs. The circle is used to define the span to rise ratio in pointed arches and the rib thickness in relation to the arch geometry (Figure 2.5). The development of geometrical design procedures for arches and vaults is an interesting example of how a procedure is refined towards a better approximation of existing forces and movements of a structure. The horizontal thrust generated by an arch impact on the wall the arch springs from and tends to overturn it. The problem, which would lead to the first structural calculation in 1742 in Rome, was already encountered in Gothic times by geometrical procedures.

All those procedures were seeking for reliable and rational procedures to derive the dimensions of arches and abutments. Geometry served as an objective and scientific means of the Gothic era. This notion was supported by a regaining interest in Greek geometry. The Latin translation of Euclid's Elements of Geometry by Adelard of Bath in 1120 introduced Euclid's notion of the geometrical proof. Euclid's theoretical constructions were not meant to be drawn or built but served as a philosophical and rational means.

> *"Just as occurred after the invention of calculus some 600 years later, philosophers put the new theoretical tool to use in every conceivable way and created, quite literally, a new type of geometry – 'geometria theoretica' " (Addis, 1990)*

Geometry in the Gothic era had significance similar to the one that modern science and mathematics have today. Hence, the relation of medieval design procedures and geometry bears some parallels to later relations of calculus and the elastic theory. As William Addis remarks both are used in 'teaching' and 'doing' (design procedure); both are used to justify design proposals; both are used to give measurements (ibid.).

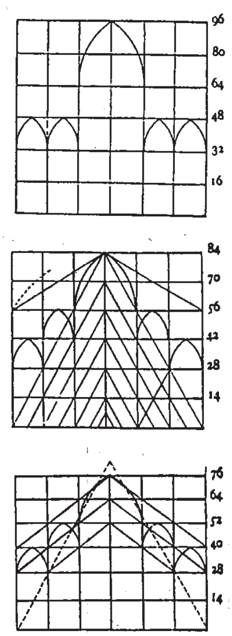



Figure 2.6: Defining the height of the Milan cathedral in relation to its width

Another evidence of the scientific relevance of geometry and harmonics is exemplified by an expertise in the 14th century concerning the Milan cathedral which was under construction at that time. Different experts argued about the final height of the building and derived measurements from the width of the cathedral. Stornaloco a mathematician recommended a cross section that is of an equilateral triangle (Figure 2.6 middle) while the initial plan foresaw a quadratic proportion (Figure 2.6 top). The work was totally stopped in 1399 and experts from all over Europe visited Milan to decide how too proceed construction. Finally Mignot from Paris delivered an expertise regarding the work, which was conducted so far, as defective. Insufficient buttressing as well as geometrical issues appeared to be inadequate. Mignot referred to his own lodge's building manual  which was based on Greek, Roman and medieval architects knowledge and provoked the protest of Milan master builders claiming:

> *scienta est unum et ars est taliud.*

Thus the geometric and proportional rules used by Mignot were conceived as science which is one thing while technology is quite another. Heyman regards this incident as

> *"the first sign of a rational approach to the science of building." (Heymann, 1998)*

The geometric approach is carried forward and refined until the 18th century although new insights were gained in physics, mechanics, and material strength since the 16th century. In 1673 Nicolas-François Blondel (1618 – 1686) proposed a design procedure for various arch shapes. Geometric rules were used for establishing abutment width. The procedure proved to be reliable and thus was published by Bernard Forêst de Bélidor (1697 – 1761) and taught throughout the 18th century.

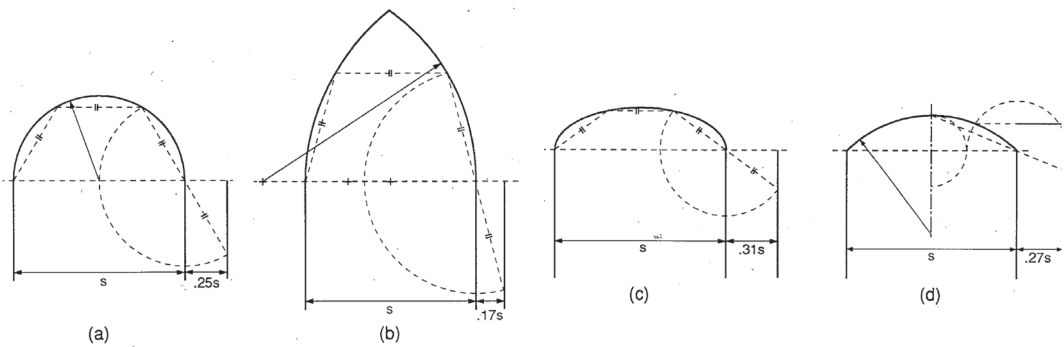



Figure 2.7: Abutment dimensions in relation to arch type and span size as decribed by Bondel.

Certain dissatisfaction was caused by the fact that those procedures lacked universality in terms of scale and size of the structures. Thus the model was not general enough to represent all possible versions of arch structures (Addis, 1990). Christopher Wren (1632 – 1723) criticized Blondel's method since the thickness of the arch and the height of the abutment are not taken into account. He expressed the need to account for the masses of masonry in the arch and the abutment and thus he aimed to broaden the model beyond mere geometry and towards quantitative aspects. Nevertheless it would take another twenty years until Robert Hooke identified in 1675 the inverted hanging chain as the "*true…*

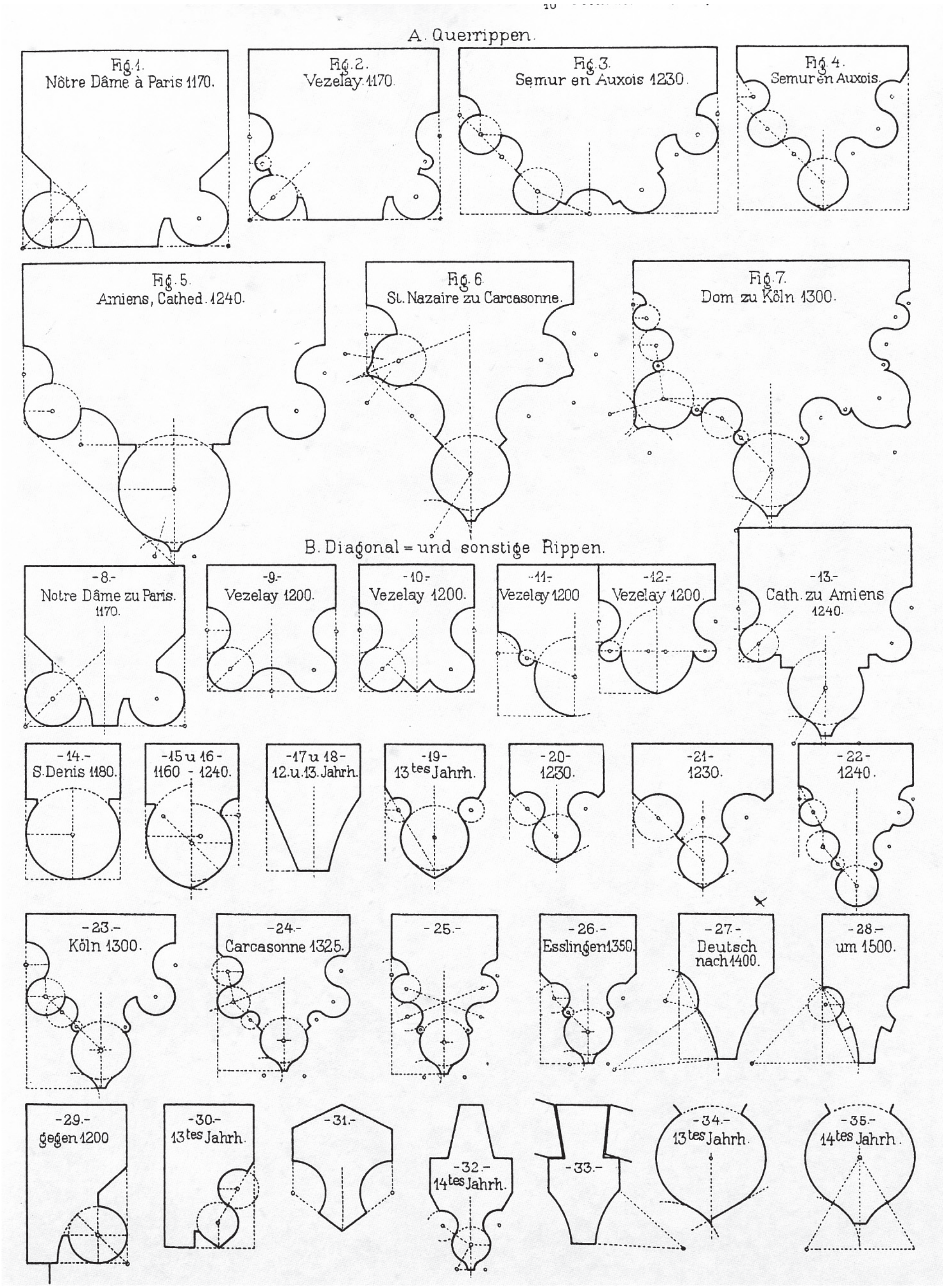



Figure 2.8: Profiles of  Gothic vault rips and their geometric principles

*form of all manner of arches for building, with the true abutment necessary to each of them.*" (Latin anagram published in 1675 by Robert Hooke). Hooke's scientific work was preceded by that of Galileo and others in the 16th century who established a new scientific paradigm and sought to explain the world as a deterministic and mechanistic system which could be reduced to masses and movements in abstract space and time.

## 2.3 The rationalist tradition

In the 16th to 18th century Kepler, Copernicus, Galilei, Descartes, Leibniz and Newton were the central figures of a new scientific approach. The world was reduced to physical masses and movements in an abstract space and time. Only quantifiable phenomenon were accepted and analyzed in this mechanistic view of the world. The new science was based on a tradition of rationalist thinking that begins in ancient times with Pythagoras and Plato. Truth is exclusively derived from intellectual and deductive criterion. Because sensory perception can be deceptive the intellect has to complement and ensure experience. Galileo Galilei was one of the founders of this view of the world and the new approach in science; he merged empirical observation with theoretical knowledge. What has been observed and analyzed by sensory perception is abstracted and mathematically formalized. Galileo introduced the dualism of object and the subject, which was successively refined by the sciences. John R. Searle (Searle, 1994) described the basic principles of a rationalist thinking in which knowledge is created exclusively through the use of intellect. Searle lists the following aspects:

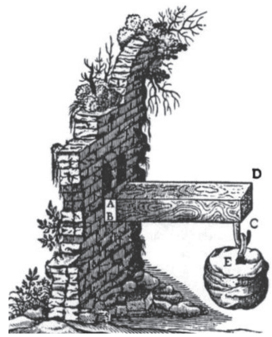



Figure 2.9: A cantilevering beam exposed to external loads in Galileo's Discoursi.

- Reality exists independent from its depiction by man.
- At least one function of language lies in the transmission of meaning from sender to receiver. Sometimes those meanings allow communica tion to refer to objects and processes in the world which exists independent from language.
- Truth is a question of precision in representation.
- Truth is objective. The world consists of a collection of facts indepen dent from human interpretation.

One key aspect of rationalist thinking and natural science in general is the experiment. Galileo does not ask why things fall but how they fall. With the experiment man actively tries to draw the mathematical laws from nature. The experiment is followed by a hypothesis and its successive testing. The final goal is to find the few general principles behind the multiple phenomena in nature. René Descartes (1596 – 1650) defines in his book "Le Discours de la Methode", the four major principles which will in succession influence the entire occidental philosophy and find its preliminary climax in cybernetics:

- Observation of a phenomenon which is regarded as the problem in question.
- Development of an explaining hypothesis represented by a determinis tic system which is able to create a phenomenon isomorphic to the observed one.
- Generation of a state or process of the system as supposed by the hypothesis.
- Observation of the determined phenomenon.

Those principles were used by the men who significantly contributed to the foundations of engineering sciences, statics, and strength of materials between the end of the 16th to mid 18th century. Hans Straub stresses that they did not belong to the discipline of architects or bridge builders. Most of them originate from the realm of physics, mathematics, or geodetics and thus they conducted their research by using the above mentioned scientific procedures. There is no evidence that one of those persons was also involved in the construction of cathedrals, domes, castles, or churches. Those collaborations of practice and theory can rather be observed in the field of mechanical engineering and optics (Straub, 1990). The theorists of mechanics used the body of knowledge and the new principles “to deepen the understanding of a particular science” (Heyman, 1998); only later did those insights become part of design procedures.

## 2.4 Procedures migrating from science to design

The thesis is not aiming for an encyclopedic overview of the history of structural design. The reader is referred to the works of Hans Straub and Jacques Heyman. Of certain interest is the migration of scientific methods which originated during Renaissance into the design procedures of engineers at a later date. While geometric and proportional rules of Gothic times could be used as an integrative tool to tackle structural and aesthetic tasks, the mathematical procedures, developed in the 16th to 18th century, contributed predominantly to the discipline of structural engineering.

The 16th century witnessed not only a refinement and sophistication of a new mathematics but also the revival of knowledge based on classical sources. Vitruvius’ ancient rules of measurements and proportions experienced a reemerging interest even further promoted through the invention of printing. His rules were easy to grasp and apply and thus attractive to not only professionals but even bishops and princes (Heymann, 1999):

*“As an example, Vitruvius gives proportions for the construction of temples, in which the diameter of a column is taken as a module – for the eustyle (one of the five standard arrangements) the distance between columns, the intercolumnation, should be two and a quarter modules, except that the central spacing should be three modules, their bases of thickness half a module, and so on.“ (Heymann, 1998)*

The master builders utilized these rules of composition. Michelangelo, Vignola and Palladio regarded architecture as an art of aesthetics and proportions. The equilibrium of forces was known and integrated into a general aim for harmonics within a building. Ernst Werner assumes a gap between this rather emotional approach on one side and the repulsion of any practical aspect which could burden scientific insights on the other hand (Werner, 1980). Mathematics and mechanics entered the realm of construction through rules of composition, proportions, construction, and rules of thumb. The extensive knowledge of contemporary scientist like Galileo (1564 – 1642), Simon Stevin (1548 – 1620) and others were not used to conduct structural calculations for buildings. Only due to the fact that medieval and renaissance structures work at a level one or two orders of the magnitude below its crushing, hence many of them still exist today (Heymann, 1998). The vaults and domes which survived the critical phase of construction during which their structural capacity was not fully unfolded were most likely to withstand dead load and external forces until today. Stresses are very low in ancient and gothic structures and thus material failures or deflections have not been an issue in the rules of construction of the master builders.

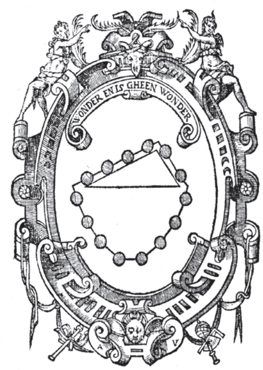



Figure 2.10: The inclined plane in the vignette of Simon Stevin, 1586. As an advisor for the Prince Maurice of Nassau Stevin became the inspector of dykes of the Low Countries, and quartermaster-general of the Government. Hans Straub sees his activity in hydraulic engineering as a major reason for his interest in a scientific approach towards mechanics and statics. While vaults and bridges could be designed in an intuitive way, the construction of dykes and canals required certain mathematical knowledge of hydraulics, the precise leveling and surveillance.

It was not until the mid 18th century that the exact methods of science were applied to an actual construction task. Like in 1399 in Milan the shift from a master builder approach to a scientific based engineering approach was first conducted as an expertise of an already built structure in 1742 - 1743. It was supposed to conduct an expertise to identify the causes for cracks in the dome of the Basilica of Saint Peter in Rome. The commissioned authors Thomas Le Seur, Francois Jacquier and Ruggero Guiseppe Boscovich underlined the need for a theoretical mathematical method due to the extraordinary size of the building. Furthermore, as stated above, the horizontal thrust of domes and vaults acting on their abutments is very hard to tackle with mere geometrical or proportional measures since tension forces act on the masonry.

The expertise was conducted following the scientific principles defined by René Descartes:

- Observation of a phenomenon:
  The cracks and damages of the dome were the objective of detailed

observations and documentation.

- Development of an explaining hypothesis:
  Several possible explanations for the damages were stated. The yielding of the abutment is regarded as the actual reason.
- Generation of a state or process of the system as supposed by the hypothesis:
  The horizontal thrust of the dome was calculated and set into relation to the strength of the two existing iron tension rings. A graphical scheme was developed to represent the assumed movement of the dome which caused the cracking.
- Observation of the determined phenomenon:
  Based on those calculations the installation of additional tension rings was recommended.

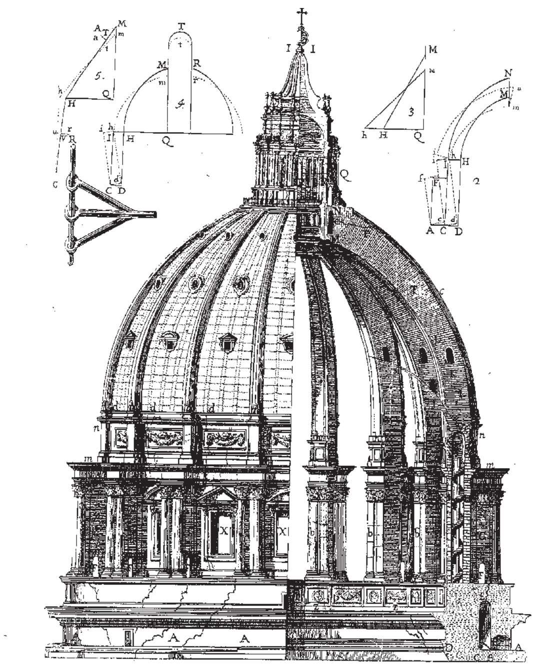


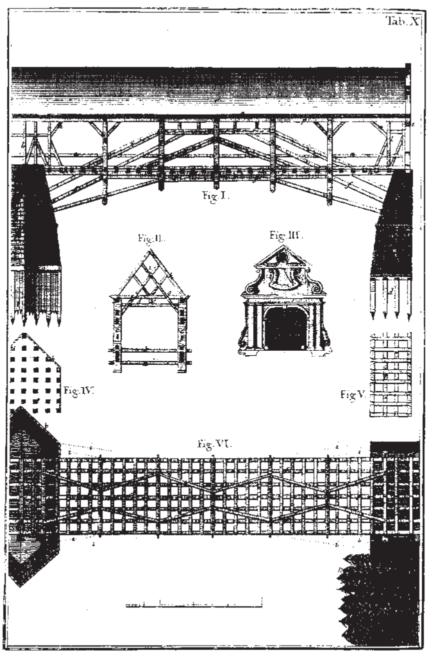
Figure 2.11: Detailed record of cracks in the dome. The drawings on top depict the notion that cracks were caused by the horizontal movement of the abutments.

The three experts calculated the missing horizontal force which should counteract the thrust of the dome and proposed the installation of additional tension rings. The new procedure of using mathematics to calculate the structural performance of a dome aroused the disagreement of the practitioners. If Michelangelo was able to build the dome without the use of mathematics then its restoration should be conducted in the same way. The application of mathematics to represent a physical structure was perceived as an abuse of science (Poleni, 1748).

## 2.5 Procedures in bridge design

The migration of mathematical methods into design procedures proceeded gradually. Geometrical procedures were used side by side with structural design procedures which underwent an increasing refinement due to new scientific insight. This process is most clearly exemplified in the development of truss bridges. Their changing structural typologies clearly articulate the different design procedures at work. Williams lists eight different categories of bridge types that embody different design procedures:

Traditional truss bridges up to the mid 18th century were based on empirical design procedures. Timber was used mostly in compression since joints that carry tension were difficult and too expensive to make. Thus the members were arranged in a polygonal arch configuration to keep all members in compression. The member configuration displays no attempt to reduce material or structural elements. Those structures are hard to calculate even with today’s tools. The design procedure relied on experience, precedent examples and simple algebraic formulae.



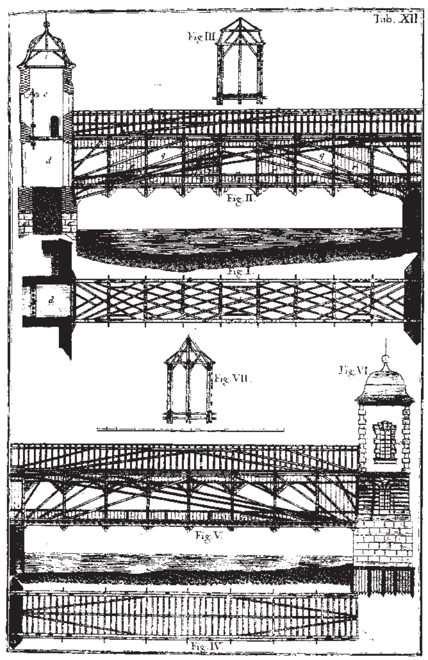


Figure 2.12 (left): A truss bridge with mainly beam action. Only the vertical members receive tension as hanging elements

Figure 2.13 (right): Timber bridge with walkway and compression members on the same level providing increased clearance underneath

With increasing spans in the 18th century truss bridges became arc-trusses. They underwent a rationalization due to its shape and a reduction of material since the dead load of the larger structures became more important. The shape became more arch-like by refining the resolution of the polyline of timber elements. Besides the shape the arch was conceived as a structural arch. The statics of arch equilibrium was known and used for masonry arches. It allowed a rough calculation of the horizontal thrust that the arch would transfer to its abutments. The arch was constructed independently and stiffened with bracing elements.

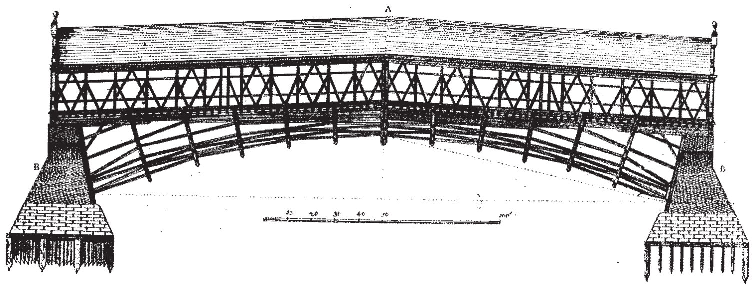


Figure 2.14: Arch-truss bridge with a wodden polygon approximating an arc shape

In the 1828's Claude Louis Marie Henri Navier (1785 – 1836) separated material properties from cross section properties and defined the e-modulus and moment of inertia. Due to this separation his theory gained a general meaning. Navier's achievement is the thorough simplification of a general theory for practical use. With maintainable mathematics, a sufficient precision of results is achieved (Walter, 1980). The new elastic theory led to a design procedure which treated cross braced or lattice truss bridges as solid beams, thus Navier's theory could be applied and an existing structure was perceived through a simplified mathematical model at hand. Parallel top and bottom chords in many of those bridges indicate the effort to approximate the actual structure towards the mathematical model of the beam. The ability to calculate shear forces in the model led to highly differentiated diagonals of lattice truss bridges demonstrating the optimistic faith in the calculations (Addis, 1990).

A lack of stiffness in those bridges led to a hybrid construction of arch-braced trusses. An arch was added to brace the truss bridge. Two systems with well-known properties were combined to complement each other. Since calculations could not be conducted within one model the loads were split to arch and beam and calculated separately.

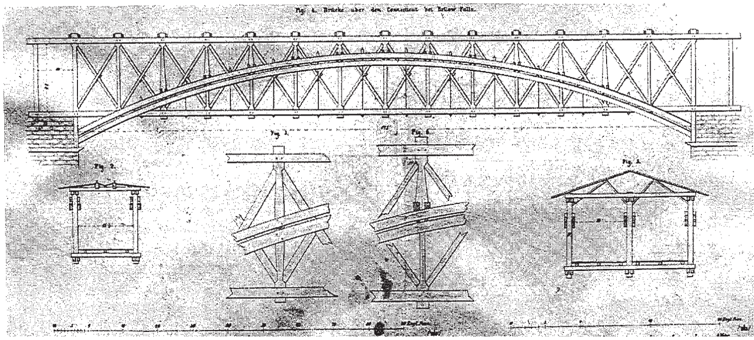


Figure 2.15: Lattice truss with superimposed structural arc

With the use of wrought iron in construction, it became the first material which is gained from an additive production process to be used in construction.  While stone and timber is cut from larger volumes, iron is cast or wrought into shape. To save on this costly material the number of members were increasingly reduced. This reduction and the use of members in tension allowed the use of another mathematical model of simple statics and the force triangle. And again the actual structure was designed to approximate the mathematical model in the most proper way; since only statically determinate structures could be calculated by those models, the structures were further reduced. The new model brought along another perception of the bridge. Instead of a beam in bending the structures was seen as made from pin-jointed members that act in either tension or compression. The triangle of forces was further developed into highly sophisticated analytical and geometrical models like the graphical statics that led to an enormous popularity of those pin-jointed vector-active systems (Addis, 1990).

## 2.6. The impact of design procedures

The predominance of such vector-active lattice systems can be traced back to a technical innovation in 1866. In this year Karl Culmann, Professor of engineering science at the 'Eidgenössischen Polytechnikum' in Zurich, published his 'Graphic Statics' that was based on Jean Victor Poncelets' scientific work on projective geometry, including his developments of the most important graphic methods for calculating structural behavior. With these novel methods being particularly suited for the calculation of lattice girders, no other structural typology signifies better the succinct impact of new calculation methods on the changing understanding and employment of structures (Straub, 1992).

The development of the above described design procedure exemplify the influence of contemporary scientific knowledge and procedures on engineering.

Those models have been constantly improved to represent actual structures more precisely which reflects the notion of rationalist thinking that truth is a question of precision in representation. This notion is most radically displayed and extrapolated in the Laplace`s demon, a hypothetical demon envisioned by Pierre-Simon Laplace (1749 - 1827) in 1814:

> *We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes. (LaPlace, 1814)*

Three decades later William Fairbairn (1789 - 1874) one of the greatest engineers of his time expressed his hope that structural models will gain ultimate precision in representing physical structures:

> *I sincerely believe that there is yet before us a coming age when the exact rules of physical truth will be brought to bear upon the constructive and useful arts, with the same certainty and effect in the practical operations of the artificer and the mechanic, as they now do in the laboratory of the chemist or the observatory of the astronomer. (Fairbairn, 1856)*

Both citations rely on the unlimited validity of Newton's laws. One basic paradigm of the rationalist tradition of western science is that cause and effect have to be linked by explanatory models. The anticipation of causality became the driver of modern science since the 17th century. At that time the experiment was introduced to confirm the cause-effect mechanism and complement the Greek logic, mathematics, and rationality. Furthermore Newton and Leibniz share the credit for the development of calculus, thus they created a formalism to mathematize causality such that no questions remain unanswered except that of the starting conditions. Calculus is based on formalizing logical inference which means that the rule-based manipulation of symbols is separated from its meaning. Logical calculus is based on four elements:

- A finite set or alphabet of symbols (operands)
- A grammar (operators) which define how well-formed formulas are constructed out of symbols
- A set of axioms.
- A set of inference rules.

Such a system is used to derive a new expression from one or more existing expressions. A formal system is self-contained which means that everything outside the system is irrelevant including any kind of meaning. Truth of expressions is depicted and proven by well-formed formulas. Thus new insights can be gained from known expressions by a mechanistic application of rules (Haugeland, 1985). Leibniz logical calculus is a milestone in the mechanization of calculation and logical inference. It was preceded by his invention of a calculation machine in 1672 which was able to tackle the four basic arithmetic operations. The introduction of the stepped reckoner that could handle positional notation and extended the existing machines by performing multiplication, division, and evaluation of square roots.

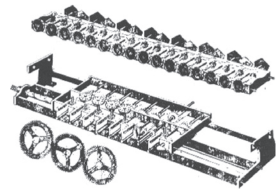


Figure 2.16: Calculating machine by Leibniz 1672/73

Formalization and mechanization first externalize cognitive processes and furthermore encapsulate them. The insights that have been necessary to invent those machines and procedures are not necessary anymore when using them. Karl Culmann, who developed graphic statics based on the projective geometry of Poncelet, perceives similar advantages when using geometrical and graphic procedure:

> *„Die Lösungen Poncelet's waren immer nur Uebersetzungen vorher entwickelter analytischer Ausdrücke. Dass dies ein Umweg sei und dass eine geometrische Construction viel weniger leicht sich einprägt, wenn man bei Anwendung derselben eine analytisch entwickelte Formel, deren Herleitung vielleicht nicht immer gegenwärtig ist, im Kopfe haben muss, als wenn das durch die Aufgabe gegebene Liniengebilde selbst die Grundlage bildet, aus der sich die Lösung einfach geometrisch entwickelt: hat wohl Poncelet selbst innig gefühlt, und eifrig studierte er Geometrie, gleichsam ahnend, welchen Nutzen sie gewähren könnte." (Culmann, 1875)*

Culmann regards Poncelet's geometrical representations of analytical expressions not as a cumbersome detour but rather appreciates the fact that a solution can be derived from a given configuration of lines. Geometry becomes a formal system which bears solutions by applying predefined rules without the need of additional external information like formulas and their derivation. The geometrical and proportional models of the master builders exploited available knowledge of Greek geometry and refined those models through empirical knowledge. The Graphic Static by Karl Culmann encapsulated the insights of projective geometry and the geometrical representation of forces to provide a sound and handy design procedure. In general structural models and design procedures tended towards the representation of quantitative aspects whereas qualitative considerations remained in the design procedures of master builders and architects. The structural models became predominately mathematical models thus gaining

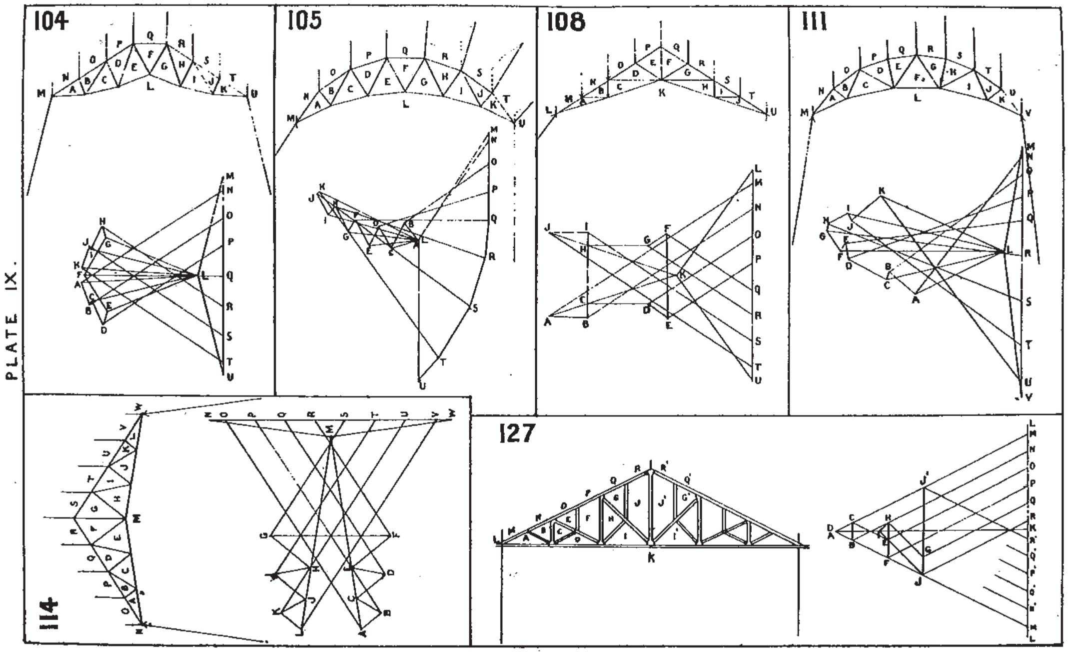



Figure 2.17: Robert Bow' s application of graphical statics for various roof trusses.

a higher precision in representing actual structures. New insights in mechanics, stiffness, and strength of materials were consequently formalized to augment the model in order to converge it with reality. The expectation to ultimately determine structural behavior through models and formalized procedures is expressed by William Fairbairn in the 19th century and represents a general mood of that period which was not reduced only to the realm of engineering.

# 3.0 Design Procedures in the age of Cybernetics

In the 20th century Laplace`s demon finally met its end with Einstein's theory of relativity, Heisenberg's uncertainty principle and chaos theory. Furthermore the common scientific procedure of decomposing complex systems into its components and their successive observation was challenged by Ludwig von Bertalanffy (1901 – 1972). In the 1920's to 1930's von Bertalanffy developed the General System Theory (GST) which provided an alternative model to Newtonian science:

*"It was the aim of classical physics eventually to resolve natural phenomena into a play of elementary units. This however is opposed by another remarkable aspect. It is necessary to study not only parts and processes in isolation, but also to solve the decisive problems found in the organization and order unifying them, and making the behavior of parts different when studied in isolation or within the whole". (Ludwig von Bertalanffy, 1968)*

## 3.1 Cybernetics

Besides GST which originated from biology, cybernetics as the study of feedback in living organisms, machines, and organizations arose more from the realm of engineering and had a greater influence, especially in the field of computation. The term Cybernetic is derived from the Greek kybernetes, which translates to "steersman". It appears in the title of Norbert Wiener's publication "Cybernetics, or control and communication in the animal and the machine" of 1948 (Wiener, 1948) which already serves as one possible definition of cybernetics. Cybernetics arises in circular systems where effectors are connected to sensors which act with its signals upon the effectors. Thus simple and linear cause – effect relations are replaced by circular systems. Due to the circular organization, the future state of the system is not only controlled by external input but also by its current, and

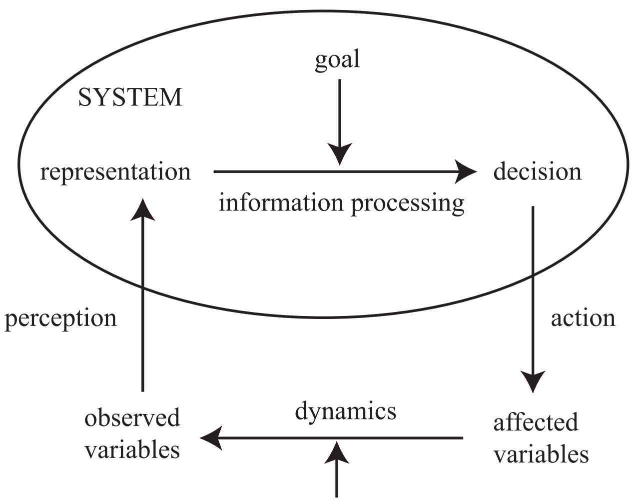



Figure 3.1: The circular concept of cybernetics. A system pursues a certain goal while being influenced by feedback and variables observed in the environmental.

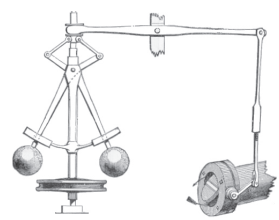


Figure 3.2: A centrifugal governor regulates the admission of steam into the cylinders of a steam engine to maintain a constant speed of the machine. The speed of the central spindle is controlled by the engine. Faster rotation leads to increased centrifugal forces and causes the two masses to move outwards hence lowering the amount of steam admission by means of a throttle.

Figure 3.3: Image series of the animated object

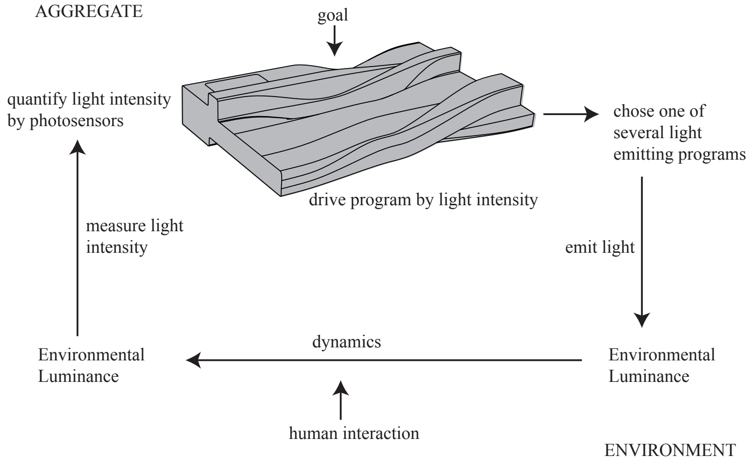



Figure 3.4: The circular concept of aggregate

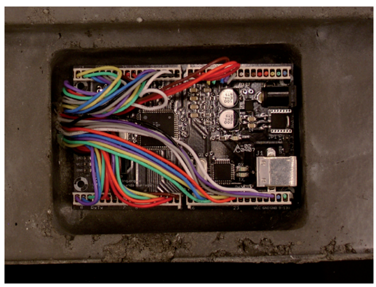


Figure 3.5: Wiring I/O Board by Hernando Barragán, http://wiring.org.co

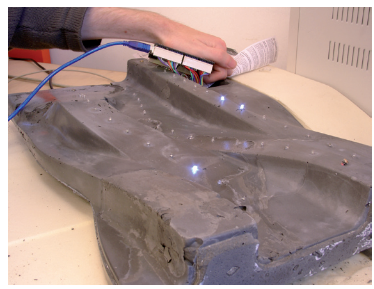


Figure 3.6: Custom programs can be uploaded on the board

## Experiment: aggregate - a cybernetic sculpture

Aggregate is an objects which incorporates a cybernetic system. For an exhibition in Philadelphia (PA) a team of architects, structural engineers and material scientists developed a prototype for animated concrete. The piece senses, computes, and interacts with the environment and visitors. It points towards the potential of embedded sensing and processing meta materials. The body of aggregate is cast in Ultra High Performance Concrete (UHPC) embedding networked electronic components. UHPC and electronic components form one aggregate which performs as an prototype for material embedded sensing-, computation-, and display-system.

A microprocessor controls a series of LED's embedded in the concrete. A series of animations can be depicted by the LED's. Their execution is influenced by the environmental luminance which is measured by photosensors. A circular feedback loop is established through the emittance of light by the LED's which is fed back into the system through photosensors.

Project Team:
Mirco Becker, Oliver Tessmann, David Seeland, Jan Alexander Wecker, Gregor Zimmermann

occasionally its former, state. James Watt's steam engines are early technical implementations of such a system.

Cybernetics is often defined as an interdisciplinary study of complex systems. In fact it is better described as a meta-disciplinary science. Instead of focusing on the interaction between different fields of research, cybernetics sought to provide descriptive and explanatory models of complex systems, independent from their physical nature.  Various fields of research like control systems, network theory, evolutionary biology and neuroscience contributed to the new science since the 1940s. Linking the output of a system with its input in a circular fashion is referred to as feedback, a term which became common in various fields. Cybernetics describes two sorts of feedback: Positive feedback is achieved when a system responds to a decreasing (increasing) system value by reinforcing this value. In contrast negative feedback counter steers a current value hence it tends to maintain a stable equilibrium.

In 1943 Warren McCulloch, a neurophysiologist and Walter Pitts, a mathematician published an article with the title "*A logical calculus of the ideas immanent in nervous activity*", which provided basic concepts for further brain theories (McCulloch et al., 1943). They showed that neurons transmit information by changing between two states only. A neuron either fires, meaning an electrical signal is propagated to another neuron or it is not. There is no state in-between. If a neuron receives impulses from other neurons it acts in a similar way, it fires or it fires not. McCulloch und Pitts conceived this activity of a brain cell as the calcula-

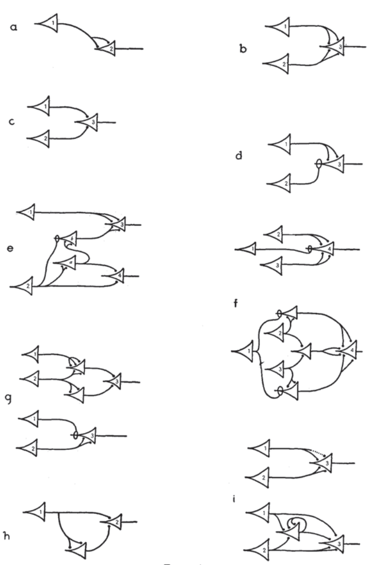



Figure 3.7: Diagrams of neural networks by McCulloch and Pitts, 1943

tion of a logic function. Based on this research it was possible to imagine neural networks that calculate all logic functions. The cerebral system was interpreted as a kind of calculator/computer that executes a logic calculus and thus the single neuron becomes one single operator that calculates logic functions. These ideas and mathematical models led to the construction of artificial neural networks. John von Neumann showed in his famous “First Draft of a Report on the EDVAC “ written in 1945, that the neural networks of McCulloch and Pitts and the Turing Machine displayed equivalent operators which would subsequently led to the first computers:

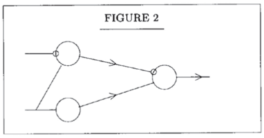



Figure 3.8: Network of “E-elements” based on McCulloch and Pitts notion of neural networks. John von Neumann, 1945.

> *“Following W.S. MacCulloch and W. Pitts [...] we ignore the more complicated aspects of neuron functioning[...]. It is easily seen that these simplified neuron functions can be imitated by telegraph relays or by vacuum tubes...” (von Neumann, 1982)*

The development of computers, based on research about the brain, initiated the computer-metaphor in cognitive science and the assumption that it is just a matter of time to come up with an artificial brain that resembles the human brain. Besides this, in retrospect, overambitious and not yet achieved goal the research paved the way for computational methods and design procedures in many other fields such as engineering.

## 3.2 FEM - A computational design procedure

Cybernetics not only offered alternative explanatory models of complex systems in science but also contributed to a systemic approach in design. Cybernetic systems and the act of designing display certain similarities. Both pursue particular goals and are, at the same time, influenced by the feedback of this exploration. Designing is subsequently described as a recursive process, comprised of three steps: analysis, synthesis, and evaluation. Architectural design, in fact, needs to incorporate complex organizational and functional requirements and therefore constitutes a recurrent negotiation of analyzing existing and requisite conditions as well as generating and evaluating possible responses. Additional knowledge gained through such iterative processes may require further analysis of the specific context or even the adjustment of previously defined design objectives (Lawson, 2006).

In 1960 the term finite element method (FEM) was first used by Clough (Clough, 1960) in a paper on plane elasticity problems. The increasing complexity of civil and mechanical engineering as well as aeronautical design problems of shell-type structures reinforced by ribs demanded new structural models and design procedures. While structures like lattice trusses, with a finite number of elements

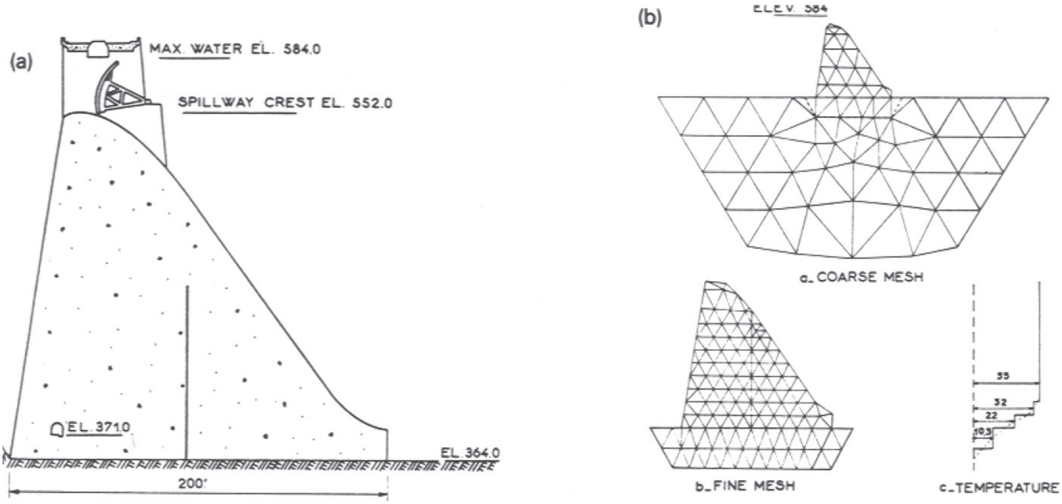



Figure 3.9: Ray W. Clough's proposal to perform a finite element analysis of Norfork Dam in 1961, which suffered a temperature induced vertical crack. The program automatically created a coarse mesh of the dam cross section followed by a nonlinear solution of crack closing due to hydrostatic loading (Clough, et al., 1990).

and interconnections points, could be calculated in the 1930's, elastic continuum structures with an infinite number of interconnection points demanded new design procedures. The finite element method discretizes such a continuum into a finite number of elements with various shapes and sizes thus the problem reduces to that of a conventional structure.

The numerical analysis technique delivers approximate solutions for many engineering problems ranging from structures to computational fluid design (Huebner, 1975). Solving partial differential equations was certainly a standard technique before the 1960's, but only the computer was able to tackle the sheer quantity necessary to achieve meaningful approximations. Thus FEM, first of all, is an analytical technique that provides numerical simulations of envisioned or existing structures as exemplified by the Norfork Dam study (Figure 3.9). The concept of circularity and feedback, at that time discussed in cybernetics and GST, could not yet been integrated into structural design procedures. It should take another ten to twenty years until optimization procedures like Genetic Algorithms converted the finite element method from an analysis tool into a design tool by evaluating and ranking analysis data and feeding it back into the systems for successive iterations. This delay in implementing new scientific insights parallels and confirms William Addis' observation that the coeval body of scientific knowledge is not instantly available in practices such as engineering (Addis, 1990).

In a linear design procedure the structural performance of an envisioned structure can be analyzed, but the result not necessarily provides any information on how to improve the design in case of unsatisfying outcomes. A circular configuration, in contrast, that takes such outcomes as the new input of the system promises to turn the analysis tool into a design tool (Huebner, 1975). Replacing traditional trail-and-error approaches requires the implementation of fitness functions, selection criteria, and design parameters that become the objective of stochastic or directed modification. Feedback loops allow the evolution of an initial design, a strategy that was further refined in the 1980's in form of Genetic Algorithms. Those algorithms are based on mimicry of the process of evolution, which leads to the effect, that through the accumulation of small improvements over time the maintained solutions gradually converge towards the defined criteria. Inheritance of specific properties, from one generation to the next, guarantees development instead of mere random versioning.

The cybernetic concept of circularity thus provided a methodological framework for optimization techniques in engineering.

## 3.3 Second-order cybernetics

Besides the application of cybernetic principles in technical and military systems like thermostats and air anti-aircraft warfare, a group around Heinz von Foerster focused on epistemological and theoretical questions heavily influenced by the science of neurophysiology. Based on the research of Warren McCulloch, Norbert Wiener, and John von Neumann amongst others who initiated cybernetics, Heinz von Foerster focused on self-referential systems as an explanatory model for complex phenomena. In his numerous publications and lectures he challanged the mechanistic approach of the rationalist tradition and its notions on the relation of subject and object. Advances in neurophysiology and neuropsychiatry by Warren McCulloch, Humberto Maturana and others led to a shift of interest from the looking at things out there to the looking at looking itself. The terms of second-order are reflexive and accept that asking questions about consciousness and cognition require consciousness and cognition of the questioner:

> *'… a brain is required to write a theory of a brain. From this follows that a theory of the brain, that has any aspirations for completeness, has to account for the writing of this theory. And even more fascinating, the writer of this theory has to account for her or himself. Translated into the domain of cybernetics; the cybernetician, by entering his own domain, has to account for his or her own activity. Cybernetics then becomes cybernetics of cybernetics, or second-order cybernetics.' (Rey, et al., 1991).*

Thus circularity and self-reference are fundamental aspects with regard to epistemology. Using a brain to explain and understand another brain creates a loop

Figure 3.10: Fixating the star with the left eye closed and moving the head until the appropriate distance will make the black spot disappear. While now moving the head parallel to the display, the spot remains invisible.

between object and subject. The subject starts to integrate itself into the explanation of the object. The subject becomes part of the world which it aspires to explain. Furthermore the whole purpose of the observation gains more importance because the way we ask questions often implies the possible answer already. Those ideas and concepts of second-order cybernetics led to the philosophical paradigm of radical constructivism promoted by Heinz von Foerster and Ernst von Glasersfeld. The terms of second-order are reflexive and accept that asking questions about consciousness and cognition require the consciousness and cognition of the questioner. A famous illustration of the concept of second order is the parable of the blind spot.

COGNITION → computations of

Figure 3.11: "…I propose to interpret cognitive processes as never ending recursive processes of computation, …." (von Foerster, 1973)

The local blindness is caused by the optic disc which is the location where all fibers exit the eye to form the optic nerve. When the black spot is projected to the optic disc we are obviously not able to see it. What is remarkable is that

> *"…this localized blindness is not perceived as a dark bloth in our visual field (seeing a dark blotch would imply "seeing"), but this blindness is not perceived at all, that is, neither as something present, nor as something absent: Whatever is perceived is perceived "blotchness". (Preiser, 1973)*

Heinz von Foerster thus concludes that rather than perceiving reality we construct it within our brain by a never ending recursive process of computation (ibid). Furthermore Humberto Maturana who was trained as a biologist and Francisco Varela introduced the term autopoiesis to characterize the nature of self-organization in living systems, which is perceived as determinate by its internal structure:

*„An autopoietic machine is a machine organized (defined as a unity) as a network of processes of production (transformation and destruction) of components which: (i) through their interactions and transformations continuously regenerate and realize the network of processes (relations) that produced them; and (ii) constitute it (the machine) as a concrete unity in space in which they (the components) exist by specifying the topological domain of its realization as such a network.“ (Maturana et al., 1980)*

In consequence the separation between object and subject and the rationalist requirement to abandon any properties of the observer from the description of his observations is unsustainable. Perception and cognition are heavily influenced by the internal structure of the human brain and at the same time they constitute the essence of observation. Heinz von Foerster thus distinguishes those who discover their world, like astronomers, physicists and engineers, from those who invent it, like family therapists, poets and biologists (von FOERSTER, 1991). The author agrees to this differentiation and proposes to add the architect to the list of those who invent their world.

Engineering design procedures extensively rely on formal systems that provide unambiguous results that depend only on the input. In case the input parameter and a suitable design procedure are known a problem is well-defined and solvable.  In architectural design many problems are not well-defined and suitable procedures have to be developed. Horst Rittel and Melvin Webber distinguish between ‘tame’ and ‘wicked’ problems which parallels Heinz von Foerster’s notion of inventors and discoverers.

## 3.4 ‘Tame’ problems and ‘wicked’ problems

While the separation of observer and the observed proved successful in many fields of science and in engineering, it fails when it comes to design problems which demand the generation of novelty and the integration of multifaceted, conflicting, and non-quantifiable aspects. Horst Rittel and Melvin Webber argue in the article “Dilemmas in a General Theory of Planning” (Rittel et.al., 1973) that science learnt to deal with ‘tame problems’ which are characterized by a definite and well described goal that has to be reached and a known strategy how to get there. Accurate criteria exist, telling the person in charge when a solution is found and the design process ends. Design tasks in the field of structural engineering are often conceived in a similar way. Brian Lawson (Lawson, 2004) cites an engineer defining design in the following way:

*The optimum solution is the sum of the true needs of a particular set of circumstances (Matchett, 1968)*

The “true needs” of a project are the required functions, which a design proposal has to fulfill. This approach of designing resembles the principles of rationalist scientific research: the observed ‘phenomenon’ is replaced by ‘required functions’. Instead of an ‘explanatory hypothesis’ a ‘design proposal’ is tested and ranked against the previously defined requirements. Finding the ‘optimum solution’ implies that the performance of a generated design proposal can be quantified by numbers, a procedure similar to the observation of an experiment and its determined behavior. Following Rittel and Webber, only ‘tame’ problems can be solved that way.

In contrast ‘wicked problems’ have no definite formulation, no stopping rule; their solutions are not true-or-false but rather good or bad. Furthermore Rittel and Webber list criteria that emphasize the subjective understanding and approaching of a design problem.

> *“Problems can be considered to be a symptom of another problem”, (ibid.)*

Thus they are part of a more complex system. The nature of the problem can be described in several different ways depending on the subjective perspective of the person in charge, leading to different solution strategies. Solutions are ranked by ambiguous criteria based on individual interests. Rittel and Webber’s problem description indicates a notion which resembles positions of radical-constructivism and second-order cybernetics. Both see a need for this notion because:

> *“…the classical paradigm of science and engineering - the paradigm that has underlain modern professionalism - is not applicable to the problems of open societal systems.” (ibid.)*

Scientific or engineering problems can be fully formulated. Bridging a canyon or optimizing structural systems towards an efficient use of material are clearly stated goals. Most often a formalized method provides a strategy to generate a solution. ‘Wicked’ problems require recursive loops between problem understanding and problem resolution. Asking a question in order to gain additional information requires the understanding of the problem. Understanding the problem “depends upon one‘s idea for solving it.” (ibid.). Faced with such ‘highly constraint situations’, as Jane Drake calls them (Drake, 1978), a design proposal is most probably not derived from a preceding analysis only. The quality of a project and its repercussions cannot be anticipated in advance and not all given constraints can be considered in the first proposal. Interviews with architects conducted by Drake revealed that designers rather tend to approach a complex problem by generating a relatively simple idea to narrow down the range of possible solutions and construct and analyze a first scheme accordingly. Lawson describes this process as

> *“…first decide what you think might be an important aspect of the problem, develop a crude design on this basis and then examine it to see what else you can discover about the problem.” (Lawson, 2006)*

Conceiving design as a solution-focused process is reinforced by the common practice of architectural design competitions. Competitions invite architects to develop proposals based on detailed briefings which represent a major part of an analysis of the existing situation. Nevertheless every competition reveals as many solutions as there are participating architects. The very personal understanding of a problem and the idea upon a possible solution plays a major role in planning and designing. A personal language or style of an architect can be considered as individually formalizing a method to approach and solve problems.

Rittel and Webber conclude that:

> *“The formulation of a wicked problem is the problem! The process of formulating the problem and of conceiving a solution (or re-solution) are identical, since every specification of the problem is a specification of the direction in which a treatment is considered.” (Rittel et al., 1973).*

In consequence a wicked problem cannot be broken down and solved in subsequent discrete steps of analysis, synthesis and evaluation but rather unfolds as a dialog between different parties involved including their subjective points of view. The results of such discussions provide solutions that cannot be judged as true or false. While the outcome of mathematical calculations can be described with unambiguous criteria, the classical logic cannot be applied to all aspects of design proposals.  A solution is judged from a subjective perspective as rather good or bad.

Heinz von Foerster takes the same line when he distinguishes the decidable from the undecidable questions.

> *“Only those questions that are in principle undecidable, we can decide.” (von Foerster, 1991).*

Von Foerster sees a choice of a particular framework in which one asks a question as crucial for the kind of answer one receives. The decidable questions are already decided by the framework no matter how many steps it takes to come to an answer. Decidable questions are those that can be answered by using an existing framework or formalism to come to unambiguous answers by flawless deductions. In mathematics the Principia Mathematica by Bertrand Russell and Alfred North Whitehead, written between 1900 and 1910, was supposed to erase every any ambiguity, contradiction, and undecidable of the discipline (ibid). In engineering ambiguity emerges when design procedures and models lack precision in representing physical behavior of structures. A major effort was spend in the last 300 years to close this gap as tight as possible and computational power was a very welcome and influential means to achieve this goal.

## 3.5 The programmable machine

The computer as the universal machine is coalescing mechanization, formalization, and logic into one coherent system and thus represents the spearhead of rationalist thinking and our scientific tradition. The strict formalism raised the question if novelty generation is possible through the use of algorithmic thinking. Or does a choice of a particular framework in which one asks a question already determine the kind of answer one receives?

The programmable machine, which is controlled by software and not by hardware anymore, describes data and program with the same set of symbols. Both are stored in the same memory and thus are able to shift their relationship to each other. The structure of systems and the information exchange between the elements of systems define the behavior of such a machine. Those complex relationships between symbols led to several concepts which exceed determinability and the mere cause and effect paradigm.

In 1936 Alan Turing describes in his paper “On Computable Numbers, with an Application to the Entscheidungsproblem” for the first time, the concept of the Turing Machine. This abstract symbol-manipulating device was never intended to be physically built but instead it was supposed to simulate the logic of any machine/computer.

> *“We may compare a man in the process of computing a real number to a machine which is only capable of a finite number of conditions q1, q2, ..., qR which will be called “m-configurations”. The machine is supplied with a “tape”, (the analogue of paper) running through it, and divided into sections (called “squares”) each capable of bearing a “symbol”. At any moment there is just one square, say the r-th, bearing the symbol S(r) which is “in the machine”. We may call this square the “scanned square”. The symbol on the scanned square may be called the “scanned symbol”. The “scanned symbol” is the*

*only one of which the machine is, so to speak, "directly aware". However, by altering its m-configuration the machine can effectively remember some of the symbols which it has "seen" (scanned) previously. The possible behaviour of the machine at any moment is determined by the m-configuration qn and the scanned symbol S(r). This pair qn, S(r) will be called the "configuration": thus the configuration determines the possible behaviour of the machine…" (Turing, 1936)*

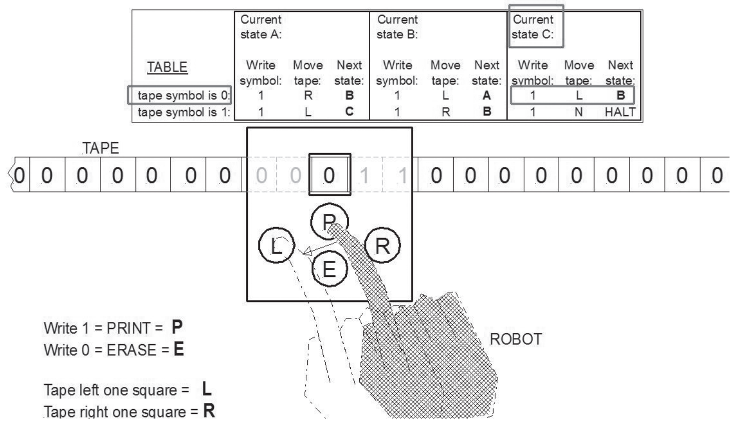



Figure 3.12: Diagram of the Turing Machine

The Turing Machine is one crucial milestone in the human effort to further abstract of the notion of machines. The computer as the universal machine coalesces mechanization, formalization, and logic into one coherent event. Formalization is an important concept in making knowledge accessible to a broad audience. Scientific knowledge for e.g. is formalized in a way that everyone who is able to read the code and follow the instructions will be able to comprehend and reconstruct common knowledge. Holling and Kempin refer to such formalized knowledge as 'implemented theory' (Holling et.al., 1989). Computer science uses the term implementation as the transformation of an algorithm (formalized instructions) into a particular programming language and a specific program. Holling and Kempin regard the 'implemented theory' as the major type of theory in occidental thinking and science. Today science is almost exclusively operated by programmable machines, which was only achievable through preceding developments of formal models and calculus. Formal models allow the description of problems and tasks as successive operations that can in principle be executed by machines. The necessary language is provided by occidental logic which was completely formalized by George Boole in the 19th century. Alan Turing subsequently provided the abstract machine to operate calculus. The computer finally embodies the actual machine. In contrast to the preceding calculating machines the computer is in-different regarding its hardware. The question is not ‘what is this machine made of?’ but ‘which program is this machine executing?”. The computer becomes the cybernetic machine which embodies a concept similar to that described by Ross Ashby in 1957:

> *Cybernetics, too, is a “theory of machines”, but it treats, not things but ways of behaving. It does not ask “what is this thing?” but “ what does it do?” (Ashby, 1957)*

In consequence the software defines and controls the functionality of the machine. Changes in functionality can be made without interfering with the physical structure of the hardware. Software is described by algorithms which calculate in consecutive steps new values on the basis of given input values. Every step is comprised of a defined number of executable, deterministic operations. Ambiguity is impossible within an algorithm, a requirement which proves painful for every newcomer in programming.

## 3.6 Determinism versus predictability

Algorithmic procedures constitute an unambiguous causal chain that seems to lack the potential apparent in a process of becoming (Trogemann et al., 2005). Despite the start condition or input parameters all the questions are already answered by the algorithmic framework which acts as a trivial machine (von Foerster, 1970).

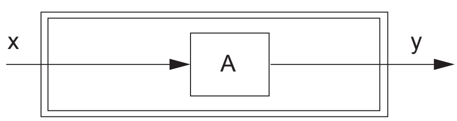
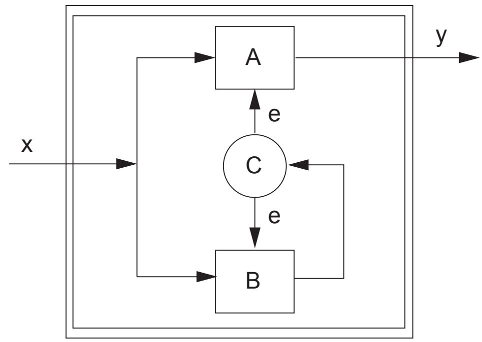



Figure 3.13: Diagram of a trivial machine

Trivial machines associate a specific input to a corresponding specific output. This relationship is determined and thus predictable and analyzable by an observer. The internal state of the trivial machine is unchanged and is independent from its previous state. The majority of machines and formalized systems in the everyday world are trivial and therefore predictable. Structural design procedures have to be predictable to provide correct assumptions of the behavior of structural systems in the physical world.

In contrast, the nontrivial machine is changing its internal state during runtime, that is, different functions are realized in relation to the history of the machine. Chipper machines, for instance, are nontrivial machines. The German engineer

Figure 3.14: Diagram of a non-trivial machine




Arthur Scherbius developed a nontrivial machine, later known as Enigma, which is comprised of two trivial machines. While machine A is processing input (x) to output (y), machine B is processing input (x) to an internal state (u). However the internal state (u) has additional influence on A (execution procedure) and B (reading procedure) thus a feedback system is established. Machine A acts on the basis of the previously ‘experienced’. Machine B reads dependent on what was previously read. Non-trivial machines embody at least one second-order rule, that is, a currently active rule is transferred into another rule which is active in the next iteration. Like the trivial machine, a non-trivial machine is unambiguously defined but in contrast its current behavior depends on a former state. Even so the machine is determined by its construction; the outcome is unpredictable if the inner state of the machine is unknown.

Non-trivial machines are formal systems which are not able to exceed their framework but nevertheless the output is not only defined by the input but also by the internal state of the machine. The questions are not decided until the machine goes through the entire process of calculation. Furthermore computational power enlarges the space of possible solutions.

When programming and scripting migrated into the field of design exploration those non-trivial machines attracted attention. Operating on the symbolic level of a programming language made custom-written algorithmic procedures accessible as generative means in 3D modeling environments. Evolutionary Algorithms, neural networks, cellular automata, non-periodic tilings etc. represent formal systems which carry their potential within the process of becoming which cannot be skipped. An overview of the use of those procedures in a creative environment is given in the book CodeArt by Georg Trogemann and Jochen Viehoff (Trogeman et al, 2005).

# 3.7 Experiments of algorithmic design exploration

The author explored a range of concept in research, practice and teaching. The second case study presented in this thesis utilizes an Evolutionary Algorithm to improve a space frame structure. Several additional experiments are shown the next paragraph.

### 3.7.1 Cellular Automata

In a diploma thesis, supervised by the author, Thomas Wortmann developed a design proposal for the National Library in Prague. He chose a cellular automata as design procedure. The concept of Cellular Automata is described by five basic terms: 'cell', 'grid', 'state', 'rule', 'neighborhood'. In an n-dimensional grid cells can have different states. Those states are defined by simple rules that describe the behavior of the cell in relation to the state of the neighboring cells. Every cell is an automata which permanently calculates its state based on local properties. Various stable, periodic or chaotic pattern emerge out of this self-organized behavior. The concept of Cellular Automata was first mentioned by John von

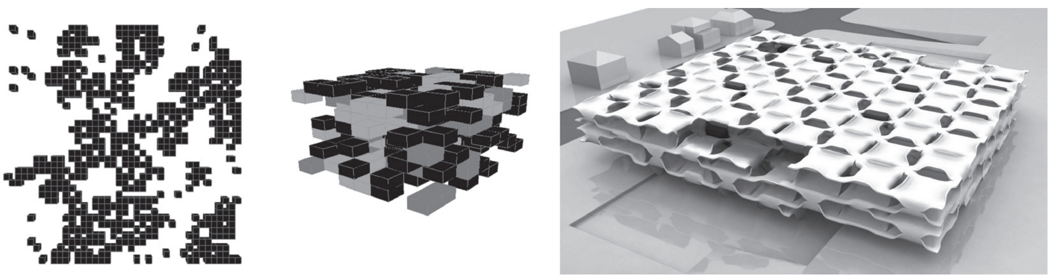


Figure 3.15: Conway's Game of life (left), Clustering of three dimensional cells, proliferation of different modules, rather representing the program and its internal relations than a final design proposal, Wortmann 2007.

Neumann in the 1940s in one of his manuscripts with the title *'The theory of Automata: Construction, Reconstruction, Homogeneity' (von Neumann, 1966).*

Cellular Automata are proper means to explore complex systems and represent network relation by simple rules. John Horton Conway's "Game of Life" (1970) and Thomas Schellings "Dynamic Models of Segregation" (1971) served as role models for the functional organization of the complex library program.

### 3.7.2. Recursion

The cybernetic concept of circularity is furthermore reflected by recursive functions. Those functions are able to call themselves repetitively until a certain condition is fulfilled. Recursive functions were used by the author to implement a L-System for  a tree-like structure and a fractal panelizing strategy.

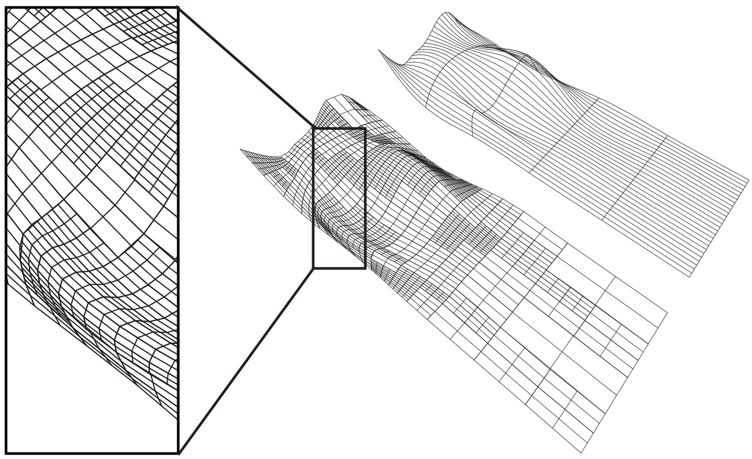
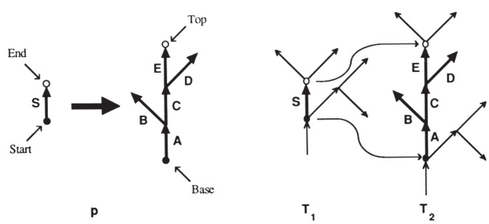


Figure 3.16: Panelizing procedure implemented by the author. A recursive function subdivides a NURBS surface in planar quads. Subdivision procedes in a fractal manner until a predefined planarity is achieved.



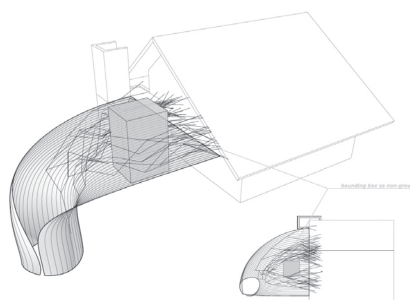
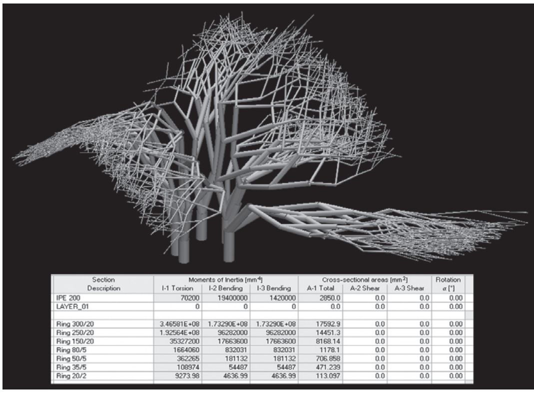



Figure 3.17: Diagram depicting the general principle of a Lindenmayer System

Figure 3.18: Lindenmayer System along the uv-parameter of a NURBS surface. To overcome the two-dimensional notion of the surface the branches unfold along surface normals. Yellow boxes represent areas which should be free from elements. Branches that penetrate this volume are automatically deleted.



| Section Description | Moments of Inertia [mm⁴] I-1 Torsion | I-2 Bending | I-3 Bending | Cross-sectional areas [mm²] A-1 Total | A-2 Shear | A-3 Shear | Rotation α [°] |
|---|---|---|---|---|---|---|---|
| IPE 200 | 70200 | 19400000 | 1420000 | 2850.0 | 0.0 | 0.0 | 0.00 |
| LAYER_01 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.00 |
| | | | | | | | |
| Ring 300/20 | 3.46581E+08 | 1.73290E+08 | 1.73290E+08 | 17592.9 | 0.0 | 0.0 | 0.00 |
| Ring 250/20 | 1.92564E+08 | 96282000 | 96282000 | 14451.3 | 0.0 | 0.0 | 0.00 |
| Ring 150/20 | 35327200 | 17663600 | 17663600 | 8168.14 | 0.0 | 0.0 | 0.00 |
| Ring 80/5 | 1664060 | 832031 | 832031 | 1178.1 | 0.0 | 0.0 | 0.00 |
| Ring 50/5 | 362265 | 181132 | 181132 | 706.858 | 0.0 | 0.0 | 0.00 |
| Ring 35/5 | 108974 | 54487 | 54487 | 471.239 | 0.0 | 0.0 | 0.00 |
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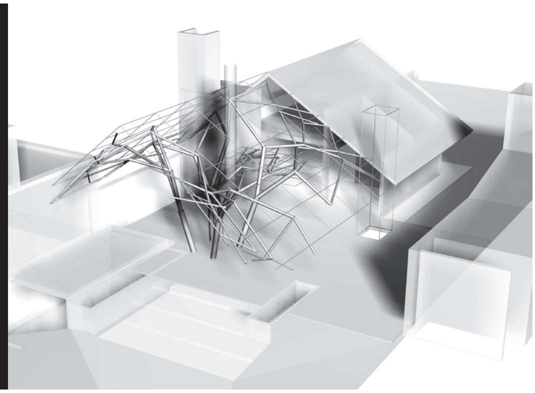


Figure 3.19: Structural model of the tree-like structure by Bollinger + Grohmann.

Figure 3.20: Lakehouse Patagonia. Design proposal as envisioned by the architects (ArchiGlobe, Johan Bettum, Luis Etchegorry). The author developed and provided the algorithmic tools for design exploration and the generation of structural models.

# 4. Designing Design Procedures

As described above the realm of engineering experienced an increasing improvement of structural design procedures and analysis methods in terms of the precision and approximation of physical behavior. But David Billington points out that the ever more complex mathematical formulations for the calculation of barrels and domes, developed in Germany in the 1920s, limited the formal repertoire rather than extending it.

Meanwhile engineers like Nervi, Torroja and Maillart liberated their thin shells in terms of formal expression as well as the dependence on formulas (Billington, 1985). Leading figures of the discipline denied a mere analytical and formalized approach and focused on simple calculations and observations of physical behavior. This was either because an architectural design proposal required a structure which could not be calculated with existing design procedures or general formalized procedures proved too cumbersome to apply in a design process.

Furthermore the notion that engineering is a matter of putting theory into practice was consciously rejected and the focus on the quantitative aspects of design was criticized:

> *"The pre-eminence given to mathematics in our schools of engineering, the purely analytical basis of the theory of elasticity, and its intrinsic difficulties persuade the young student that there is limitless potency in theoretical calculations, and give him blind faith in their results. Under these conditions neither students nor teachers try to understand and to feel intuitively the physical reality of a structure." (Nervi, 1956)*

Felix Candela expresses a similar opinion:

> *"…all calculations, no matter how sophisticated and complex, cannot be more than rough approximations of the natural phenomenon they try to represent by means of a mathematical model…" (Candela, 1973)*

Moreover the gap between actual structure and its formalized representation in general mathematical theory contributed little to stimulate design innovations.

## 4.1 Isler's shells

Heinz Isler, in contrast, developed his own design procedure which relied on physical form-finding. A large number of his realized concrete shells are based on a form that is derived from stretched cloth, coated with plastic, and held at several points. The cloth sags and after the plastic hardens the inverted form makes a thin shell roof which is exclusively exposed to compression forces.

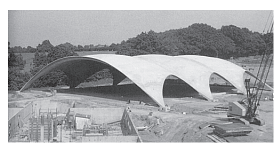


Figure 4.1: Tennis Center by Solothrun, Heinz Isler.

Certainly, Isler was not the first to use form-finding. The most famous precursor is probably Antonino Gaudi, who generated hanging models comprised of wires with attached weights to derive the complex vaults for the Colonia Guell. Although the structural properties of a single catenary arc are easy to calculate by rules of thumb, the complex configuration of stacked arches and vaults could not be predicted by contemporary structural design procedures. The hanging model provided the geometry of segmented catenary curves that were loaded by tension forces alone. The inverted structure thus could be built from stone without any horizontal thrust and therefore without any flying buttresses recognized in Gothic structures. The model served not only the structural exploration but was also used by Gaudi to render the interior by painting on top of photographs of the inverted hanging model. The translation of the wires into actual material could not be derived from the model but relied on additional procedures that were rather driven by constraints of model makers and masons (Johnson Sweeney et al., 1960).

Isler's cloth and plastic models closely approximate the full-scale concrete shells. The material system comprised of cloth fibers and a plastic matrix resembled the reinforced concrete shells, an additional translation step was not necessary. David Billington conceives these design procedure as the opposite of the above described formalized systems:

> *"Isler's game is not like chess, which the computer can handle, but rather a game of solitaire played on a board with no fixed boundaries: each game has new borders which shift with the play and no one else makes any moves. It is a lonely business, and when Isler is at work on a new design he is always alone…" (Billington, 1985).*

The author only partly agrees with Billington's position because the range of possible forms is determined by the choice of framework and materials with which the process is conducted. Nevertheless, the procedure proved extremely successful in terms of the structural performance of the shells. The unprotected concrete structures suffered no serious cracks or leaks and the smoothness of the surface closely resembles the cloth and plastic model. But as Billington states above, Isler's design procedure is not a collaborative one, thus it is not surprising that the most successful projects are those that have been developed by Isler alone. In a project for a school in Chamonix, the overall shape of the roof shell was previously defined by the architect, which finally led to extremely strong edge ribs and a loss in lightness. The design procedure better suits tasks that belong to the category of structural art rather than architecture, which is less constrained by program but rather driven by the largest impacting force (ibid.).

## 4.2 The Multihalle Mannheim

The grid shell of the Multihalle Mannheim by Ove Arup & Partners and Mutschler + Partner with Frei Otto is another example of a form-finding through the use of hanging models. The shell was derived from a suspended net that is free from any moments and forces except tension. Like Isler's cloth and plastic models the net refers already to the construction logic of the full scale project. The shell was built using a double-layer grid of timber laths connected with sliding joints.

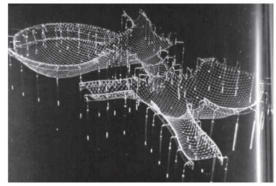


Figure 4.2: Hanging model of Multihalle Mannheim by Frei Otto

Isler's and Otto's projects stand out due to their level of integration. Structure and skin merge into one single layer. Geometry is not conceived as a transcendental force that regulates a formless material but instead the capacity of self-organization of material systems under the influence of extrinsic forces which is exploited to generate form. The shells of Nervi, Candela, Torroja, and others display a similar approach (ibid.).

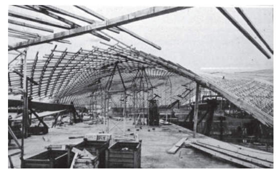


Figure 4.3: Construction of Multihalle Mannheim. The double-layer timber grid was laid out flat and subsequently lifted into the final shape.

Ove Arup assumed the reason for the excellence of Candela's works was due to him combining architect, engineer and contractor in one person, with a clear dominance of engineering over architecture. He believed that the creative process needs to be synthesized in one mind, which is aware of all aspects relevant to a project's success (Arup, 1963). Interestingly Ove Arup & Partners was working on the Sydney Opera House with Jørn Utzon at that time and the engineers were struggling with the complexity of the projects for several years already. Architecture usually is a product of a collaborative effort which distinguishes it from structural art, best exemplified by the Sydney Opera House.

## 4.3 The Sydney Opera House

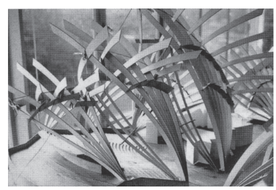


Figure 4.4: Scale model of parabola-shaped rips by Jørn Utzon

Jørn Utzon's shells were unprecedented even though many shells had been built before. But those earlier projects obeyed the laws of structural art as defined by David Billington: Large scale projects with mono-functional program driven by the impacting forces (Billington, 1985). In contrast Utzon's shells were supposed to cover a large number of irregular spaces organized on a narrow site. The initial roof, as envisioned by the architect, was formed by two parabola-shaped shells that lean against each other to form ogival arches. The proposal would have caused huge bending moments and appeared to be physically impossible. Arup's engineers instead advocated for a form that was derived from structural considerations and costs. A double-curved shell covering one or both halls would have solved most engineering problems but was rejected by the architect, which led to a four year period of extensive analytical work and model tests. Finally Utzon changed the initial design by proposing to derive all the shells from one potential sphere which would cut down formwork cost by a significant amount. The dramatic turn made thousands of hours spent on the development of new design procedures and analyzing method useless for the ongoing project. Furthermore Ronald Jenkins one of Arup's partners resigned from the project (Fromonot, 2000). William Addis regards the development and testing of new design procedures as the major achievement of the project. Relying on previously established formalized systems and design procedures was impossible due to the architectural specifications by Jørn Utzon. The development of new procedures turned out to be a major part of the work (Addis, 1990).

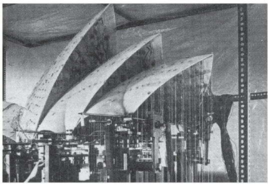


Figure 4.5: Load test conducted with a physical model due to the absence of a proper calculation method by Arup.

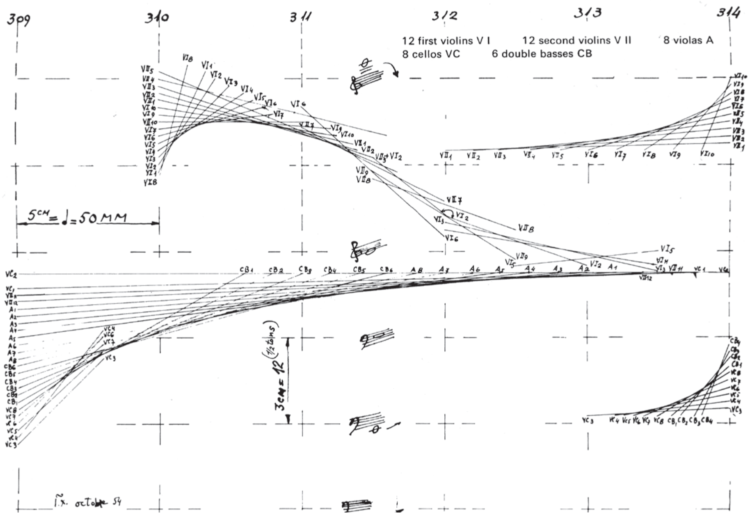
William Addis' remark refers to the act of gaining insights and subsequently formalizing them into procedures which can be applied by others, generating reproducible results. The very act of designing is shifted from the design of an object to the design of a design procedure through abstraction, formalization, and mechanization. The utilization of established procedures can be conducted following the notion of the rationalist scientific tradition which insists on the separation of subject and object. Designing a design procedure, in contrast, requires certain decisions which rely on the experience, education, and skills of the designer/ engineer. Abstraction means that certain aspects of a problem are regarded as important to integrate into a model while others appear irrelevant and are subsequently dismissed. If there is no procedure for this process of differentiation the designer has to decide what is relevant and what is not. In the words of Heinz von Foerster, these questions are not decided in advance by any framework but have to be answered by the designer. Designing design procedures thus becomes an example for the famous dictum of second-order cybernetics that the system cannot be separated from the object.

## 4.4 The Philips Pavilion

Figure 4.6: Philips Pavilion at the World's Fair 1958 in Brussels by LeCorbusier and Iannis Xenakis

In 1958, one year after Utzon's competition entry was awarded first prize, the Philips Pavilion at the World Fair in Brussels that was designed by Le Corbusier with Iannis Xenakis opening its gates to the public. The temporary building was comprised of an integrated play of shells that followed a stomach-shaped floor plan. The ruled surfaces of the pavilion walls resemble a graphical representation of the musical composition, Metastasis by Xenakis from 1953.

Impressed by the numerical proportions of the Modulor, Xenakis applied its divisions to control the succession of tempered intervals two years prior to the design of the pavilion (Figure 4.8). The diagram of glissandi (sliding sound) from Metastasis most probably served as an early prototype for the hyperbolic and conoid surfaces. An early physical model transferred the diagram into three dimensions while maintaining the initial idea of successive linear elements represented as piano wires (Figure 4.7). The crude model not only indicated the complex geom-



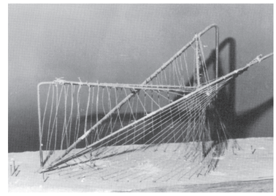



Figure 4.7 (top): Early scale model of the pavilion, a spatial translation of the two-dimensional diagram of Metastasis by Iannis Xenakis, 1953

Figure 4.8 : Graphical representation of a musical composition

etry of the pavilion but also its prestressed construction.

Of particular interest is the multiple repurposing of the Modulor as a formalized system to derive harmonic proportions. Developed by Le Corbusier to discover mathematical proportions in the human body (Le Corbusier, 1956), Xenakis rather used the system to compose music. Its graphical representation in turn reverberates back into an architectural design and links both realms through mathematics.

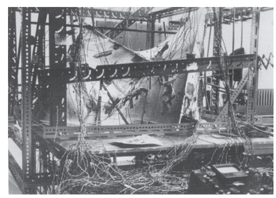


Figure 4.9 (top): Scale model connected to measurement devices

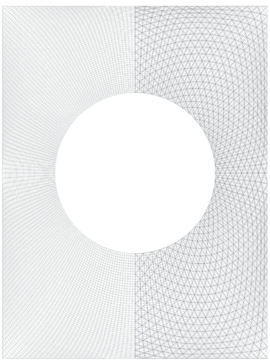
Figure 4.10: Load test with sand bags and engineers

Similar to the Sydney Opera House the curved geometry which carried already a certain structural potential was refined and adjusted towards structural and architectural requirements. In contrast to the architects, the engineers had no design procedure at hand to calculate the complex geometry. Even though the calculation of stresses on shells had improved in the 1950s, no mathematical means provided the possibility to determine the structural behavior of the pavilion (Treib, 1996). Instead the structural system was explored using physical scale models which could be exposed to external loads. Strain gauges were connected to measurement devices and polarized light was used to ascertained stresses in the panels. The design procedure reflects the work of Antonino Gaudi who pioneered the use of physical models to explore and find forms. Furthermore he used similar geometrical concepts to suit the constraints of craftsmen. Nevertheless Gaudi's design procedure merely served as a starting point for an increasingly sophisticated procedure.

In both projects, the Sydney Opera House and the Philips Pavilion, an architectural design proposal preceded the structural design in contrast to the shells of Isler, Candela and others. Thus new design procedures had to be developed or earlier established ones needed to adapt to the new requirements.

## 4.5 The British Museum courtyard roof

A computational successor of the physical form-finding procedures by Otto, Isler, and others is exemplified by the courtyard roof of the British Museum by Foster & Partners in collaboration with Buro Happold. The existing buildings formed a highly constrained context. Loads of the new roof could only be taken above the façade cornice and horizontal thrust had to be directed towards edge beams in the corners. Large spans and the asymmetrical position of the central reading room contributed to the complexity of the design task.



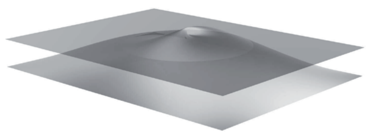


*Figure 2. Level change function,*

$$\frac{\left(1-\frac{x}{b}\right)\left(1+\frac{x}{b}\right)\left(1-\frac{y}{c}\right)\left(1+\frac{y}{d}\right)}{\left(1-\frac{ax}{rb}\right)\left(1+\frac{ax}{rb}\right)\left(1-\frac{ay}{rc}\right)\left(1+\frac{ay}{rd}\right)}$$

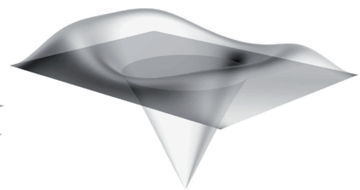


*Figure 3. Function with finite curvature at corners*

$$\left(\frac{r}{a}-1\right)\left(1-\frac{x}{b}\right)\left(1+\frac{x}{b}\right)\left(1-\frac{y}{c}\right)\left(1+\frac{y}{d}\right)$$

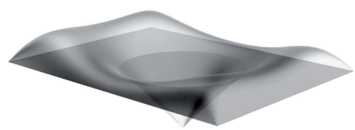


*Figure 4. Function with conical corners*

$$\frac{1-\frac{a}{r}}{\frac{\sqrt{(b-x)^2+(c-y)^2}}{(b-x)(c-y)}+\frac{\sqrt{(b-x)^2+(d+y)^2}}{(b-x)(d+y)}+\frac{\sqrt{(b+x)^2+(c-y)^2}}{(b+x)(c-y)}+\frac{\sqrt{(b+x)^2+(d+y)^2}}{(b+x)(d+y)}}$$

Figure 4.11 (top): Relaxed grid hosted by a design surface by Chris Williams

Figure 4.12: Discretized surface described by a series of mathematical functions by by Chris Williams

http://staff.bath.ac.uk/abscjkw/BritishMuseum, 2008)

The consulting engineer Chris Williams approached the task by defining a design surface for the steel grid due a mathematical description which takes the existing constraints into account. The homogeneous triangulated steel grid could only be achieved by the use of dynamic relaxation, a computational technique that shifts every node of a grid incrementally, until the length of the members between the nodes tends to an equal dimension. The iterative process represents the length of a member as a force, the longer the length, the higher the force in the member. During relaxation the entire system seeks to attain equilibrium by homogenously distributed forces. The procedure bears certain similarities with the self-organizing processes in material systems in its pursuit for equilibrium. At the same time limiting constraints, like a design surface, can originate from sources different than extrinsic forces, which help to negotiate architectural and structural requirements.

## 4.6 The Take Off node

The design of a structural node for the 'Take Off' project exemplifies an approach to converge architectural and structural requirements through a back-and-forth data exchange between the generative and the analytical softwares.

Figure 4.13: Take Off object suspended from the terminal ceiling by Franken Architekten and Bollinger + Grohmann

'Take off' is an installation in terminal 2 of Munich airport by Franken Architekten that aims to anticipate the acceleration, speed, and dislocation of travelling. The structure consists of an array of 363 lamellas mapped with images on both sides and two load-bearing offset tubes. A visual-kinetic interactivity between object and passengers is generated simply by the movement of the observer without any physical movement of the object itself. The entire object is suspended from the ceiling of the terminal building. The cable suspension system is constrained by a multitude of parameters that define cable directions. The structural system of the building provided specific nodes that were able to bear the additional loads of the take off object. At the other end of the cables, the offset tubes had to be suspended at specific points to achieve equilibrium. Part of the space between the ceiling and the object is occupied by a mobile maintenance device which meant that the cables had to change direction: starting at the ceiling the cables were redirected and connected to specific nodes at the offset tubes. The redirection is achieved by a node that was generated in a cooperative approach of architect and engineers, both using different kinds of simulation software.

The architect aimed for a curved continuous change of direction: a rubber-like morphology that reflects the internal tension of the node. The node was generated with the help of animation software capable of simulating cloth behavior under the influence of external forces. Applied garment properties and tension forces generated a form that was later exposed to the actual forces of the node.

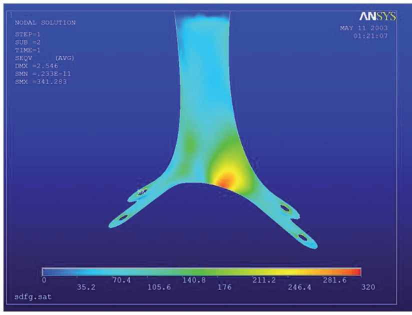


Figure 4.14 (left): FEM analysis of the node
Figure 4.15: Five different cable directions in different planes,

This structural simulation was carried out with Finite-Element software. In a manual iterative process the nodes were generated, analyzed and altered again in the animation software. This back and forth process went on until morphology and required structural performance converged.

This generation/analysis loop was carried out with manual data exchange and slight iterative adjustments done by hand in the animation software. Convergence was achieved by trial-and-error without using computational power to generate different versions of the node. The study exemplifies the cooperative design approach that seeks a convergence of formal and structural needs. Two different simulations of forces and material properties finally matched in one model. The optimization of fabrication was not incorporated into this process. The node was milled out of a solid block of steel.

## 4.7 The D-Tower

In contrast Lars Spuybroek (NOX), the architect of the D-Tower did not accept any change in shape. Thus a different approach to match structural performance with architectural design became necessary. A solution could finally be achieved using the differentiation of material. Anisotropic materials like reinforced concrete or glass-fibre reinforced plastics can be adjusted to locally changing stress values in complex shapes. For the realization of the D-Tower, FEM analysis was conducted by Gregor Zimmermann (University of Kassel, Department of Structural Design). The glass-fibre reinforced sculpture with a height of eleven meters coalesces architectural form, skin and structure into one single element. Simulation of form and material behavior under vertical and lateral loads led to a subtle differentiation in surface thickness between 4.5mm and 18mm and fibre orientation. The applied procedure is well-known from topology optimization procedures but thus adapted to the requirement of maintaining the initial shape and topology. Instead

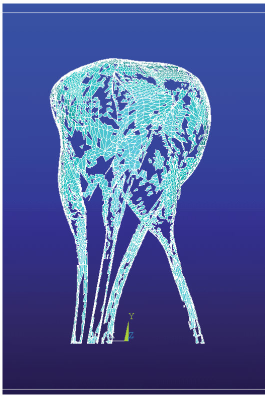


Figure 4.16: FEM model of the D-Tower. Topology optimization precedures were repurposed to differentiate material thickness by Gregor Zimmermann

Figure 4.17: D-Tower a glas-fibre reinforced sculpture in Doet-inchem, NL by Lars Spuybroek, NOX, 2001

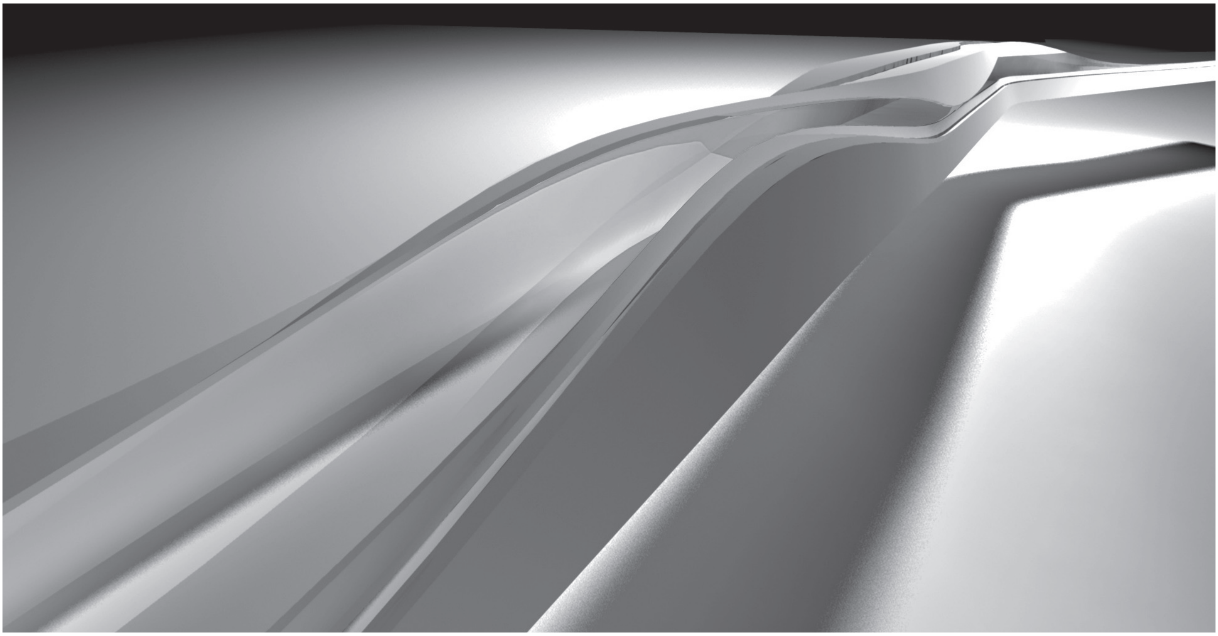
Figure 4.18: The illumination color represents the collective mood of the citizens surveyed by an online questionnaire

of deleting elements in the FEM mesh as shown in Figure 4.16 the information is used to locally differentiate the thickness of the skin so that the resulting objects did not need any further structural components.

The form-finding procedures of Frei Otto and Hans Isler provide a high level of integration. Structure, skin and overall form coalescing into one single object. Furthermore the material used in the original scale is already approximated by the form-finding scale model. The procedure is transferred to the digital realm by projects like the British Museum courtyard roof or the D-Tower which responds to additional constraints that are not necessarily derived from structural aspects. The author regards the presented work as precedents and inspiration for the first case study. In the experiment, an analysis software is repurposed as a form-finding device. Transferring this process into the digital realm allows the interfacing of this procedure with a 3D modeling environment to negotiate the results of form-finding with additional design criteria.

# 5. The case studies
# Form-finding, Optimization, Sizing

## 5.1 Technical prerequisites



Architectural concepts are predominantly represented through geometrical models in two or three dimensions. The repurposing of animation and special effect software during the mid 1990s introduced Non-Uniform BSplines (NURBS) modeling into the field and unleashed a previously unknown formal repertoire. Until then continuous surfaces could only be represented through physical models constrained by their particular material system, whereas NURBS curves and surfaces are defined by polynomial functions which offered a broad range of new shapes, while, needless to say, creating different limitations.

But creative stimulation occurred bi-directional: in the early 1990s the architectural discourse shifted from “linguistic and representational focus of both Post-Modernism and Derridean Deconstruction towards the spatial, artistic and mathematical models of Deleuze, Foucault, …” (Lynn, 2004) shortly before those novel digital tools conquered the discipline.  On the other hand 3D modeling was a suitable tool to easily represent those new ideas. In a lecture at the Städelschule in Frankfurt, attended by the author, Greg Lynn once expressed his relief discovering formZ during his engagement in the office of Peter Eisenman. The 3D modeling software should eliminate a significant amount of draftsmanship that was needed to display Eisenman’s iterative topological transformations of volumes. The interest in topological models thus originated from an academic discourse and luckily matched with affordable hardware and the migration of tools from other disciplines.

Structural design, as well, experienced the development of analysis software with increasing capabilities. Engineers today are able to evaluate rather complex design proposals emerging in the field of digital architecture. A design proposal has not necessarily to be decomposed to a basic structural system, but can be analyzed as an holistic model with a multitude of structural members and their intrinsic relations. Both, architect and engineers, use digital tools but the data input needs of engineers are different from the information produced by architects. NURBS surfaces, for instance, conveniently represent the topological approaches of architects like Foreign Office Architects and UN Studio which rather explore relations and dependencies than describing exact Cartesian dimensions. In contrast the conduction of structural analysis requires centre lines and discretized surfaces to evaluate structural performance. To improve a cooperative design approach of architects and engineers either an integrative digital model, incorporating all information, is needed or the process of deriving data from an architectural model and feed them into analysis software has to be streamlined. Leo Argiris, structural engineer and principal of Arup’s New York office states in an interview conducted by the author in February 2007:

> *“Structural engineers have been thinking three-dimensionally since the beginning of time. This is fundamentally nothing new in structural engineering. If you look at the evolution of analytical computational tools in engineering it became common to analyze three dimensional structures probably 25 years ago. About 15 years ago we are at the point where every structural engineer is regularly developing and analyzing three-dimensional structures. Those models were typically not linked to the architectural drafting tools. It was the matter of the engineers to understanding what was on the mind of the architect and then recreate that geometry in an analytical program. Those programs were initially numerically based and a matter of coding in geometry and then*

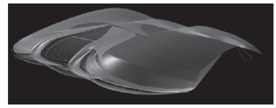


Figure 5.1.1:  Surface model of the Gatehead Music Center. Form-finding study for Forster and Partners. The team claimed:

*“...challenged to devise new ways of deriving such forms elegantly we didn’t so much ‘design’ the form as to create methods by which the form could find itself - as a series of forces acting on elastic surfaces. the slight indeterminacy of the process was nonetheless highly precise, since we worked with mathematicians and used highly accurate 3d engineering software.” (decoi, 1998)*

Design team: Mark Goulthorpe, Gaspard Giroud, Arnaud Descombes. Technical design: Mark Burry, Deakin University. Mathematical studies: Alex Scott.

Figure 5.1.2: Gateshead as build project. The specialist Modeling Group (SMG) at Foster and Partners rationalized the geometry. A series of torus patches with continuous translations generates a form which could be build by planar facade panels. (http://www.fosterandpartners.com)

*over the time developed graphical interfaces with all sorts of tools that made the generation of geometry easier. We arrived at a point, three to four years ago where most structural engineers are very comfortable with making and analyzing three dimensional models and doing what-if scenarios with those models. Today we are getting into the idea of linking analysis into the tool that are used as interface between architect and engineer and that's what is really different about where we are heading...There is development happening, but the tools are still relatively crude and have a long way to go to allow this back and forth interaction. We are using Maya and Rhino at the front end of the design on a very conceptual level where we think about massing and form, these are great tools for communication. But later on in the process when we are actually getting into construction documents we would use tools such as either Triforma© or Revit© which are three-dimensional modelling tools and they are very much focussed on getting construction documents in a three-dimensional environment but at the same time produce proper drawings. Revit©, for example, is not made for complex geometries but it's a three-dimensional tool that is very good for production of straight forward orthogonal models. What we really need is a tool that allows to span from the conceptional work due to the construction work in a single environment and that does not exist yet." (Argiris, 2007)*

In several studies conducted by the author for the engineering office Bollinger + Grohmann the data exchange process could be improved through the algorithmic descriptions of the structural system.

### 5.1.1 The Mariinsky Script

The design rules for the triangulated shell of the Mariinsky Theatre by Dominique Perrault in Saint Petersburg were algorithmically described and implemented into a Rhino Script which created a 3D centre-line model. In a second approach the parametric modeling software Generative Component© was used to describe the model with associative geometry. Both models derived from an architectural representation of solids and volumes lacking the centre lines of the structural members which were required for evaluation in RSTAB©, a stick model based structural analysis software.

The new Mariinsky Theatre is an extension to the existing historical building. It is wrapped into a crystalline golden shell that creates an impressive public space between theatre and the city used as lobby, restaurant, foyer and reception.

The shell is composed of 56 inward facing tetrahedrons creating a crystalline appearance. The outer faces act as a surface-active folded plate system. Each face of the tetrahedrons is subdivided into a series of primary and secondary structural beams. This kinetic system formed by the group of tetrahedrons is supported by insular pinned columns at roof and ground level, transferring the gravitational and lateral forces.

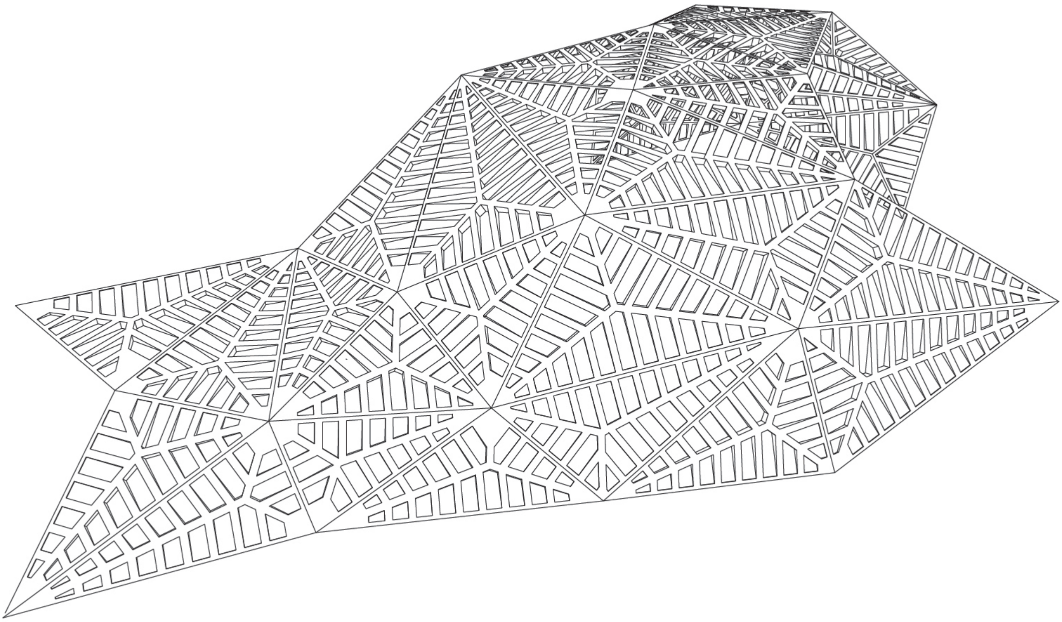


Figure 5.1.3: The shell is comprised of 56 tetrahedrons.

### 5.1.1.1 Design rules and implementation

The topology and structure of the prototypical tetrahedron is described by a set of precise design rules taking three vertices, one sloping angle and two beams distances as input. In six steps 420 structural members could be generated from these input parameters. The operation was tackled with using Rhinoceros© and its Application Programming Interface (API). Digital draftsmanship and time could be significantly reduced due to the automated process.

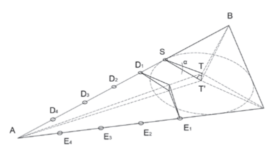



Figure 5.1.4: Diagram of geometrical principles

The approach resulted in a mere static representation of a possible solution. Geometric relationships defined and used during the generation process are not

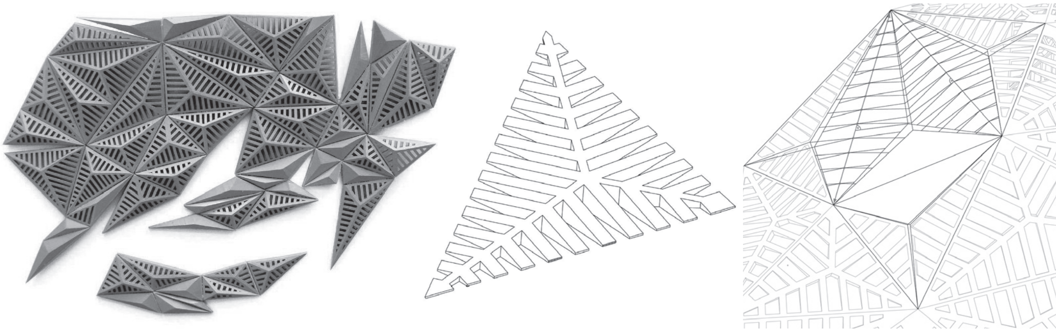


Figure 5.1.5: Physical and digital model of tetrahedron

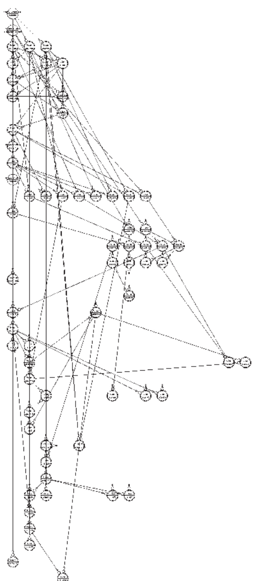


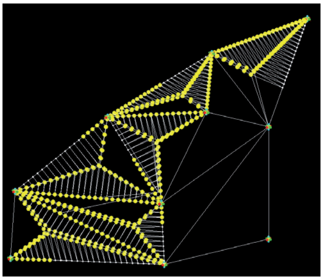
Figure 5.1.6: Generative Component Dependency Graph of one tetrahedron

inscribed in the finished model. Altering input parameters meant deleting the old and regenerating a new structure.

### 5.1.1.2 The parametric model

In a second approach Generative Components© (GC) was used to implement the tetrahedron structure. GC is a "model-oriented design and programming environment which combines direct interactive manipulation design methods based on feature modelling and constraints, with visual and traditional programming techniques" (Aish, 2004). The environment is based on the CAD application Microstation XM©. A single tetrahedron was modeled parametrically and defined as a component (GD feature). The component then serves as a generic prototype with defined input and output parameters which could subsequently be instantiated along the predefined shell geometry of the theatre. Thanks to the associative geometry changes in the design which did not exceed the parametric range could be dynamically fed into the model. Dynamic representation could be enhanced by defining global variables that control properties of the tetrahedrons like side beam distance and sloping angles of the faces. Changes of these variables affect all instances of the tetrahedrons which made dynamic changes and adaptations possible.

The geometry, generated in a CAD application, had to be transferred to RSTAB©. To maintain fluid automation during data exchange, the common procedure of sharing a DXF file was replaced by a custom-written Visual Basic Application (VBA) that interfaced the geometrical and the analytical model.  The Drawing Exchange Format is often used not to maintain information but as the least common denominator reducing information previously inscribed in the existing model. In contrast the VBA interface saves information added to every node during analy-



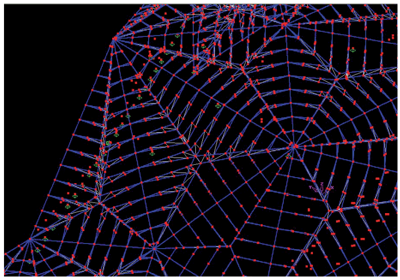


Figure 5.1.7: Generative Component model; Figure 5.1.8: Nodes and poles represented in RSTAB©

sis. Beyond mere coordinates a node number and its assigned poles are stored. A change of coordinates is possible without loosing the topological information of the structure.

## 5.1.2 Discretizing

Geometrical representations of architectural models generally lack information necessary for the description of a structural system. A Rhino© model consists of

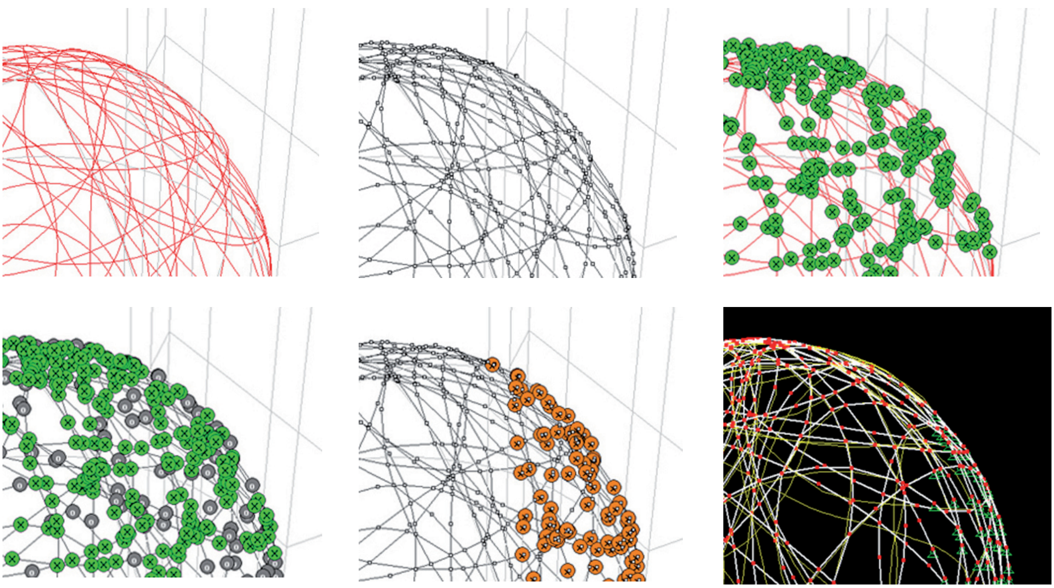


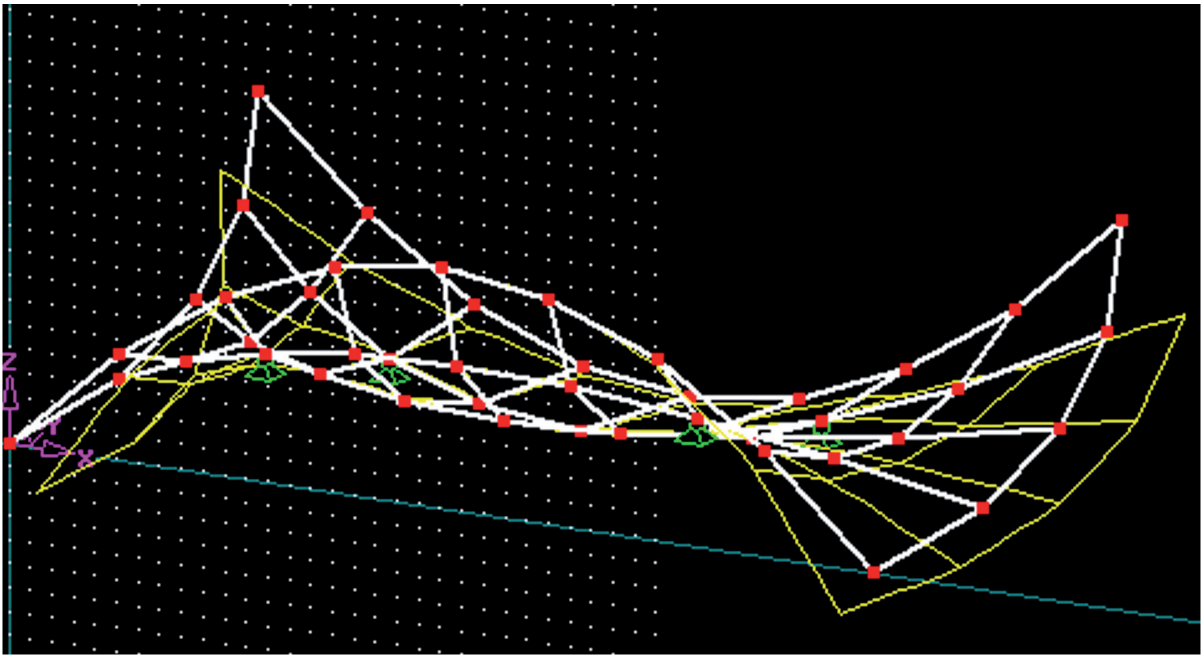
Figure 5.1.9: From an accumulation of circle to a structural model. 1. Rhino model with circles on a sphere, 2. Polygonized circles, 3. Identifying intersection points, 4. Identifying additional nodes, 5. Nodes that act as supports, 6. Structural model with simulated deflection.

an agglomeration of isolated non-discretized NURBS objects whereas a RSTAB© model defines not only loci but also a system defined by nodes and members in-between. Furthermore material, cross section, and orientation is assigned to every member and specific nodes act as supports with certain degrees of freedom. Updating a model through via drawing exchange format (dxf) eliminates all information beyond geometrical description. Sometimes the manual modeling of the structure in RSTAB© is even not feasible especially when early project phases implicate frequent changes of rather complex models.

For a model, comprised of a series of circles on a sphere, the author in collaboration with Markus Schein from the Kassel School of Arts explored an automation procedure from geometry generation to structural analysis. The process exemplifies the complexity involved in interfacing both representations. A circle is described through three polar coordinates with constant radius. The agglomeration of circles is subsequently scanned for intersections, which become structural nodes. The arches between those nodes are converted into lines or further subdivided into polylines with additional nodes to approximate the circle precisely. The discretization is necessary because RSTAB© requires linear members. The orientation of those members in relation to the sphere origin is measured and later used for cross section orientation. Nodes located inside predefined boundaries are assigned as supports. The additional information is stored during the generation process and transferred to RSTAB© via the above described custom written VBA interface.

The case studies predominately relay on this interface between Rhino© and RSTAB©. Of particular interest was the dynamic exchange of data, utilizing the Component Object Model (COM) interface standard. The following design procedures, presented in the case studies, benefit from circular feedback loops, developmental processes or sheer quantity at best handled automatically.

## 5.2 Case Study 1: Surface Structure



This research argues for novel strategies to integrate structural design procedures and analysis data in architectural design. The approach regards structural performance as one design criteria within a network of different requirements. Equilibrium of multiple parameters is aspired instead of a single-parameter-optimum. In this case study the subject is approached on a geometrical level. As described above, geometry plays a major role in the performance of structures since Gothic times. Geometrical principles were increasingly exploited and brought to perfection by architects and engineers like Antoni Gaudí, Frei Otto, Hans Isler, Felix Candela, Luigi Nervi amongst others in the last century. Gaudi, Otto, and Isler found their forms by the use of physical hanging models made from chains, nets and textiles. Those forms have thus been optimized towards one structural parameter: The reduction or elimination of bending forces within the resulting grid-shells and concrete domes.

Today three-dimensional modeling helps to design and represent complex geometries in the architectural practice. The resulting forms represent multiple architectural aims that originate from technical, sculptural, stylistic, and many other sources.

In the case study it was the aim to investigate whether form-finding strategies could also be employed within an architectural design process in which geometry is driven by more than one parameter. Therefore well known form-finding strategies are transferred into the digital realm and applied to architecturally designed shapes to initialize a negotiation of architectural and structural demands. It is not sought to completely alter the existing form in order to eliminate bending but to improve an already articulated form in terms of structural performance.

The case study is conducted by a custom-made digital interface between a 3d modelling software and an application for structural analysis of space frame structures to foster the collaborative approach. Surfaces are translated into meshes with supports at user-defined nodes, material properties, and specified cross sections. Subsequently those structures are exposed to its dead load in the analysis software. The resulting nodal deviation is feed into an algorithm that steers the appropriate reaction towards the local stresses and deviations, taking into account the mesh topology, its supports and their position in the mesh. The initial mesh is slightly altered in shape and evolves into an interconnected two-layer space frame that is transformed back into a double-layer surface model in the 3d software. An instant feedback from generation to analysis and vice versa is installed.

## 5.2.1 Structural geometry

Geometry in the field of structural form defines objects in space with positive characteristics in redirecting forces. In structural design the relation of force diagrams and their proper mathematical geometry is of fundamental interest. Cable structures i.e. that cannot resist bending materialize a force diagram for a specific load case that has an essential connection to its geometrical abstraction.

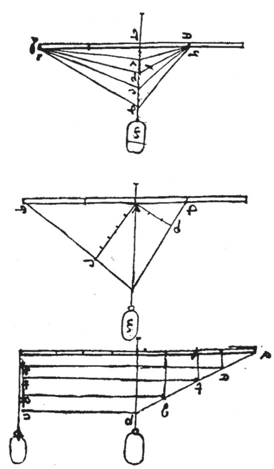


Figure 5.2.1: Composition of forces by Leonardo Da Vinci

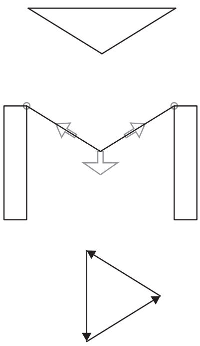


Figure 5.2.2: A suspended cable with central load, the geometric abstraction of an isosceles triangle, and the triangle of forces.

The simple example depicted in Figure 5.2.2 exemplifies the most fundamental rule for efficient structural systems. The principle is already described by renaissance master builders and engineers like Leonardo Da Vinci and Simon Stevin (Straub, 1992). Tension and compression along the axial direction exploit the entire cross section of a structural element whereas bending causes stress only in the outer areas and therefore disrates the remaining material to be useless ballast.

The distribution of forces within a massive beam is hidden from the observer's eye as the mass-active system does not indicate its specific load transfer. However, if one visualizes the isostatic force trajectories, a number of system-inherent structural types can be recognized, as for example arch, truss, lenticular girder and suspension system. In the lattice girder the trajectories of forces are materialized into structural elements that transfer only axial forces and a geometric model that can be easily analyzed with systems like the 'Graphic Statics' of Karl Culmann. The ratio of dead load to service load decreases by dissolving the massive beam so that a light girder takes a maximum load without any bending forces. The lattice girder can be regarded as the outcome of an optimization process that started with a massive beam. Material is removed until only the areas of compression and tension remain. The result is transferred into an abstract geometrical model and becomes a generic system and a structural type.

The predominance of the lattice girder, in comparison to other structural types, can be explained by the introduction of wrought iron as a new material. But also through the use of Graphic Statics as a new design procedure which had a major impact on the development. No other structural typology signifies better the succinct impact of new calculation methods on the changing understanding and employment of structures (Straub, 1992).

Form finding is taking the reverse path. The Institute for Lightweight Structures at the University of Stuttgart founded by Frei Otto in 1964 (http://www.freiotto.de) conducted an extensive research in the field of form-finding models based on a broad range of different material systems like soap bubbles, hanging chain models and foams that self-organize under the influence of extrinsic forces. These empiric approaches exploit the basic physical behavior of physical systems to create equilibrium of internal and external forces. The results of many years of research are published in the "IL" series by Otto and others.

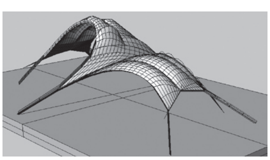


Figure 5.2.3: 3D model derived from digital form-finding, Axel Kilian, 2006

Axel Kilian transfers the concept of the hanging model into the digital realm. His system provides a real-time three-dimensional-modeling environment that mimics hanging chain behavior through a particle spring system. Furthermore a technique is proposed to instantiate chain segments by structural elements whose dimensions are driven by present forces. Thus form-finding is set in relation to volumetric representation of structural elements. In comparison with chain models or cable net models additional information is provided (Kilian, 2006).

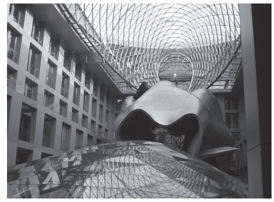


Figure 5.2.4: DZ Bank Berlin by Frank Gehry and Partners in collaboration with Schlaich Bergermann und Partner. The projects exemplifies two extreme optimization objectives: While Gehry is optimizing the conference room towards pure form the engineers sought a roof shape which allows lightness and structural integrity.

Further developments in using double curvature for lightweight structures are the glazed grid domes by Schlaich Bergermann und Partner (SBP). The spherical shape, guaranteeing proper structural behavior, is tessellated into triangles. Differentiated node geometry within the triangles, a huge problem for the geodesic domes of Buckminster Fuller, poses no problems due to CNC manufacturing. Another system has a principle borrowed from the kitchen sieve: In a first step a quadratic mesh is laid out flat. By changing the angle in the mesh the squares become diamonds and the mesh can be transferred into almost any shape while the member length is not changing. A prestressed diagonal cable-net is used to brace the system. Based on these systems SBP realized a couple of projects like the roof of Frank Gehry' s DZ Bank in Berlin and a courtyard roof for the Museum für Hamburgische Geschichte in Hamburg/Germany (http://www.sbp.de).

The above shown projects demonstrate what Heino Engel calls

> *"The affinity, existing between the figures of the space geometry with their mathematical roots on the one hand and the structural figures of force geometry with their mechanical background on the other …" Engel sees " … a profound association between the two, a kind of cohesion that confirms the universal validity of geometry and its elementary figures for any three-dimensional endeavor" (Engel, 1999).*

## 5.2.2 Structural principles of domes and shells

Surface structures like shells or domes resist forces through their double-curved form and integrity. The bearing mechanism is achieved by a membrane-like behavior. Like a balloon that is not able to resist bending moments with its thin surface, shells resist external loads through tension and compression. In case of symmetrical loads the form will be kept in equilibrium by meridional forces and ring forces only (Figure 5.2.6). Evenly distributed loads will be counteracted by tension forces running tangential to the curvature of the shell (Figure 5.2.5). This mechanism fails if high loads such as punctual supports impact on small areas of a shell. While forces along meridional direction are exclusively comprised by compression the ring forces change from compression above a so-called 'cracking-seam' (Bruchfuge) to tension in the lower part of the form. This state of pure membrane-tension can only be achieved by a hemisphere with continuous linear support, a structurally ideal condition which is rarely desired in practice as openings and punctual supports are necessary for programmatic issues. Furthermore

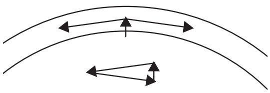


Figure 5.2.5: Tangential tension forces in a shell

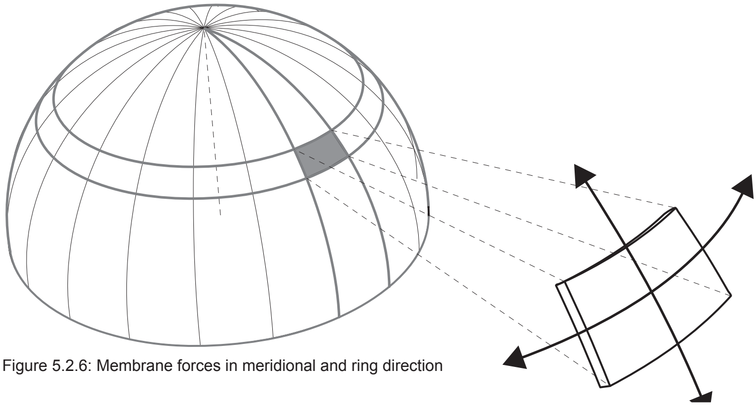


Figure 5.2.6: Membrane forces in meridional and ring direction

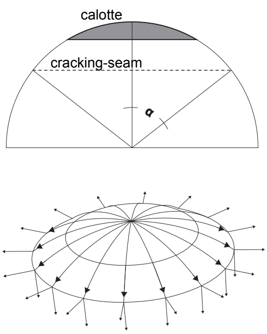



Figure 5.2.7: Compression forces above the cracking seam

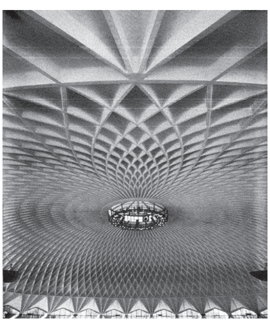


Figure 5.2.8: Dome of the Palazzo dello Sport by Pier Luigi Nervi

the calotte is preferred to the hemisphere due to proportional reasons of the height to width ratio.

Using a calotte, which is positioned above the 'cracking-seam' of the hemisphere, produces pure compression forces in both directions resulting in tension forces in the rim-like supports. But tension in the rim and compression in the surface causes different deflections thus creating undesired bending moments. Besides the alignment of inclining columns in tangential continuity to the calotte as exemplified in the Palazzo dello Sport by Pier Luigi Nervi in 1957 the problem can also be solved within the surface geometry. Franz Dischinger proposed in the 1920s already to extend a calotte with a transition-arc which creates a fillet tangential to the surface that gradually changes direction until it reaches the supports in vertical alignment. Due to this extension the 'cracking-seam' becomes part of the calotte again and the ring forces turn from compression to tension. The structural condition now resembles the one of a hemisphere again. Dischinger's proposal towards an integrative solution within the surface structure is succeeded by Heinz Isler's shells that stand out for their inclusive and thin appearance. Isler derives his forms from physical modeling. He stretches a cloth held by several points, coats it with liquid plastic and lets it self-organize its form. The hanging models is inverted and put into compression thus serving as a perfect form to be cast in concrete. The use of a 2-dimensional textile in combination with a plastic matrix is a close mimicry of reinforced concrete which makes a further translation, as required with the hanging chain models of Antonino Gaudi, unnecessary. By means of physical modeling and form-finding Isler refined the shapes of his shells.

The above shown projects have in common that their form is driven only by structural parameters. Following David Billington these roofs and halls are rather examples of structural art then architecture. He describes structural design as an art independent from architecture. Engineers design huge structures with mono-functional requirements. The shapes are defined by the forces in the material. The goal is to reach maximal efficiency in material use and economy issues while creating an aesthetic structure (Billington, 1985).

### 5.2.3 Structural and architectural geometry

Following this definition the work of the engineer Pier Luigi Nervi deviates from pure structural art. In a couple of projects Nervi developed a structural but at the same time aesthetic dialog between simple overall shapes and individual elements. The dome of the Palazzetto dello Sport in Rome is comprised of a shell with a diameter of 58.5m based on a shallow calotte. A polar array of triangles negotiates between a linear support for the shell and the oblique columns. The calotte geometry and the support condition ensure that only membrane-forces act in the shell and an exceptional thinness is possible. Gravity causes only small compression stresses, but they can easily lead to deformations which is called buckling. To prevent a shell from buckling it needs additional stiffness along the main direction of force flow. Nervi adds a series of rips to his shell but they don’t follow the meridional or ring direction. The pattern of the line grid is based more on aesthetic than structural reasons since the main forces are getting redirected from their initial direction in the surface of the shell. The ribbed concrete slab of the Gatti Wool Mill in Rome, of 1951, is another example of a rather ornamental approach. The rips are aligned along idealized isostatic lines within a plate with uniform loads. Nervi adds matter where the theoretical flow of forces goes. Jesse Reiser calls this “a self-fulfilling-prophecy, as forces flow where the matter goes.” (Reiser, 2006)

The work of Pier Luigi Nervi is highly appreciated by the author and the above described paragraph should not be regarded as a critique in his work. It is rather seen as a starting point towards a way to overcome the realm of a mere structural optimization which is inherent in the modernist engineering ethic. The diagonal rips in the shell of Palazzetto dello Sport created a diamond shaped pattern that was aiming for *“plastic richness”* (Nervi, 1965) besides its function as a structural system. This objective justified a configuration of individual elements that deviates from pure structural logic and reflects an architectural decision. Pier Luigi Nervi combined architect and engineer in one person which led to the highly integrative nature of his projects.

As this situation is extraordinarily rare architecture usually is a product of a collaborative effort. Thus even a shell can integrate a wide range of design criteria far beyond structural aspects only. SANAA’s “Learning Center” project for the

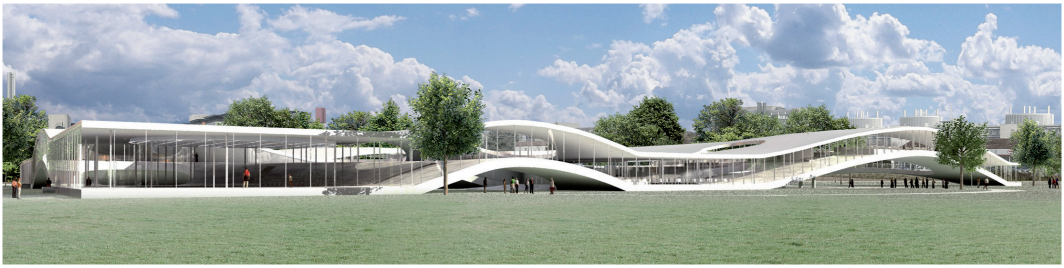
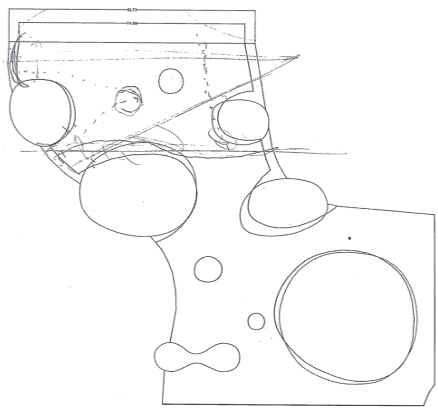


Figure 5.2.9: EPFL Rolex Learning Center , Lausanne by SANAA in collaboration with Bollinger + Grohmann



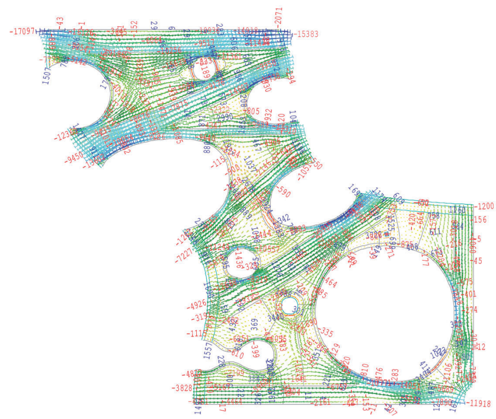


Figure 5.2.10: A sketch by the engineers: Spotting areas with possible arch-like behavior.
Figure 5.2.11 (right): Visualization of internal membrane forces.

campus of Ecole Polytechnique Fédérale Lausanne (EPFL) provides different spatial situations through the undulations of the one storey building. Containing the central library, service and study rooms, exhibition spaces, concert halls, cafés and a restaurant the building will be the functional and visual centre of the campus.

From an engineering perspective, homogeneous, idealized shells are elegant as they transfer forces without incurring bending forces and thus can be constructed with minimal material thickness as exemplified above. However, any incision in such an ‘ideal’ shape, as for instance a door, leads to fundamental, problematic changes in the structural behavior. SANAA’s undulating landscape building includes patios, openings and various spatial qualities and thus results from a design process, in which structural aspects were just one set of design criteria amongst many. Rather than prioritizing idealized geometries as known from Candela’s projects, here engineering work focused on analyzing and identifying local areas of shell or arch behaviors, which were subsequently further developed and modified in an ongoing dialogue of architects and engineers. ‘Classic’ form finding is superseded by processes of tracing performative capacities in the specific morphology. As the load bearing characteristics vary across the landscape like articulation, no region represents a pure structural typology. The analysis also reveals problematic areas that would necessitate a disproportionate thickness of the concrete shell. Wavy tensile force progression, high bending moments and redirected forces combined with the lack of support points in the patio areas were addressed by redirecting the force flow between the shell perimeters through modification to the patios’ geometry, size and location. This iterative process

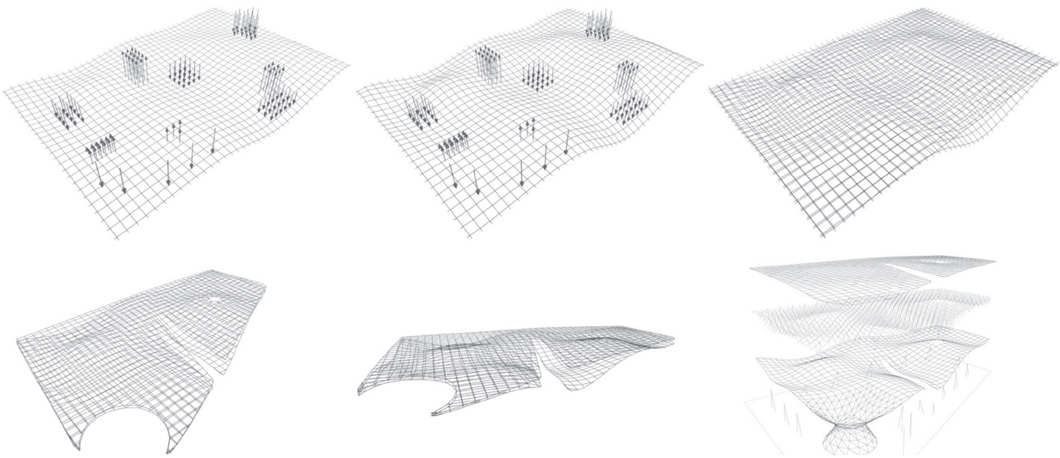


Figure 5.2.12 Stills of the BMW Welt roof form-generation processconducted by Bollinger + Grohmann

of tracking performance in collaboration entails ongoing design and evaluation cycles.

Form-finding is appreciated in this research as a generative means however the difference lies in the aim to integrate a wider range of form-driving parameters in the design process. An architectural project that exemplifies this approach is the BMW Welt by COOP HIMMELB(L)AU in collaboration with Bollinger + Grohmann. The complex roof structure of the building was designed in a collaborative process. During the competition a double layered girder grid was developed by the engineers, which demarcates the upper and lower boundaries of the roof space phase in alignment with the architectural concept of a floating cloud.

Driven by the simulation of anticipated loading scenarios the initially planar girder grid was deformed such that the upper layer assumed a cushion like bulge as shown in “Figure 5.2.12”. The lower layer also reacts to a number of spatial and structural criteria. For example, the roof integrates the customer lounge, a large incision that opens the views towards the famous BMW headquarter tower and

Figure 5.2.13: The BMW Welt under construction. The double-cone merges into the roof structure

channels the forces to the defined bearing points. The combined capacity of both girder grid layers to act as one spatial structure with locally differentiated behavior is achieved through the insertion of diagonal struts within the interstitial space. In response to local stress concentrations the structural depth of the system varies between a maximum of twelve meters and just two meters.

In the northern part of the building the roof merges with a double cone, typical for COOP HIMMELB(L)AU’s work, to form a hybrid shape. Similarly, the related bending behavior of the roof structure gradually transforms into the shell like behavior of the double cone (Bollinger et. al., 2005). Inspired by the collaborative approach of architects and engineers the start condition of the form negotiation process is defined by a B-Spline surface incorporating a morphology that is driven by architectural criteria not necessarily related to structural issue. It is not a neutral plane that is transferred into a manifestation of the existing force flow but an articulated and differentiated shape that is exposed to another parameter in the design process: the structural performance.

Such a collaborative approach was further developed by the Japanese engineer Mutsuro Sasaki who regards his work as strongly affected by Antoni Gaudí and Hans Isler. He claims that

> *"their manual shape creation process through physical model experiments can be fashioned more freely and more accurately through computer simulations…" (Sasaki, 2005).*

In his research he developed a method that transgresses the physical form-finding not only by using the computer but also by working with shapes that do not come from merely structural driven form-finding. In his collaborative work with architects like Toyo Ito or Arata Isozaki the starting point for the structural design are free-curved surfaces, imagined by the architects, which are analyzed to examine stress and deformation and subsequently modified in limited areas with structural problems. The ordinary sequential process of defining a structural type, a shape and the appropriate cross sections is usually followed by the anticipation of external loads. Structural mechanics is than applied to analyze stress and deformation. The structural analysis is a simulation or prediction of the mechanical behavior of the build form. In contrast Sasaki utilizes structural mechanics within the design process and not afterwards; he's reversing the traditional process of structural analysis. The goal is to find the "optimum structural type and shape that satisfies the design parameters …" (Sasaki, 2005). The method, Sasaki invented to optimize free-curved shells, is called Sensivity Analysis. As in the case of his predecessors Gaudi and Isler, Sasaki is searching for the form with the minimum of stress and deformation but within the boundaries that are defined by the initial architectural shape.

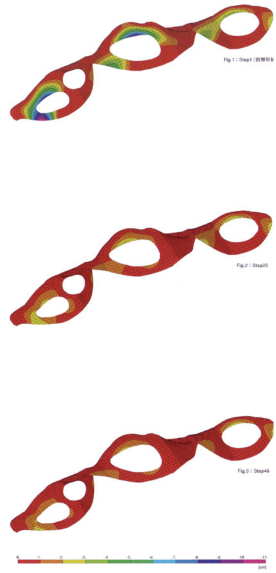
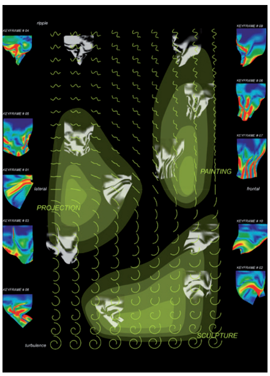
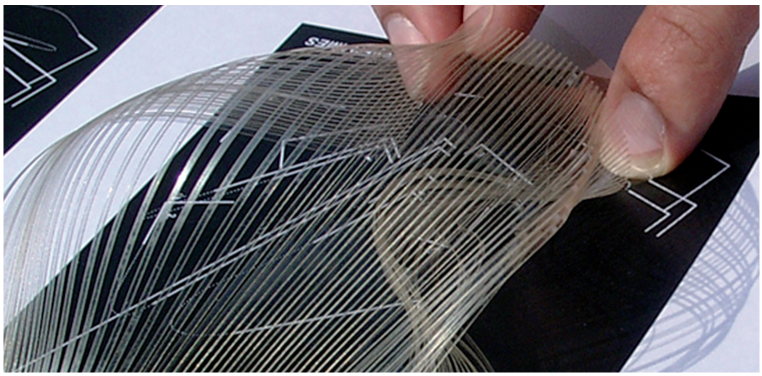


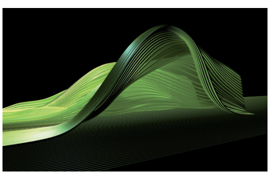

Figure 5.2.14: Sequence of modification of the initially envisioned shape by Toyo Ito using Sensitivity Analysis Method by Sasaki.

In a mesh which represents a free-curved surface the strain energy is measured at every single node. The nodes then are slightly altered in position and the strain energy in the entire structure is analyzed again to ascertain whether the change was positive or negative. The degree of nodal movement is set into relation to the change in strain energy. By verifying whether the strain energy is increasing or decreasing the direction of nodal movement is defined. The structure is analyzed after every step with the Finite Element Method until the strain energy gradually diminishes. The evolutionary process ends when no detectable change in strain energy occurs in successive steps. One crucial aspect in this optimization process is described by Sasaki as follows: "Even so, the problem is that we do not know where the nonlinear solution will converge in the relation to the initially established shape. It is necessary to establish an initial shape that is close to the desired shape. …"

The shape analysis method was tested in an academic context but also in a project that was recently build by Toyo Ito. The IProject consist of a 40cm thick complex curved reinforced concrete shell with an overall length of 190m and a maximum width of 50m. The helical shape was initially defined by the architects and subsequently subjected to the shape analysis. A maximum displacement of 2cm could be reached after six evolutionary steps meaning a convergence of the shell on a problem-free structure. Mutsuro Sasaki is conceiving his above presented work as an optimization process whereas the author is seeing this approach better described as a negotiation between different parties and their interests. The Sensivity Analysis is not optimizing the overall geometry of a shape towards the minimum strain energy but slightly moves single nodes within a mesh. The initial geometry imagined by the architect is not only accepted as a starting point but also embodies the goal of convergence in the evolutionary development.





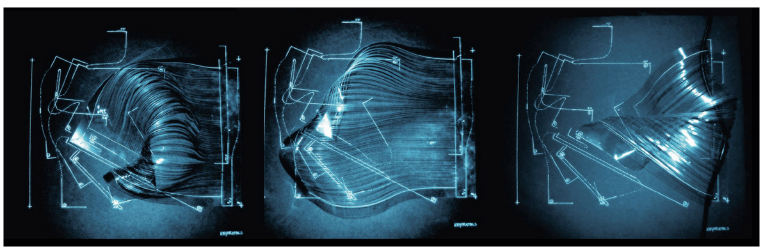


Figure 5.2.15 (top): The different shapes were set out in a matrix according to their suitability to host different kind of exhibitions
Figure 5.2.16: Perspective view

Figure 5.2.17 (top): Analog performance model which was used for form-finding through the self-organization of a material system under external forces. Those forces originated from program, site and structure
Figure 5.2.18: A series of shapes derived fro the form-finding process

The procedure of generating form from flexible material and externally impacting forces was also used by the author, but from a rather architectural perspective. In collaboration with Mirco Becker and Asko Fromm the author designed a semi-open exhibition space which was supposed to hosts cultural events during the Olympic Games in Athens 2004. The competition brief asked for an ephemeral structure not being linked to a specific site or domain but rather as an “urban parasite" which adapts to the infrastructure of the hosting sites.

Responding to the required ephemeral character the team proposed a flexible, two-dimensional membrane which remodels itself, around four key points, to create a multitude of three-dimensional forms.

The entire range of these shapes was explored, evaluated, and set out in a matrix, which took into account the programmatic tendencies and the trajectories of three different exhibition themes. The project's adaptation process also integrated the physical boundaries and flows of each particular site.

The project explored the geometries of compression deformed clamped beams. The repetition of similar elements along two curves creates an incremental variation of the members. This concept was modeled in a physical setup using a regularly cut sheet of plastic. By deforming only one side of the sheet a huge number of spatial configurations were achieved. The extremes of this morphologic exploration were marked on the base plate of the model. These curves, so called key frames, show only the projection of the deformation curve of the plastic sheet. A two dimensional curve containing as a derivation of the spatial configuration enough information to rebuild the model in that particular shape.

The model which derived its different shapes through external forces was conceived as a performance model rather than a form-finding model. Though different forms were found within a process the forces that act on the initial material system did not exclusively originate from structural considerations but rather urban and functional requirements. The strength of such a performance model was the ability to test versions of spatial configurations by deforming only two input parameters: the curvature and position of one edge within the limits of the material. The result was a spatial configuration computed by its material properties which provided a structural system of compression arches and at the same time generated a unique shape at a specific site for a specific program. Thus form-finding was integrated into larger design context. The integrative character of the proposal proved successful in the competition and was awarded with the first prize by a prominent jury including Zaha Hadid, Hani Rashid, and Elias Zenghelis . Unfortunately the project was never realized due to shortage in time and money in the run-up to the Olympic Games in Athens 2004.

## 5.2.4 The surface structures experiment

The following experiment is conducted in a similar spirit arguing for novel strategies to integrate structural analysis data in an architectural design approach. The approach is not aiming for a pure force-driven form-finding or optimization process but regards structural performance as one design criteria among others.

Equilibrium between multiple parameters is aspired instead of a single-parameter-optimum. When conceiving structure as an integral part of architecture the overall performance of an architectural project results from negotiating and balancing a complex network of multifaceted, interrelated requirements.

In a collaborative design approach form does never constitute the optimum shape derived from a structural form-finding process, but rather embodies and integrates a multitude of parameters. Within an overall system regions with structural capacity have to be identified. The structure then unfolds from these regions and adapts its capacity to local requirements. Other regions that would cause significant structural problems have to be altered without affecting the architectural, spatial, and programmatic concept.

In this process structural issues are one aspect amongst many and thus not the only shape defining parameter. Architectural design needs to incorporate complex organizational and functional requirements and therefore constitutes a recurrent negotiation of analyzing existing and required conditions as well as generating and evaluating possible responses. Additional knowledge gained through such iterative processes may require further analysis of the specific context or even the adjustment of previously defined design objectives (Lawson, 2006). A project's diverse design criteria can be understood as network of interdependent nodes. Once this network settles into a state of equilibrium of various influences a high level of integral performance of the building and its structure has been attained. This capacity cannot be achieved through single-parameter optimization of the overall system as the linearity of such processes cannot account for the complexity of architectural projects.

### 5.2.4.1 Negotiate Form

Surface-based design approaches have become widely used in architecture through B-Spline-modeling software. A surface can serve as a representative for a multitude of different aspects of a design beyond its initial function as a border between a volume and its environment. It is a two-dimensional object unfolded into the three-dimensional space without any material thickness. But instead of treating surfaces as border conditions, they are often perceived as the objects

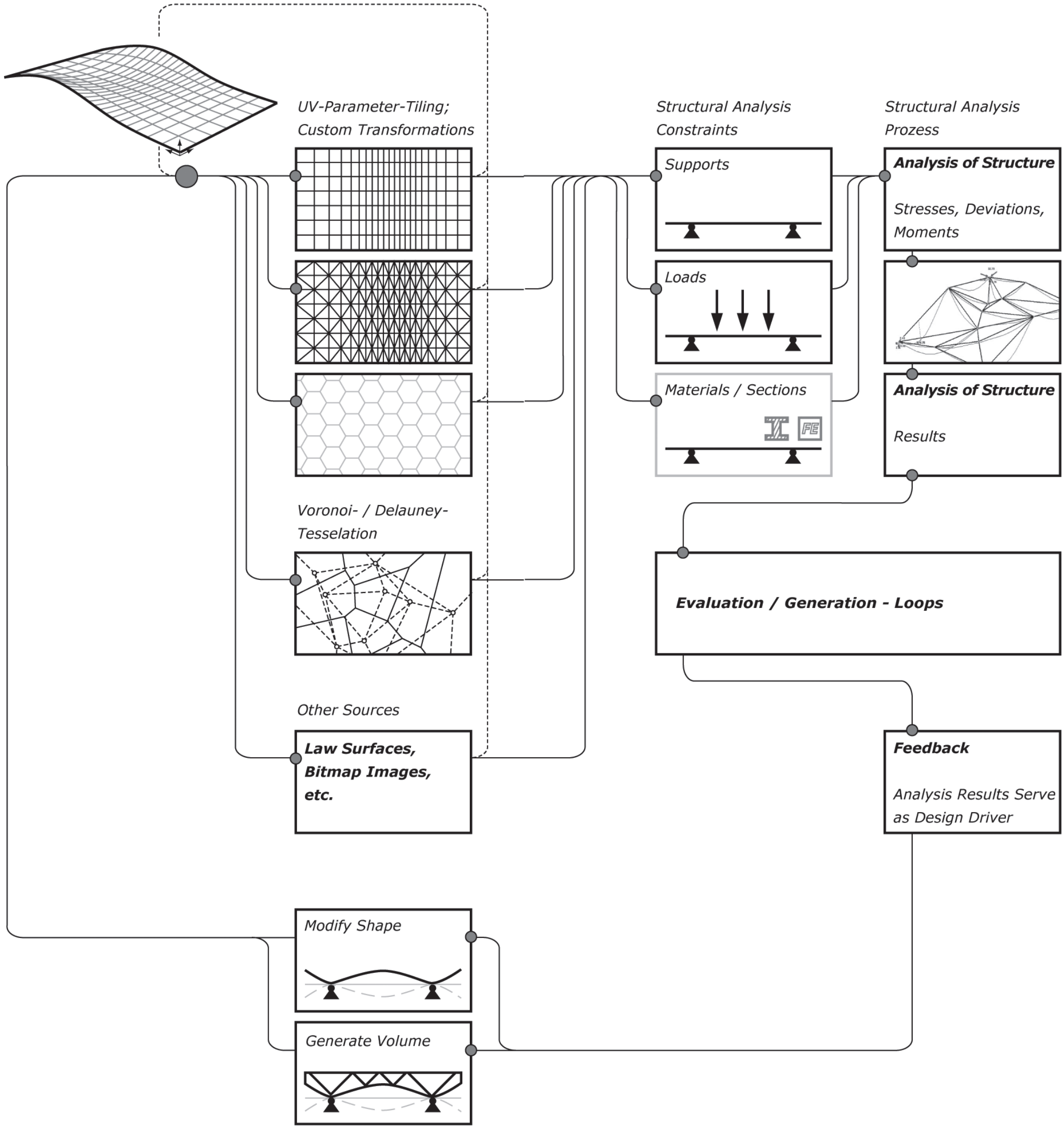



Figure 5.2.19: The design procedure starts with a surface that embodies an architectural design idea, which then is virtually driven and sequentially informed by a network of different constraints. One initial surface is translated into one or more custom meshes, which then are exposed to their dead load in the structural analysis software. The resulting deflections are fed back into an algorithm that steers the appropriate reactions towards the local stresses and deformations: The geometry of the initial mesh is slightly altered to reduce bending, while still embodying the initial architectural proposal. Unlike in sequentially organized form-finding procedures, this process negotiates the form-driving 'forces' of both realms, the structural and the architectural. The new, altered mesh then is transformed back into the 3d-modeling software.

themselves. This misconception of a surface virtually representing a physical building component is - at the latest - revealed when the surface is translated into built form with structural requirements, material thickness and material properties. To overcome this conceptional flaw and to accomplish construction requirements the strategy of the “design surface “ (Kilian, 2006) was recently introduced into the design practice. The two-dimensional surface is used as a host which is associated with secondary geometry, representing three-dimensional building components. These components fulfill fabrication constraints and at the same time represent the overall morphology of the initial surface. The concept of the design surface is used in this research to generate a mesh of structural elements along the guiding geometry of the initial surface. Bending flexibility of these members is used to improve the form of a surface structure and to activate its in-plane performance.

The project uses a 3d-NURBS-Modeler (Rhinoceros©) for surface generation, surface modification and the visualization of geometry. Structural analysis is done in RSTAB©, a structural analysis application. These two generic tools are tight together by some custom made programs (in Visual Basic for Applications©), which are basically used as data interface for automated tasks such as different ways of surface tessellation.

### 5.2.4.2 From surface to mesh

The uv parameter space of the surface is used to proliferate meshes with specific topologies along the surface. Triangular, quadrangular or hexagonal meshes with different resolutions can be generated depending on the designer’s choice. The mesh incorporates the overall shape of the initial B-Spline surface.

Before transferring the mesh into the analysis software the supports have to be defined. Supports are located at the nodes of the mesh; their location can be

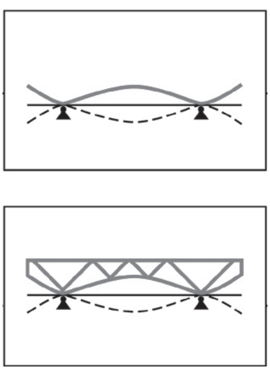


Figure 5.2.20: Form improvement and structural volume.

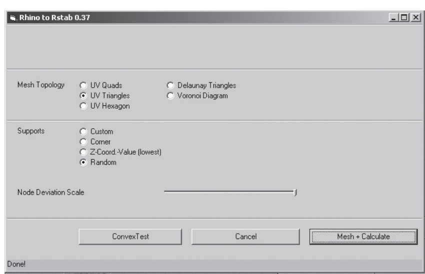



Figure 5.2.21: Selectable constructors for mesh topology and support position. A slider controls the magnitude with which the form-finding acts on the initial surface.

defined in different ways. The position and number of supports can be chosen deliberately; they can be placed randomly, at the corners or at the lowest nodes of the mesh. Mesh and support positions are transferred into the structural analysis software for space frame structures. The architectural language represented by the B-Spline surface is transcribed into a set of data suitable for structural analysis. Nevertheless in this stage of the process it is important to stress that the analysis software is considered as a kind of form-finding device and not as a structural analyzing tool.

### 5.2.4.3 Form improvement

The mesh does not act as a proper structural system yet. But exposed to its dead load its nodal deviation shows similar behavior to a hanging chain model. Depending on the topology of the mesh, the bending resistance of its members and the support position, the initial mesh is deformed. Turning the deformation upside

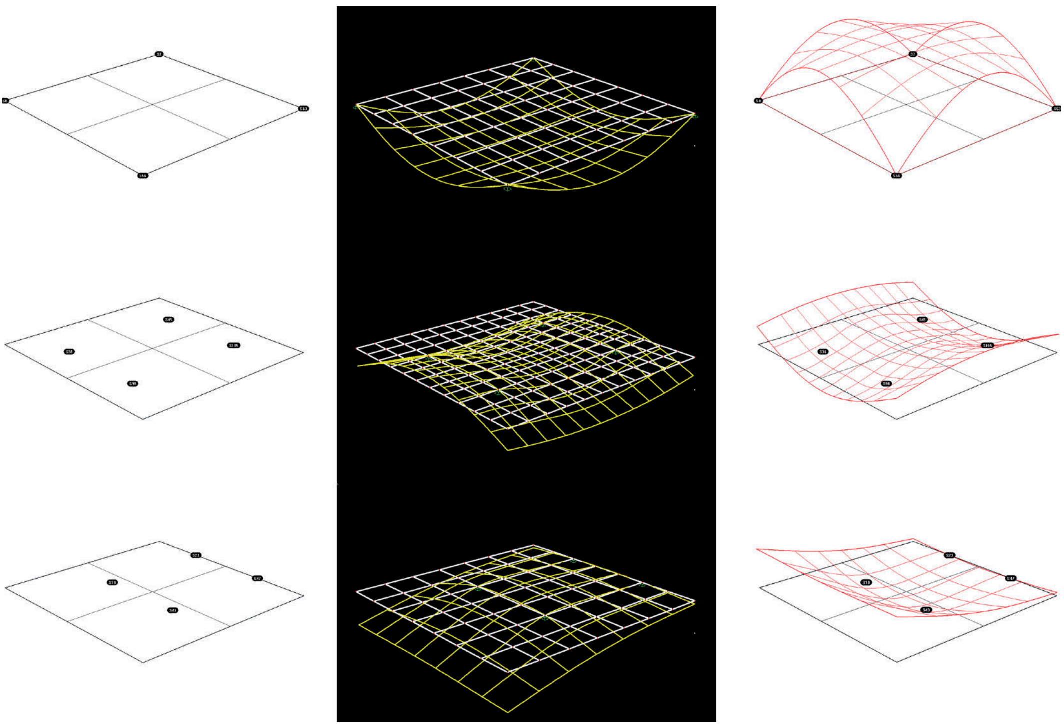


Figure 5.2.22: As a test run a flat surface with different support conditions is exposed to its dead load. Left column: Initial NURBS surface, midde column: structural model with displayed deformation, right column: resulting NURBS surface. A surface with fixed corner points should turn into a shell-like shape resembling the results of Isler's physical experiments (top). Cantilevering regions are lifted according to global deformation.

down leads to shell-like structures with reduced bending forces. This strategy is well known from the hanging models of Frei Otto. The analyzed nodal deviation is fed back into an algorithm that steers the appropriate reaction towards the local stresses and deviations, taking into account the mesh topology, its supports and their position in the mesh. The interpretation of nodal deviation is followed by two approaches to integrate these results in the architectural design process. Both approaches are currently investigated.

Rather than prioritizing idealized geometries as known from Candela's projects, here the work focused on analyzing every node according to its relative position in the mesh and to the supports. Areas between supports behave like a hanging model that constitutes in a spatially curved form when suspended from support points. Reversing this deformation creates shell or arch behavior of single or double curved grids with forces increasingly bundled in tension and compression. Surface and grid structures like shells or domes resist forces through their double-curved form and integrity. The bearing mechanism is achieved by a membrane-like behavior. In case of symmetrical loads the form will be kept in equilibrium by meridional forces and ring forces only.  This state of pure membrane-tension can only be achieved by a hemisphere with continuous linear support, a structurally ideal condition which is rarely desired in practice as openings and punctual supports are necessary for programmatic issues. Therefore the presented approach seeks to generate local areas of shell or arch behavior, without neglecting

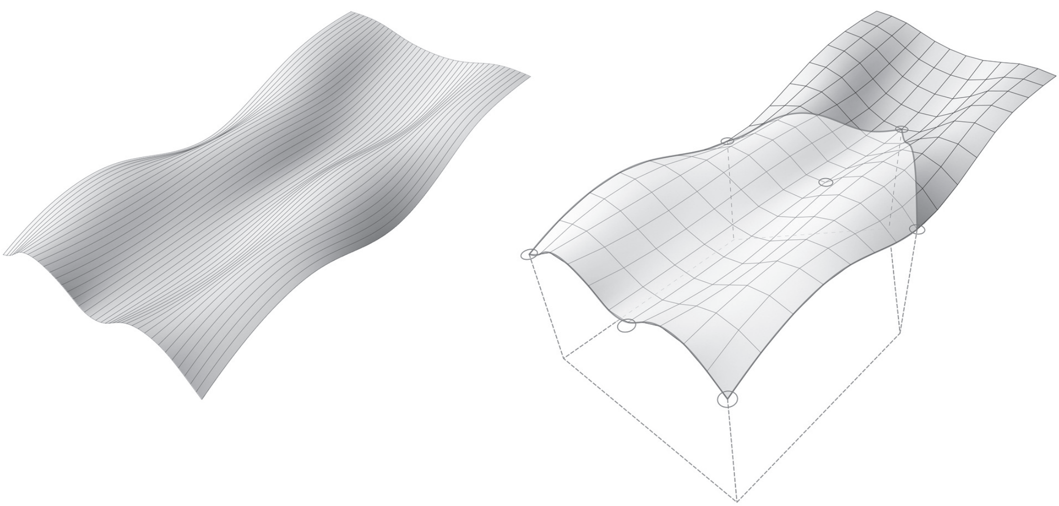


Figure 5.2.23: Initial surface (left), mesh with supports represented by circles and a convex hull (right)

the architectural shape. Form-finding is replaced by processes of tracing and generating performative capacities in the specific morphology. As the load bearing characteristics vary across the shape, no region represents a pure structural typology or a structurally optimized shape.

Cantilevering parts of the mesh are treated differently than nodes between sup-

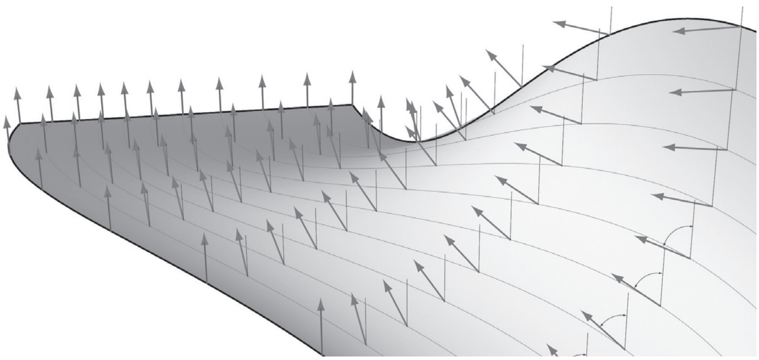


Figure 5.2.24: The angle between the surface normal and a vertical axis reveals of vertical regions of the surface. Those vertical regions are not considered in the form-finding.

ports. A geometric improvement in general is less effective in these areas. However cantilevering structures are consciously included in this research because it is a common element in architectural design practice.

To separate regions in-between supports from those that cantilever, the convex hull, as the perimeter around all supports, needs to be generated (Figure 5.2.22). Suitable algorithms, although very common, are not part of the modeling package and had to be implemented by the author. Nodes inside the perimeter are conceived as contributing to a shell-like behavior whereas nodes outside the perimeter belong to cantilevering regions.

The deviation of cantilevering nodes is either set in relation to the maximum deviation so that affected parts are lifted slightly alternatively those regions can be excluded from any geometrical changes. The same applies for nodes located in rather vertical regions of a surface. A change in location is less likely to improve the structural performance. Thus the angle between the surface normal and a vertical axis is measured. If a certain value is exceeded the node is excluded from geometrical manipulation. An improvement of those regions is rather possible through adaptation of cross sections and material properties than by changing geometry.

### 5.2.4.4 Proof of concept

As a proof of concept the design procedure is conducted with a free-formed surface. The double-curved shape carries no structural intention. Four supports are added, their positions lead to cantilevering regions.

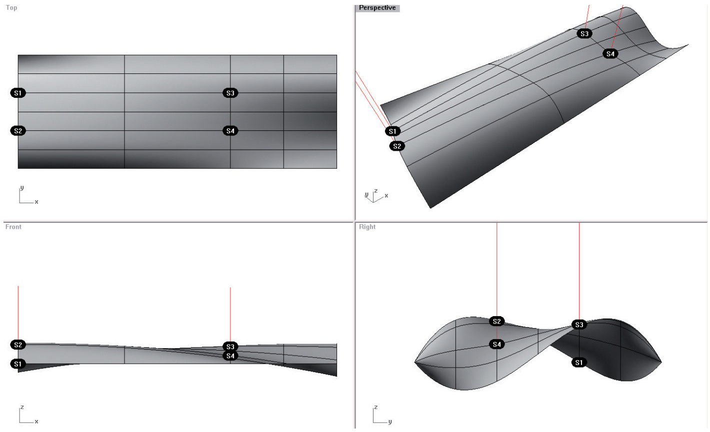



Figure 5.2.25: Screenshot of initial surface

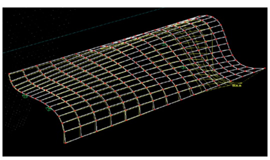


Figure 5.2.26: Exposed to its dead load the surface deforms.

Figure 5.2.27: The deformation id reversed between the supports and cantilevering regions are lifted upwards. Section of improved (top) and non-improved (bottom) form

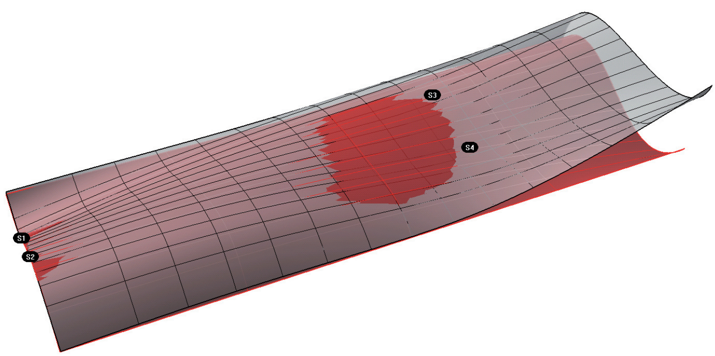



Figure 5.2.28: Non-improved (red) form, superimposed improved form (grey)

## 5.2.5 Results

The refined geometry leads to a structure with increasing axial forces. Since the initial surface is not necessarily symmetric and the supports are located in inappropriate positions axial forces will always be accompanied by bending. The form is not “found” by the most efficient force flow but instead the already articulated geometry is informed and differentiated by use of evaluation data.

The result is a mesh that is fed back in the 3D modeling software based on the improved nodal positions. The optimized mesh is transferred back into a B-Spline surface. The derived surface is supposed to incorporate an improved structural action concerning deformation because its overall shape is informed by structural analysis data. To prove this assumption the initial surface and the informed surface are compared in a different finite-element analysis software. Here the meshes are conceived as solid surface structures. The result shows a significant decrease in deformation in the cantilevering area which also leads to less bulging between the supports, as shown in “Figure 5.2.29”. The total deflection could be reduced by 22cm.

The improved surfaces still incorporate the morphology of the initial surface which was driven by architectural design parameter. At the same time the shape is slightly deformed and adapted to inherent stresses and deviations. Structural analysis is becoming a driver for geometry. Differential mesh topologies, mesh resolutions and support positions and their influence on the resulting geometry are tested in several iterations. The interactions of surface geometry and mesh topology can be analyzed instantly through the provided interface between both software packages. An instant feedback from generation to analysis and vice versa is installed.

In the second approach the initial surface is doubled such that an additional layer is added to the surface model. The initial mesh evolves into a double-surface model in the 3D software. The distance between both surfaces refers to the local deflections in the evaluated mesh. The surfaces now act as the border representation of a volume and not as objects themselves. The approach is suitable for constructions which are not surface-active. The volume can, for instance, host a space frame between upper and lower surface, an approach that is pursued in the second case study of this thesis.

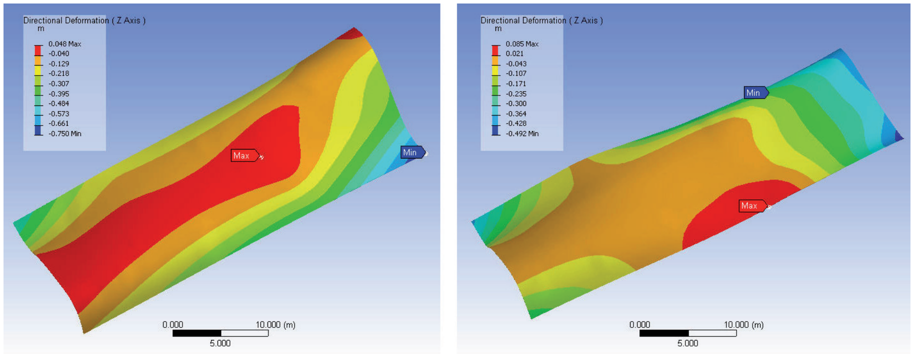



Figure 5.2.29: Directional deformation in z-direction. FEM analysis of non-improved (left) and improved (right) form

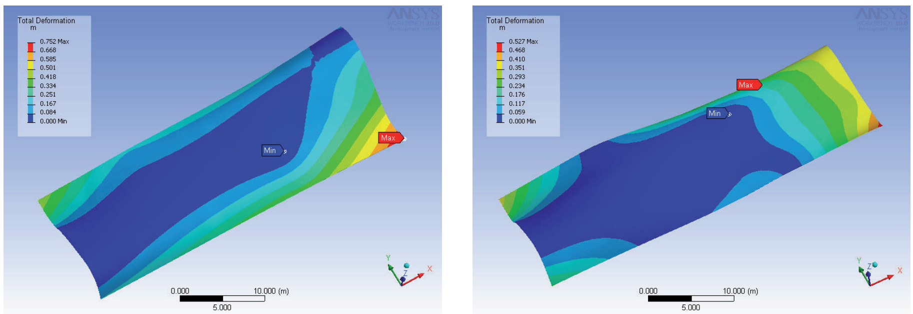
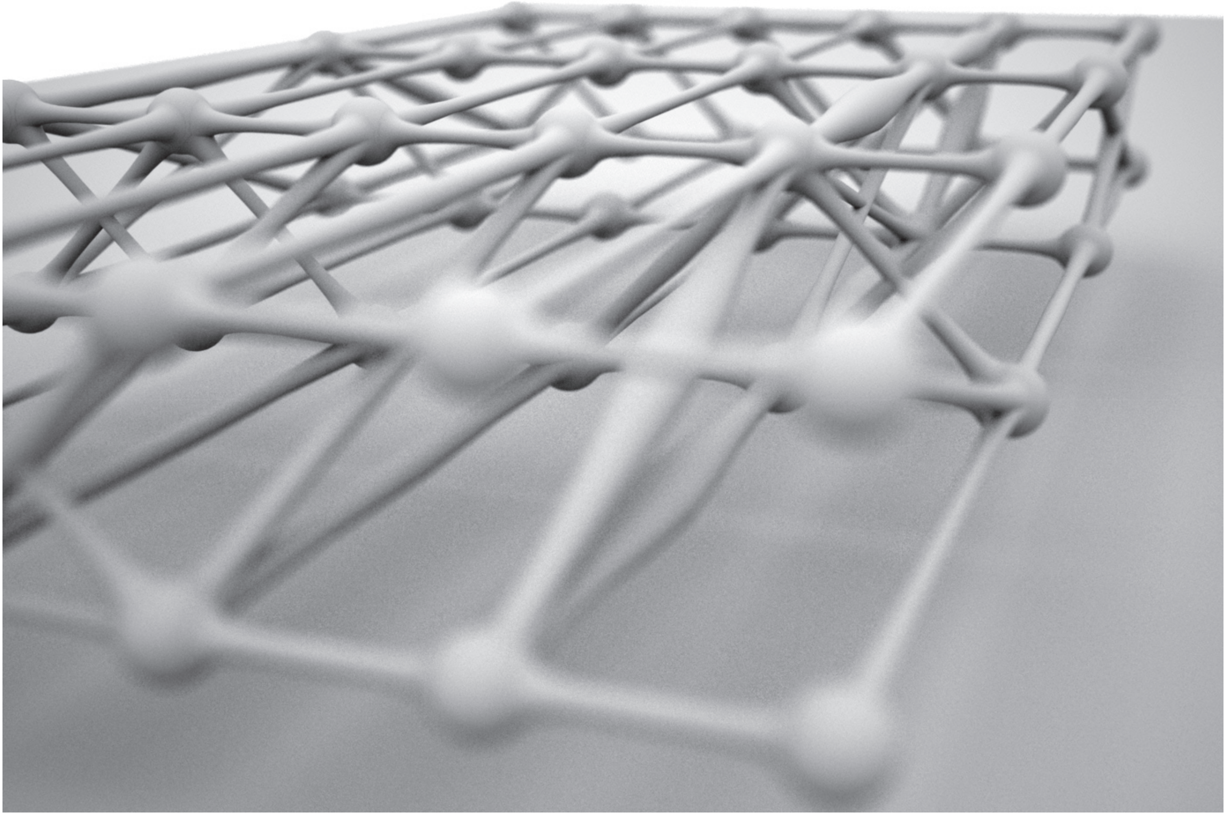



Figure 5.2.30: Total deformation could be reduced by 22cm

## 5.3 Case Study 2 - Space frames



Whereas the first case study sought to incorporate architectural and structural parameters within one single continuous surface whose form is found, the second experiment starts with a volume described by a lower and an upper surface. A structural system comprised of discrete members is populated into the volume. The aggregation of those members is derived from a negotiation process which is conducted by an Evolutionary Algorithm which takes into account quantifiable architectural and structural parameter.

The first case study sought to inform surface models with geometrical properties to embed a certain structural performance. The procedure predominantly operated with surface structures at which structural system and surface geometry coalesced into one object. A series of projects by shell builders like Felix Candela, Pier Luigi Nervi , Hans Isler and others exemplify this approach.  The Learning Center at the EPFL in Lausanne by SANAA, Kazuyo Sejima and Ryue Nishizawa with Bollinger + Grohmann which is currently under construction or Toyo Ito' s and Mutsuro Saski's IProjects stand for an approach that seeks to integrate a broader range of parameters than those of mere structural form-finding.

Formwork and construction of concrete shells proves to be labor and cost intensive so that many projects by Candela, for instance, could only be realized in Mexico where labor used to be comparably inexpensive. The second case study, in contrast, concentrates on the representation of continuous surfaces through discrete elements. A second outcome of the form-finding experiments in the first case study which had not been pursued was the generation of a volume between two surfaces which could be used for construction.  The surface evolves into a double-surface model in the 3D software. The distance between both surfaces refers to the local deflections in the evaluated mesh. The surfaces now act as the border representation of a volume and not as objects themselves. The conceptional flaw of surfaces with zero thickness is overcome by a volume that can be filled with a space frame between upper and lower surface. The system is generated by nodes and interconnecting poles.

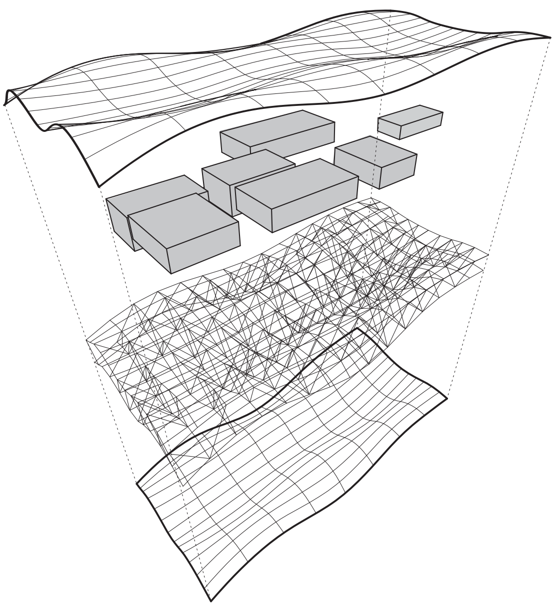


Figure 5.3.1: 3D Model for evolving space frames. Upper and lower surface define the hull geometry for the structure. A space frame is generated in-between. Boxes represent volumes which should be free from space frame elements

## 5.3.1 Improving space frames

Vector-active lattice systems like space frames are very common in structural design and can be traced back to an innovation in structural analysis in 1866. Karl Culmann, Professor of engineering science at the ‘Eidgenössischen Polytechnikum’ in Zurich, published his ‘Graphic Statics’, including his developments of the most important graphic methods for calculating structural behavior (Culmann, 1875). With these methods being particularly appropriate to calculate lattice girders no other structural typology signifies better the succinct impact of new calculation methods on the changing understanding and employment of structures (Straub, 1992). Not until the 1960’s the graphic statics were replaced by computer numeric procedures. Nevertheless the generic structural typologies established by the former scientific methods remained the dominant systems.

In this research the space frame becomes the objective of multi-dimensional negotiations. Instead of utilizing a generic structural type whose parts are subsequently evaluated the entire system is improved. Improvement is regarded as the balance of multiple architectural and structural requirements. The architectural requirements are represented by the double layer surface system that describes the desired overall morphology of the roof.  In addition volumes are defined between the surfaces that should be free from structures to provide usable spaces in an architectural sense.

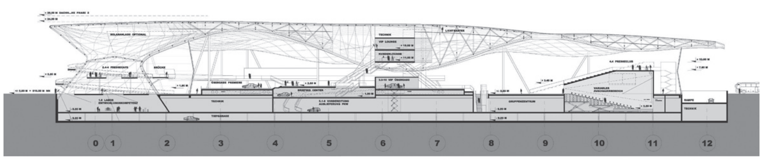


Figure 5.3.2: Section of the BMW Welt in the competition phase by Coop Himmelb(l)au, 2001. The lounge becomes part of the large roof. From an engineering point of view the lounge is a structural disturbance. In a collaborative design approach architectural and structural aspects have to be negotiated.

The initial space frame topology (element-node connections) refers to conventional structural systems. The goal of structural improvement lies in the reduction of overall deflection of the system and the use of a minimal number of elements. This objective is assumed to be reached by locally differentiated behavior of the system; double curved areas can generate shell-like behavior which gradually transforms into bending behavior in more planar areas of the system. The space frame is set up as a parametric model whose topology can be altered through external parameter.

Thus the boundary conditions are known and the desired goal is clearly defined. The parametric space frame model allows externally driven variation to achieve a solution space instead of a single solution.

## 5.3.2 Evolutionary Algorithms

An adequate means to generate and navigate such a solution space is an Evolutionary Algorithm (EA). Those algorithms are based on mimicry of the process of evolution, which leads to the effect, that through the accumulation of small improvements over time the maintained solutions gradually converge towards the defined criteria. An EA inherits some touch of unpredictability, which makes it highly interesting for design exploration. When using an EA, the elements of a design model and their properties are defined. But transformation processes, which are performed on the model, do not need to be rolled out in each detail. Of course it is necessary to determine what parameters may be changed and a general rule how this may happen. But how it happens in detail is strongly influenced by the random processes of mutation and crossover.

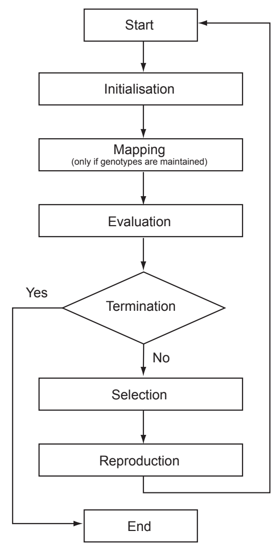



Figure 5.3.3: Flowchart of an Evolutionary Algorithm, Bentley, 1999

More technically speaking, there are four major types of Evolutionary Algorithms, but which all follow a common architecture, as described by Bentley (Bentley, 1999):

### 5.3.2.1 Initialization

In the terminology of EA's one solution is referred to as an individual; a group of such individuals is called population. Each EA proliferates a series of different solutions which increase their performance over time. In a first step an initial generation of possible solutions (individuals) is generated. At this point a general idea of a possible solution is necessary. Every gene in the genome represents one modifiable parameter (placing  or not placing an element). The chromosome is the list of all genes hence the parameters which are altered. During initialization random values are assigned to every gene.

### 5.3.2.2 Mapping

Parameters can be further encoded as a binary number which helps to control the range of allowed mutation. Further encoded parameters are called genotype. The process of translating genotype information into actual parameters is called *mapping.*

#### 5.3.2.3 Evaluation

During the evaluation every phenotype is ranked by predefined criteria. The ranking is achieved through tests called fitness functions. The definition of fitness functions is the crucial part of the design of EA's. All tests contribute to one single grade of the individual which is used to rank it. The ranking becomes the basis for the successive steps.

#### 5.3.2.4 Termination

In case the termination condition is reached the evolutionary process is terminated. The following termination condition are used:

- An individual achieved the desired fitness
- A certain number of generations is accomplished
- A predefined time period elapsed
- The rate of convergence fell below a defined value

#### 5.3.2.5 Selection

Based on the ranking of the evaluation procedure the individuals for reproduction are chosen. Selection provides a higher probability for reproduction to individuals with a higher fitness value. At the same time a certain diversity is desired. The gene pool for further reproduction can be put together by four different methods:

- Fitness Ranking. The fitness of an individual determines the number of copies that will be added to the gene pool.
- Tournament Selection. One individual is compared to randomly picked individuals of the population. The probability of being chosen for repro duction rises with the number of other individuals being outmatched.
- Roulette Wheel Selection. As the name implies individuals are assigned to sectors of a roulette wheel. Those sectors are scaled according to the fitness value of the individual. The procedure implies random selection but with a higher probability for better individuals.
- Fertility. The fitness value determines the number of offspring.

#### 5.3.2.6 Reproduction

Offspring is generated by the recombination of genetic material of the parent generation. The genetic operators crossover and mutation ensure a certain variation of the existing gene pool. Crossover splits the list of parameters (or genotype) at one or more random points and switches parts of the string between the genome of two individuals of the parent generation. Mutation changes randomly picked parameter (or bits) of the genome.

An EA can be considered as a non-trivial machine as described by Heinz von Foerster (von Foerster, 1970). A non-trivial machine can be comprised of two trivial machines.  If one integrated trivial machine changes the internal state of the non-trivial machine its behavior is not predictable anymore. The output is not exclusively dependent on the input parameter but also on the internal state of the machine. In consequence the machine is neither analyzable nor predictable. If the inner state of the machine depends on previous states the history of the machine cannot be skipped.

Algorithms are formal systems that rely on a programming language, a syntax, operators, and operands. A task is executed in a sequential manner until a certain halt condition is reached. This description applies to both types of machines. The Evolutionary Algorithm used in the space frame experiment constitutes a non-trivial machine. A genome contains the operands, parameters which define the topology of the space frames. This genome undergoes a development during the execution of the algorithm. The genome of a generation is based on individuals of a previous generation which were selected for reproduction. The ranking process depends on selection criteria but also on stochastic procedures. The variety in a novel population is achieved through crossover and mutation. Both steps are again controlled by stochastic procedures.

Due to the inheritance of genes the evolutionary algorithm depends on the history of the process. The population of phenotypes is the output data which serves to determine what will be fed back into the system as a new input. The circular process is the basis for evolutionary development.

Crossover and mutation represent changing inner states of the machine. Crossover splits the genome of one individual at one or more random points. The resulting pieces are swapped and recombined with their counterparts. The position of the splitting point is defined by a random number which can take a range of values. The same applies for mutation which changes single bits in the genome. Again the position within the genome is defined by a random parameter. Crossover and mutation constitute internal trivial machines with determined behavior. Nevertheless their states cannot be analyzed externally. Within a range of possible solutions, also called the solution space, a non-predicted solution can emerge.

This is the conceptual framework used in the space frame experiment. Similar procedures are at work in any kind of Evolutionary or Genetic Algorithm. Those formal systems operate in a determinate manner but at the same time yield single solutions derived from a solution space.

In this case study, a custom-written Genetic Algorithm (GA) is used, based on roulette wheel selection, the genetic operators of mutation and crossover and some elements of island injection, as introduced by Eby et al (Eby, 1999). GA's are a common means for optimization problems in structural design and start to emerge in the field of architecture as a generative tool (Felicetti, 2006).

The phenotype is represented by the diagonal elements that connect both layers to form a coherent space frame. Diagonal elements start from a node in the upper mesh and end at a node of the lower mesh that is in front, behind, left of right from the starting node. A node inside the field has four possible elements, a node at an edge has three possible elements and in a corner a node has two possible elements.

## 5.3.3 Evolutionary design exploration

Evolutionary strategies as a means of optimization are rather used in the realm of engineering as in the field of architecture. The author assumes the different nature of problems in both fields as the main reason. Engineering problems are more often well-defined and the goal can be clearly stated. In such a case the EA is a suitable tool. As a stochastic search algorithm it browses a search space which converges towards the predefined goal. The following paragraphs present a range of projects which seek to utilize evolutionary strategies at the interface between architectural and structural aspects or as a means to broaden the range of possible design proposals.

### 5.3.3.1 Underground Station Roof Piazza Garibaldi, Naples

During the design study of the underground station roof at Piazza Garibaldi in Naples by Dominique Perrault entire populations of structures were evolved and individuals were selected through predefined architectural and structural fitness criteria. These processes evolve articulations in response to specific criteria without relapsing into a priori defined typologies.

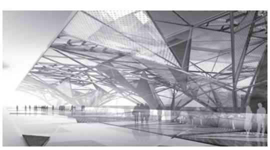


Figure 5.3.4: The station roof as envisioned by the architect Dominique Perrault.

In collaboration with Fabian Scheurer (Departement of CAAD at The ETH Zurich) Bollinger + Grohmann conducted a design study on improving the performance of the folded roof structure through Genetic Algorithms. Topologically the roof structure can be described as a two dimensional plane based on a system of self-similar triangles folded in third dimension. Each node is assigned a random z-coordinate within defined thresholds. A tube like column folded out of the roof reaches the ground and acts as support structure. To achieve cantilevering capacity and a minimum of node displacement just by folding the triangulated plane the behavior of the entire structure was simulated in RSTAB© software. By encoding the z-coordinates of all nodes into a genome and using a genetic algorithm which allowed for crossover and mutation, the performance of the structure could be significantly improved over the run of 200 generations with 40 individuals each. As a fitness criteria, the displacement of the nodes under self-weight was calculated by the analysis software, the worst node defining the inverse fitness for each individual. (Scheurer, 2005)

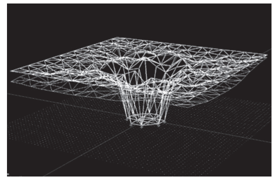


Figure 5.3.5: RSTAB© model of the triangulated root structure, Scheuer 2005

#### 5.3.3.2 Pedestrian bridge in Reden, Saarland, Germany

A method which is currently developed at the Universität für Angewandte Kunst in Vienna pursues an improvement of lattice structures with randomly placed elements. The method was first applied to the design of an pedestrian bridge in Reden designed by FloSundK Architekten in collaboration with Bollinger + Grohmann. The bridge is comprised of two hyperbolic paraboloids described by the upper and lower chords of the girders. The position of diagonals was not prescribed.

Figure 5.3.6: RSTAB© model of the pedestrian bridge in Reden Austria, Bollinger + Grohmann, 2007

An initial procedure propagates randomly placed elements between upper and lower chord. The structure is analyzed and every single element is ranked. The ranking criteria is based on the requirement that every element in a lattice structure should be free from bending moments. Hence the quotient between the observed moment and the normal force indicates the fitness of every element.

In an iterative procedure elements with a bad moment/normal force ratio are assigned to new positions in the structure. The altered lattice structure is subsequently analyzed again and the process proceeds until a predefined number of iterations or a certain structural performance is achieved. The design procedure yields regular lattice girders when applied to coplanar chords which proves its validity. In case of the bridge in Reden the procedure becomes a tool for collaborative design exploration.

The approach  is of particular interest because of the observation of individual elements and their local performance. Structural capacity emerges bottom-up  by a self-organizing procedure based on simple rules.

#### 5.3.3.3 Evolutionary Structural Optimization

Evolutionary strategies are as well pursued by Xie, Huang, Tang and Felicetti from the RMIT University in Melbourne Australia. Their procedure called Evolutionary Structural Optimization (ESO)

*“...is based on the simple concept of gradually removing underutilized material from a structure so that the resulting shape evolves towards an optimum. “(Xie etal., 2005)*

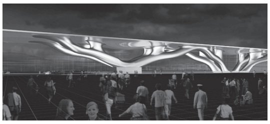


Figure 5.3.7: Competition entry for a station roof in Florence by Arata Isozaki and Mutsuro Sasaki

The design procedure was applied in an extended version for the design of a station roof in Florence Italy by Arata Isozaki in collaboration with Mutsuro Sasaki (Sasaki, 2005)

### 5.3.3.4 Generating diversity

In a completely different field evolutionary strategies are utilized to generate diversity. The design company futurefactories embraces the concept of mass customization by involving the customer in the design process of luminaires. Rapid prototyping allows to produce a multitude of different products for the same price than producing a series of the similar products. Hence a product can become a one-off for every customer

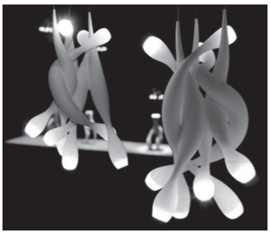


Figure 5.3.8: Tuber, a luminaire by futurefactories

An initial generic design of a luminaire is diversified by an EA which controls the constraints imposed by technical requirements. The customer interacts in the process by choosing the most appealing version which will then be further developed (futurefactories, 2008).

The above presented examples utilize evolutionary procedures for different purposes from optimization to collaborative design approaches to design exploration. In the space frame experiment the author seeks to negotiate structural and architectural requirements by a means of evolutionary strategies.

## 5.3.4 The space frame experiment

The algorithm used for the experiment is based on an implementation for a different purpose, conducted by Markus Schein from the School of Art in Kassel. The algorithm was subsequently adapted to the requirements of the evolving space frame experiment by to author.

The environment of the GA is provided by the double-layer surface system. As in the previous case study the surfaces represent an architectural design intent developed in a 3D modeling software. Both surfaces are translated into meshes with similar sample rates along their uv parameter space. The proliferation of elements between both meshes will be the objective of evolutionary improvement. Supports can be defined by the user at any node of the meshes in response to the actual design task. The meshing procedure and support definition are not objectives of variation but defined in advance.

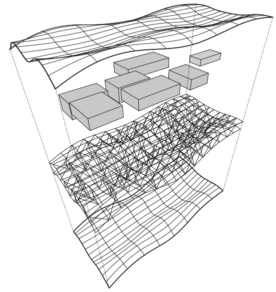
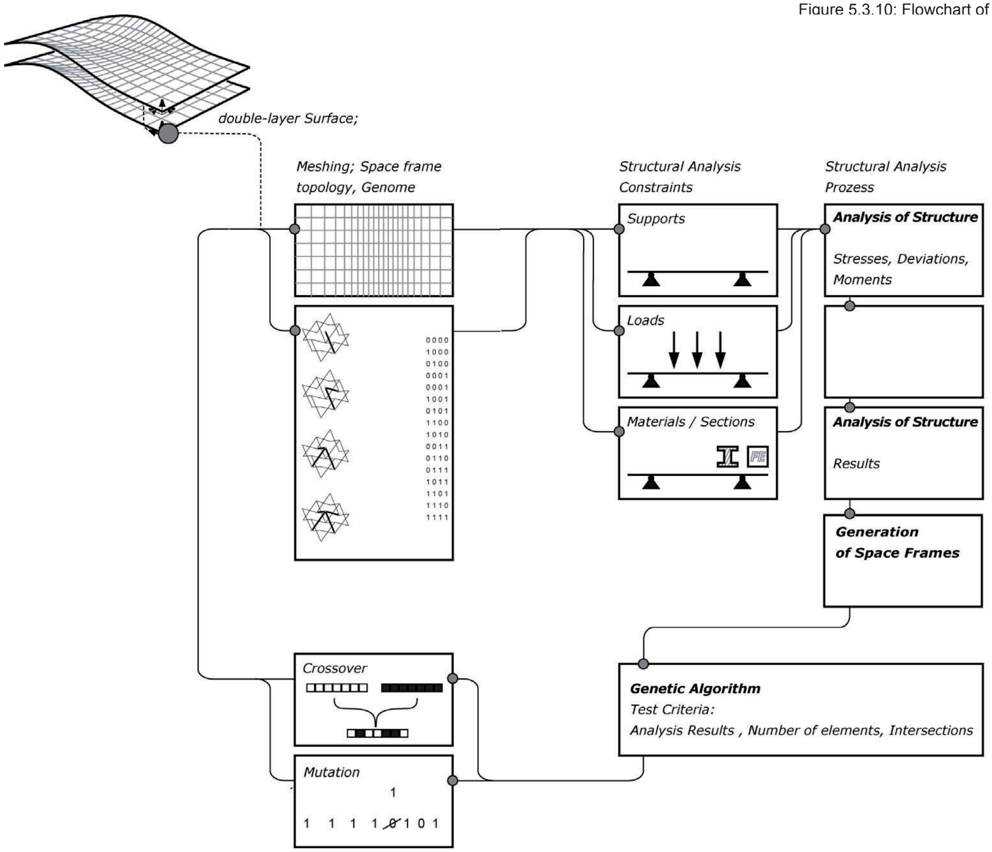


Figure 5.3.9 (top): Two surfaces, a space frame and several spaces define the starting conditions.

Figure 5.3.10: Flowchart of the space



The objective of evolutionary development is the changing number of diagonal elements between upper and lower mesh. Every node of the upper mesh has two, three or four possible connecting elements depending on its position in the mesh. The actual number of diagonal elements at a node is controlled by a genome. A binary code is directly translated into the space frame topology. A ‘0’ in the genome stands for ‘no element’ while a ‘1’ stands for ‘element’. During initialization a space frame with random topology is generated.

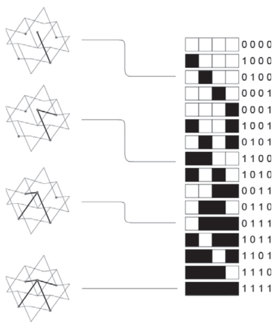



Figure 5.3.11: A four digit binary string controls the number of elements at every node of the upper mesh.

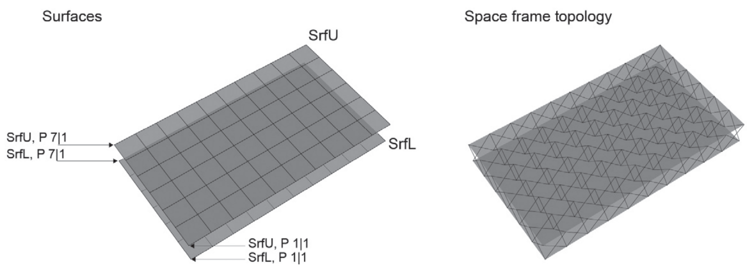



Figure 5.3.9: Design surface, quad mesh, and space frame topology

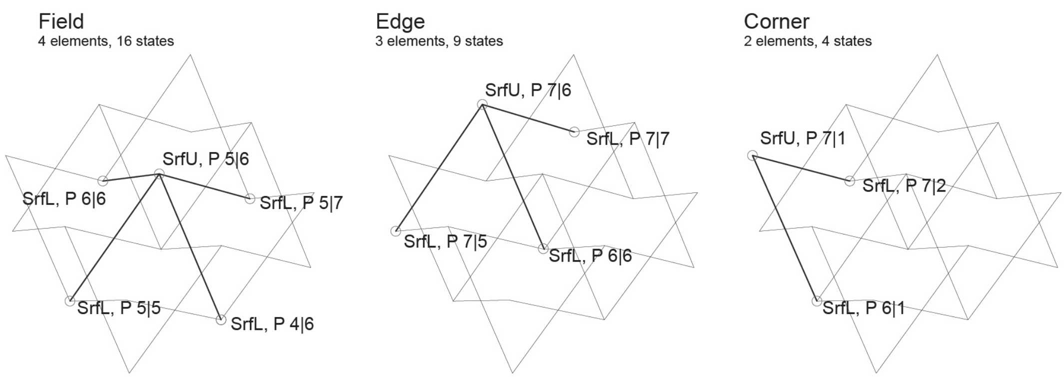



Figure 5.3.12: Space frame topology with only diagonal elements between upper and lower mesh. The number of possible elements depends on the position of the node within the mesh.

### 5.3.4.1 The Evaluation/Fitness Functions

In the current experiment the total deflection of the structural system, the total number of diagonals and the number of diagonals that interfere with predefined spaces constitute the fitness criteria.

#### Structural performance

Each space frame individual is evaluated and ranked by three fitness functions. The first fitness function creates a three-dimensional model in the structural analysis software RSTAB© based on the information of the individual genotype. A cross section profile and a material are assigned to each element although this cannot be regarded as a proper sizing of the space frame. Of major interest at this moment is a comparison of deflection of the different individuals under the influence of dead load. The maximal nodal deflection is identified and the aspired deflection value of the fitness function is subtracted. This value quantifies the performance of the solution.

#### Number of elements

The second fitness functions simply counts the number of diagonal elements that incarnate in the phenotype. The fewer elements an individual presents the higher it climbs in ranking. This fitness function obviously constitutes a conflicting interest to the first fitness function which rank rigid structures higher than those which show significant deformations.

#### Spaces without structure

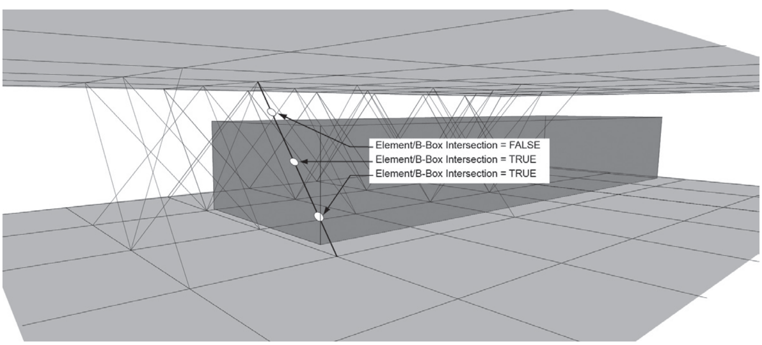



Figure 5.3.13: The third fitness functions checks how many elements intersect with the volumes that should contain no structure. Three vertices on every element are observed.

The last fitness function checks whether an element penetrates defined volumes between the two horizontal surfaces. Three vertices along the element are analyzed regarding their position in relation to the bounding boxes of the volumes that should be free from structural elements for architectural reasons. The lower the number of points inside the bounding boxes the higher the individual ranking. The volumes provoke structural disturbances due to architectural requirements which have to be incorporated into the system.

**Selection and reproduction**

After all individuals are generated and ranked by the fitness functions the space frames are selected by the roulette wheel method. Thus better ranked space frame individuals will survive more likely but also weaker individuals are not completely without chance. This selection procedure prevents from early stagnation in the development because even weaker individuals may inherit properties that might prove successful in future generations.

The individuals selected by this procedure are used to produce offspring for the next generation. The two genetic operators mutation and crossover vary the number and position of the diagonal elements connecting the upper and lower part of the space frame mesh.

## 5.3.5 Results

The evolved space frame shows an improved performance regarding a significant decrease in element number while maintaining only little deflection.

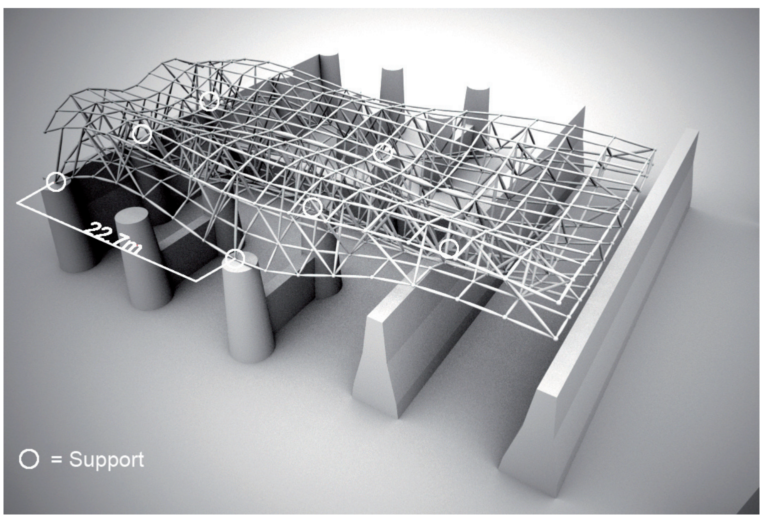



Figure 5.3.14: Space frame result after 280 generations.

The process starts with a high number of elements (406 in generation 1) generating a rigid space frame with small deflection of 103mm.  During the evolution the number of elements decreases (298 in generation 280) while the deflection is significantly changing (~11mm). The number of element/space intersections is reduced from 300 in generation 1 to 50 generation 280. The fitness landscape in Figure 5.3.18 depicts the development.

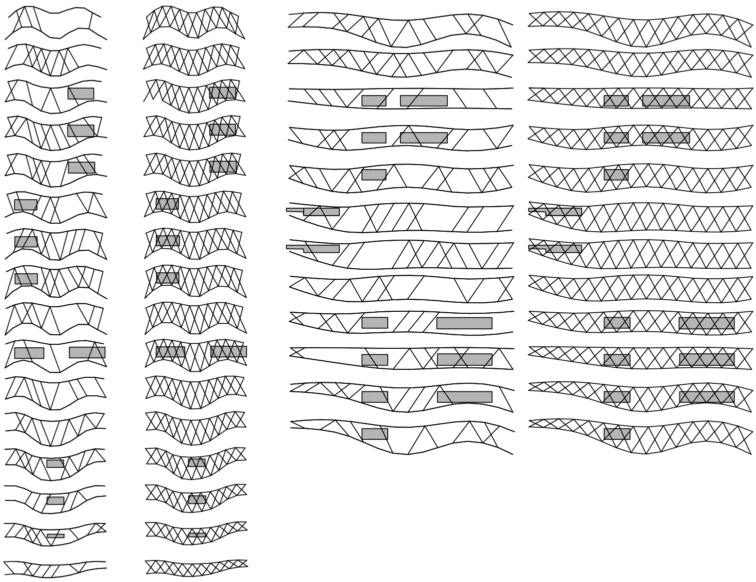


Figure 5.3.15: Cross and longitudinal sections of space frame from generation 215 in comparison to space frame with all possible elements.

## The structural system

The series of sections in cross and longitudinal direction of the space frame individual from generation 215 display parts of a system with a very unconventional topology. A systematic arrangement of diagonal is not observable. The allocation seems rather arbitrary. Instead of a preconceived structural typology the system embodies a certain randomness which is owed to the generation process. More important, however, is the remarkable performance of the system; while minimizing the deflections it also reduces the number of elements in total and those that penetrate the spatial volumes (represented by the grey squares in Figure 5.3.15). The system is the best from 5375 evaluated versions. The space frame topology emerges out of an interaction with the overall geometry defined by the guiding surfaces and the predefined support positions. While adapting to local conditions the system still maintains an overall coherence. The result reveals the potential for collaborative design approaches. A space frame can be more than a system that merely establishes the large spans. The case study exemplifies the interaction of the structural system with an overall form intended by the architect and local spatial requirements within the system. David Billington's dictum of structural art which is defined by large spans and forces, efficiency and mono-functional program excluded architectural aspects. The presented case study offers a procedures for lively collaborations yielding novel structural and architectural solutions.

**Pareto Frontier representation**

Collaboration means the negotiation of multiple and even conflicting parameters of a design proposal. EA's proved helpful in this process of balancing various constraints. The space frame should have a minimal deflection and at the same time a minimal number of elements and additional disturbances through the spaces within the system. EA's are heuristic algorithms. The pursuit for the optimal solution is abandoned in favor of a pretty good one. As shown in Figure 5.3.18 the evolution converges towards the predefined optimum but never reaches it. Instead a range of pretty good solutions with various properties evolve. The achieved solutions embody different equilibria. While one solution bears almost optimal structural properties, its spatial volumes are penetrated by many structural elements. Other solution are architecturally preferable at the expense of a larger deflection.

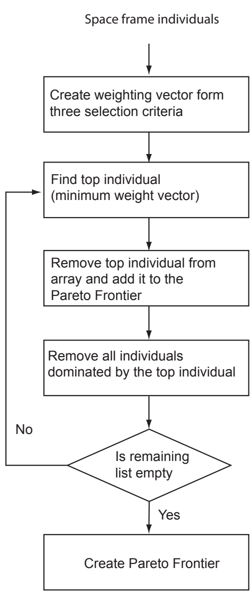



Figure 5.3.16: Pareto Frontier algorithm as utilized in the space frame experiment

An suitable way to represent the different versions is the Pareto Frontier. The concept of the Pareto Frontier is named after the Italian economist Vilfredo Pareto (1848 - 1923) who developed this concept for his studies in income distribution. Pareto explored the distribution of goods/money. If the reallocation of a good from one individual to another is positive for at least one individual without being negative for another a Pareto Improvement is achieved. If the reallocation of goods is continued until no change is possible without creating a disadvantage for any individual the Pareto Optimal is achieved. This equilibrium of conflicting parameters is not necessarily located in one single point but constitutes an n-dimensional frontier; the Pareto Frontier.

In the space frame experiment the Pareto Frontier is based on three parameters and can therefore be represented by a surface or a point cloud. Every point in the point cloud represents one space frame individual. Space frame solutions which are not part of the frontier surface did not achieve the possible Pareto Optimum. Solutions beyond the surface may be conceivable but were not "found" by the EA.

Solutions on the frontier surface constitute the best negotiated versions, still varying in individual criteria. The Pareto frontier visualization enables to spot those solutions and choose between them. The decision-maker can choose from a range of balanced solutions. This selection process can finally be driven again by subjective criteria, since all solutions on the Pareto frontier a balanced.

The goal value for the total number of diagonal elements was set to 200. This value was quickly achieved but many elements were still intersecting with the spaces. An improvement of this criteria was not achieved by a further reduction of elements but by a reallocation. The roulette wheel selection method proved helpful because obviously an individual with very different topology provided a different and better solution.

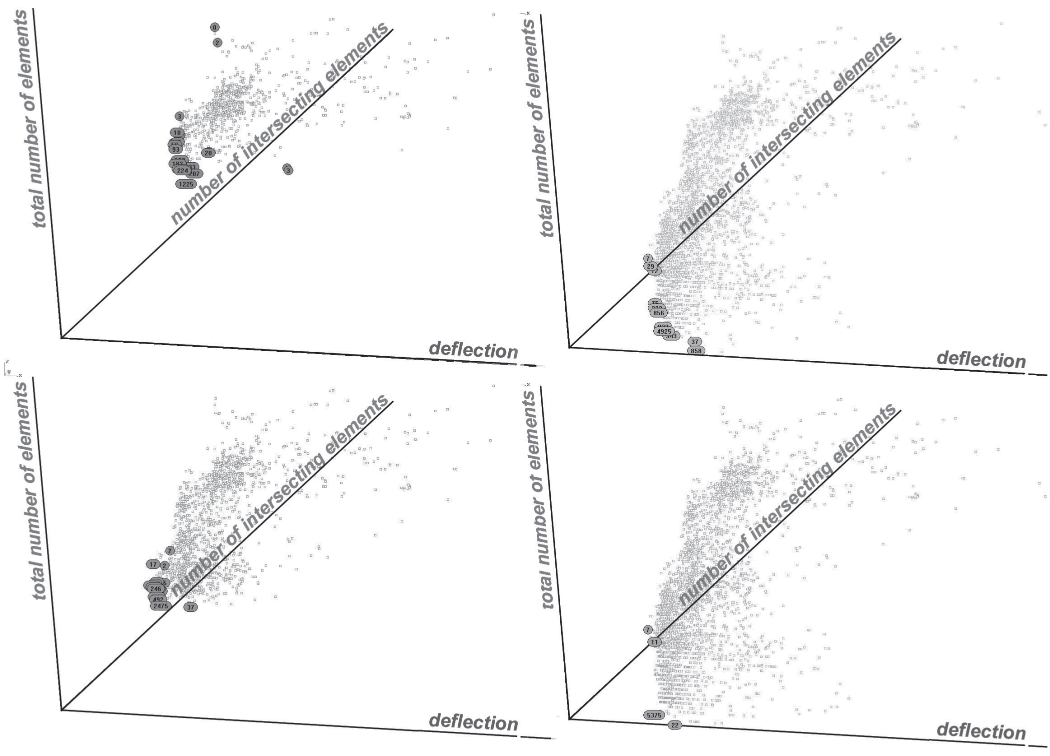



Figure 5.3.17: Pareto Frontiers after 50, 100, 150, and 280 generations. Representation of all generated solutions in a three-dimensional graph. The position in the space represents the total fitness of the individual but also the values of the different fitness functions. The x-axis shows the deflection of the system. The y-axis represents the elements which intersect the bounding boxes and the total number of diagonals of assigned to the z-axis. Deflection and number of elements are increasingly reduced. The number of space frame individuals constituting the Pareto Frontier is shrinking with increasing number of generations. Hence, with improving solutions the number of versions to chose from is getting smaller.

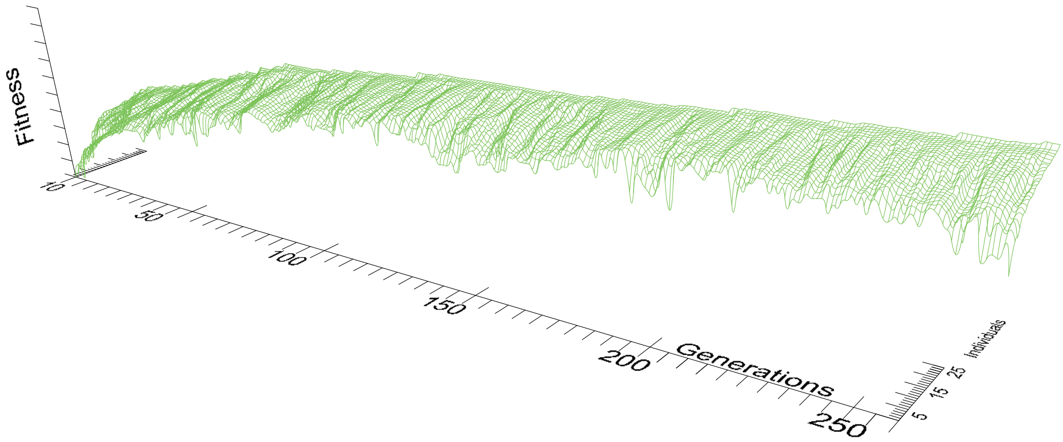



Figure 5.3.18: Fitness landscape. The surface represents 280 generations with 25 individuals. The individuals are sorted by fitness along the x-axis. The landscape depicts the typical converging curve towards an optimal solution.

### Instantiation/Sizing

A centre line model represents the resulting space frame solution. This generic data has to be instantiated by a material system, a subsequent task which is only briefly addressed in this case study. The procedures is explored in detail in case study 3.

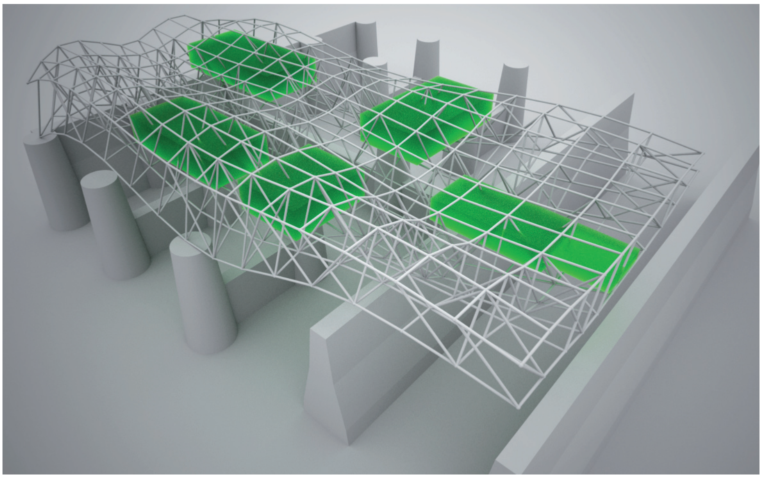
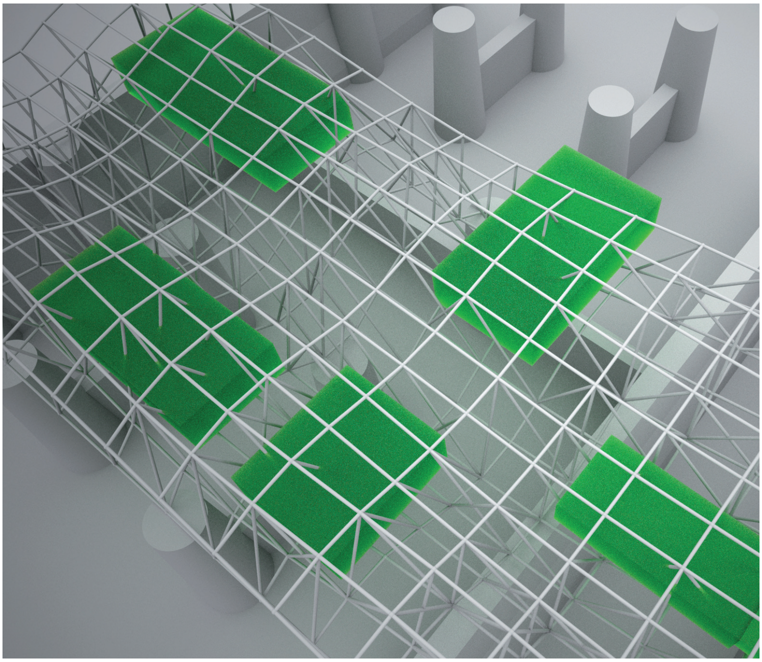


Figure 5.3.19: Rendering of the final space frame with green boxes representing spaces almost free from structure



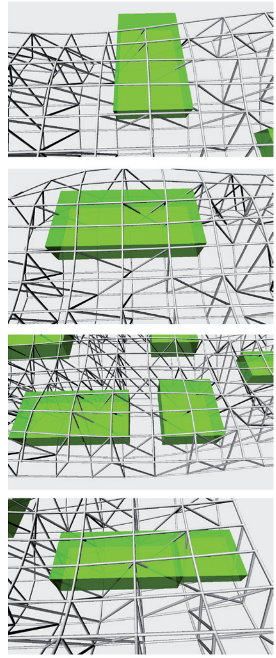
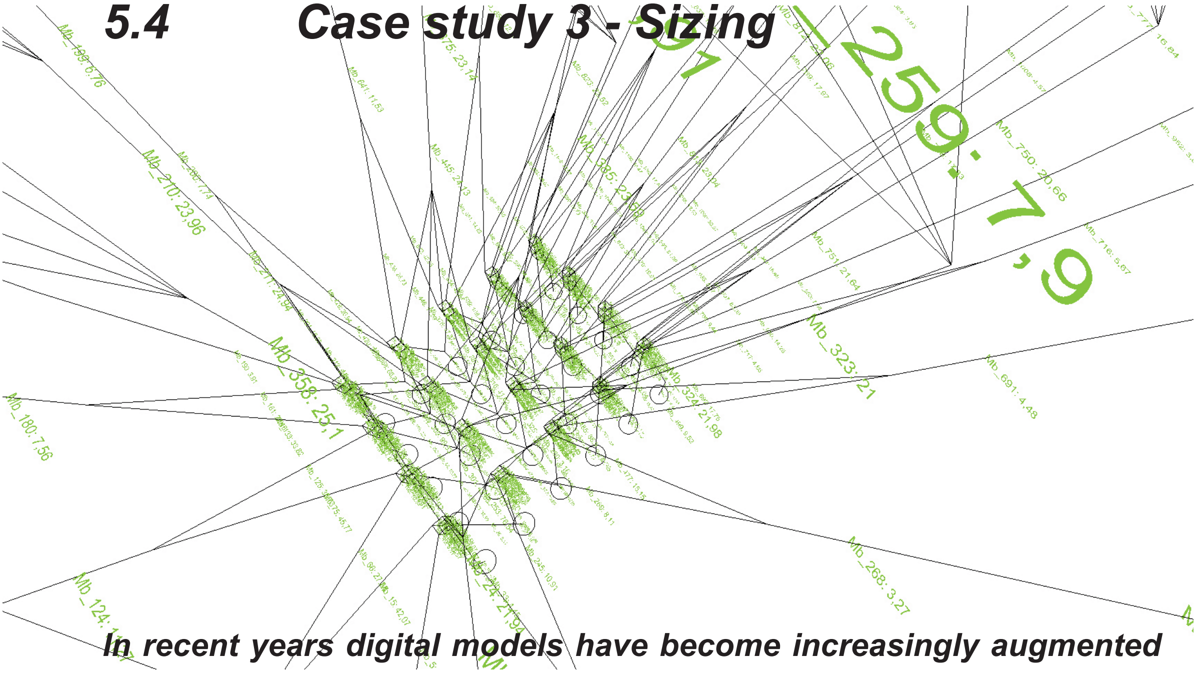


Figure 5.3.20 and Figure 5.3.21 (series on the right): Bird view reveals the allocation of diagonal elements. Structural density is organized between the boxes.

# 5.4 Case study 3 - Sizing




***In recent years digital models have become increasingly augmented by embracing requirements of computer-numerically-controlled fabrication techniques, constraints originating from geometry, material properties, panel sizes, etc. The case study aims to embed this rationalization into the design process by using constraints as driving forces. Furthermore another crucial aspect of architectural design was supposed to be integrated: the structural performance of building components as design driver from early on. In collaborative design processes of architects and engineers structural design is thus becoming an integrated node within a network of multiple requirements which have to be balanced.***

While one discipline is carefully engaged in providing security and determinability by relying on established procedures the other urges for the generation of novelty in processes, procedures and products. One promising way to blur the realm of quantitative data with qualitative approaches is seen in the use of macro-scripting and programming.

The research was initialized by a competition entry of the author in collaboration with Mirco Becker, Asko Fromm and Gregor Zimmermann for a landmark tower in Paris. The case study is comprised of two design studios conducted by the author in collaboration with Markus Schein and students from the University of Kassel. Both studios relayed on custom-written scripts and programs by the tutors. Thus the role of the author changed from being a designer to being a tool designer who observes the use of his tools.

## 5.4.1 Surfaces and components

The immaterial digital surface is a very elegant means in architectural design. It is defined by networks of curves, point clouds or curves that describe spatial movement while spanning a surface in space. Those objects are spatial and superficial at the same time and embody a dynamic capacity, continuity, and gradual change. The surface is the outermost border of a body interfacing its environment. It is described by two dimensions that unfold curved or planar, limited or endlessly into three-dimensional space. At the same time geometry describes every point on the surface by three coordinates, thus in Cartesian space. Following this paradox a solid is reduced to its outermost border. A boat hull dissolves

> *“into a coat of bright paint deftly applied to the wood planks of the hull[…] the body reduced to its limiting part lies neither inside nor outside the figure but right at the juncture…” (Liaropoulos-Lengendre, 2003).*

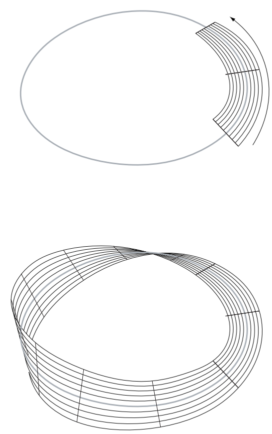


Figure 5.4.1: The Möbius strip generated by a line which is extruded along a path while revolving by 180°.

In the digital realm this contradiction causes no problems. In a 3D modeling environment a surface is accessible and can be manipulated directly or through its control polygon. Textures, applied like a thin veneer, simulate depth and material properties and let the surface appear like a physical object. But when converting such digital surfaces into physical objects the contradiction between depth and superficiality is finally revealed.

### 5.4.1.1 Design surface and component

The incoherency of digital surface and physical objects is exposed whenever unlimited digital continuity is confronted with the architectural scale involving joints, seams and panelizing.  To overcome this conceptual flaw and to accomplish construction requirements the strategy of the “design surface “ (Kilian, 2006) was recently introduced into the design practice. The two-dimensional surface is used as a host which is associated with secondary geometry, representing three-dimensional building components. The mathematical description of NURBS curves and surfaces by polynomial functions allows identifying every point on a surface and its inherent geometric properties like surface curvature and normal direction. The information is utilized to align components that fulfill fabrication constraints and at the same time represent the overall morphology of the initial surface. Their local geometric properties are passed to discrete components that build up a fine-grained organizational system linking initial digital shape and physical object. The procedure embraces the fact that architecture is never comprised of one continuous material but composed of multiple ingredients.

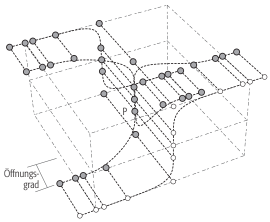



Figure 5.4.2: Parametric component derived from a bounding box.

### 5.4.1.2 Component and series

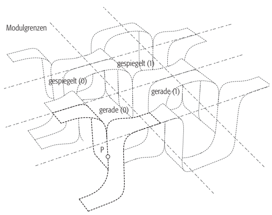



Figure 5.4.3: Component in a regular array.

A component is initially represented as a three-dimensional diagram that describes its elements and their topological relations. The generic system gains specificity when placed on a surface and informed by its local parameters. The series of components experiences a gradual differentiation. Such a transformation affects all elements in a group and needs a critical mass to be perceivable. The individual element is not unique but a part of a larger self-similar structure that tackles multiple requirements, such as program, structure, and constraints originating from material properties, geometry and fabrication. The whole emerges out of the interaction of a series of individual elements. Interaction and feedback acts bi-directional: from overall form to component by modifying the guiding geometry and vice versa, when the component reacts on structural and material requirements.

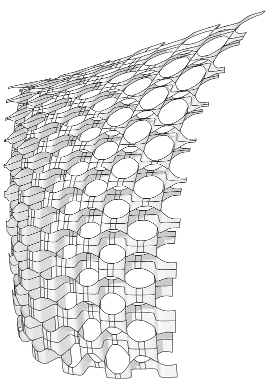


Figure 5.4.4: Component proliferated along a design surface. Component and design proposal by Jana Bermann, 2007

### 5.4.1.3 Repetition and difference

Konrad Wachsmann perceived the principles of industrialization similar to those of mass-production. The benefit of automation is only attainable through quantity in production, a principle that distinguishes industrialization from craftsmanship. In consequence the term “tool” changes its meaning from a generic means for multiple purposes to a specific device for mechanical casting, punching, or cutting. Thus, every instance of the final product is copy of the only original in the process: the form-defining tool.

To guarantee sound assembly of mass-produced objects Wachsmann introduces a series of coordinate systems and an ultimate standard that defines properties and quality of products. Modular coordination is the name of Wachmann’s organizing principle. It refers to points, lines, surface, and solids in space and provides consistent measures within one single system. Every individual element is organized internally and in relation to its neighbors. A superior universal module coordinates the different categories of modules like geometry, tolerances, construction etc (Wachsmann, 1959).

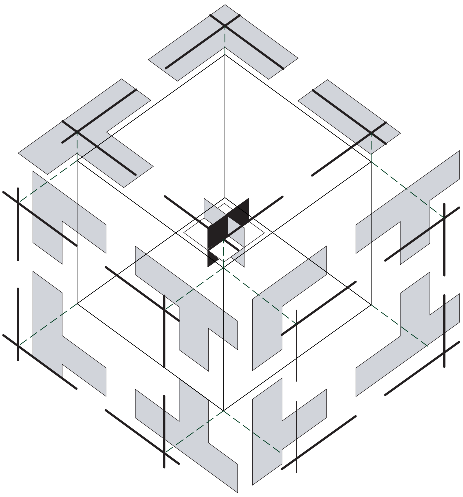


Figure 5.4.5: Konrad Wachsmann's modular coordination. The diagram serves as a means to control spatial relations while conducting two-dimensinal studies. Grid lines match the center lines of any kind of element.

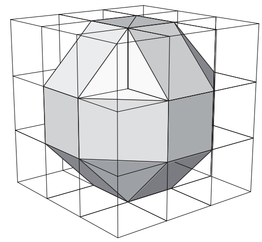


Figure 5.4.6/5.4.7: The MERO© node is based on a spatial grid of 27 cubic cells and comprised of 26 faces in a point symmetric array.

The implementation of such an industrial logic ensures constant and repeatable quality but at the same time the formalized system limits the range of what is buildable.

> *"[Die Industrialisierung] kann nicht als Hilfsmittel missbraucht werden, um frei erfundene Konzeptionen zu verwirklichen. Sie kann nur als direkte Ursache für die Entwicklungsbestimmung irgendeines Produktes verstanden werden, das als Teil oder in Kombination mit anderen die Ausdrucksform bestimmt" (Wachsmann, 1959).*

Industrialization cannot be abused to realize freely envisioned concepts but always acts as the origin and framework for development of a certain product. This notion of mass-production was necessary in the beginning of industrialized procedures in the building industry and yielded systems like the Mero node and Fritz Haller's furniture and architecture kits. Nevertheless it precludes any deviation from the idealized type the system is reduced to. Variation becomes a deviation from the ideal and is always perceived in relation to this starting point. A honeycomb is thus reduced to an array of homogeneous hexagonal cells. Singularities, as a reaction to a specific context, are treated as an anomaly rather then as a part of the system. The industrialization of the building industry promoted by architects like Konrad Wachsmann, Fritz Haller, Jean Prouvé, and others is succeeded by the digitalization of fabrication since the 1990s. Both developments share certain similarities. Wachsmann, for instance, advocates for a novel educational agenda and prefers anonymous teamwork instead of individual authorship. The primary focus is directed away from traditions and craftsmanship towards new materials, technologies, and methodologies. A similar euphoria can be spotted in the publications since the late 1990s. Quite many texts report about computer numerically controlled machines that apparently

> *"… fabricate unique, complexly-shaped components at a cost that is no longer prohibitively expensive. Variety, in other words, no longer compromises the efficiency and economy of production" (Kolarevic, 2003).*

But the benefit of numerical control in fabrication can only be attained when the entire design procedure forms a continuous digital chain including geometry generation, identifying and labeling components, and assembly procedures. A process, although technically achievable, often spoiled by legal issues and liability that arise when data, produced by the architects, is supposed to be used by the contractor for fabrication.

Figure 5.4.8: Every NURBS surface is described by uv parameters. This continuous representation provides information like, Cartesian coordinates, curvature and normal direction for every point on the surface.

A continuous digital workflow is comprised of elements similar to those described by Wachsmann but adapted to novel technological possibilities. In the actual case study the modular coordination is repetitive but at the same time differentiated. The framework for every single module/component is derived from four surface normals forming a non-orthogonal bounding box. Similar to Wachsmann's

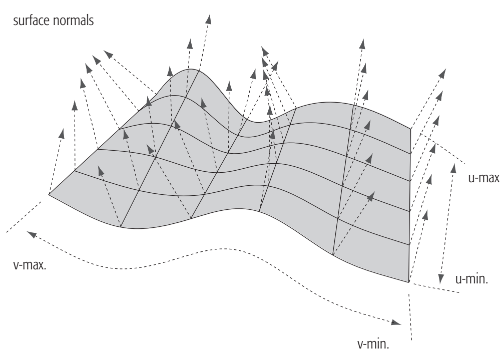



Figure 5.4.9: The "Take Off" sculpture by Franken Architekten in collaboration with Bollinger + Grohmann. Every lamella is an instance of a parametric component with a unique geometry.

universal module all subsequent information is derived from this initial hull geometry. The double- curved surface becomes the guiding geometry for the modular coordination.

The original within such a process is the algorithm that generates the geometry. It produces data that is subsequently instantiated as g-code for milling or laser cutting, 3d printing, rendering, or drawing. Form is of subordinated interest and separated from the underlying principles which organizes the relations of the different elements within the component. Every component can differ in geometry as long as the relations between its elements are correct.

There is no ideal component and subsequent deviation. Every component is unique and gets informed by local parameters of the guiding geometry. A typology could be derived from the entire body of components but not from a single one. A notion, precisely expressed by Ernst Mayr in 1976:

> *“The populationist stresses the uniqueness of everything in the organic world. What is true for the human species – that no two individuals are alike – is equally true for all other species of animals and plants. Indeed, even the same individual changes continuously throughout its lifetime and when placed into different environments. All organisms and organic phenomena are composed of unique features and can be described collectively only in statistical terms. Individuals, or any kind of organic entities, form populations of which we can determine the arithmetic mean and the statistics of variation. Averages are merely statistical abstractions, only the individuals of which the populations are composed have reality. The ultimate conclusion of the population thinker and of the typologist are precisely the opposite. For the typologist, the type (eidos) is real and the variation an illusion, while for the populationist the type (average) is an abstraction and only the variation is real.” (Mayr, 1976)*

#### 5.4.1.4 Scripting

The approach can only be tackled through the use of scripting which automates the proliferation of the components along the surface and the generation of cutting pattern for fabrication. The very act of designing is shifted from the generation of objects towards envisioning, implementing, and controlling generative processes. Scripting is helpful to close gaps in the continuous production chain and transfer sheer quantity into a compositional quality.

#### 5.4.1.5 Analysis data

Digital design and analysis applications use the same core logic and fundamentals of computer graphics and math. Once all parties develop a mode of describing design problems in this language they have the tool for a collaborative dialogue. Such a description is referring to point-coordinates in space and their relation to each other. It is used to describe the design, analyze the structure, and revise the design based on the results of an analysis cycle. Hence a basis for collaborative design is already latent in any digital design tool. Establishing modes of exchanging, integrating and referencing various kinds of information becomes a key factor for collaborative approaches.

For a successful design development it is crucial to establish that dialogue early during a sketch design phase. That attitude leads to a different way of sketch-designing which is rather programmatically driven and allows for a gradual increase of complexity without loosing information or control. The early implementation of analysis data and their interpretation in an architectural way is exemplified in the succeeding second design studio.

### 5.4.2 Preliminary experiment – A landmark tower

The cooperative strategy of architects and engineers as well as the use of programming is exemplified by the project “augmentedFRAME”, a competition entry by the author in collaboration with Mirco Becker, Asko Fromm and Gregor Zimmermann. The competition asked participants to design a landmark tower that supports Paris’ bid to organize the Olympic Games 2012. The two crucial aspects

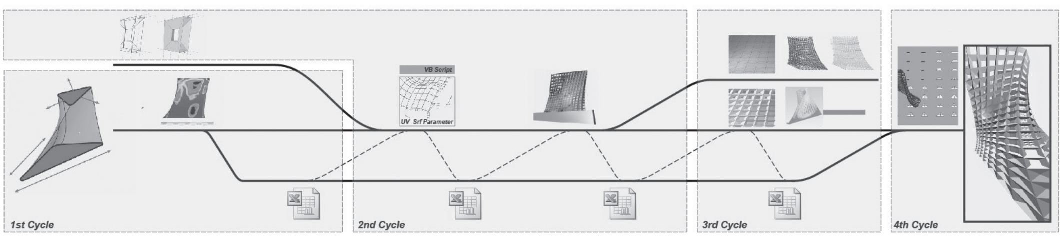



Figure 5.4.10: Diagram showing the development cycles and collaborative dependencies

of the design were firstly the morphology of the tower in its relation to site and program and secondly the consideration of the tower as a surface structure depicting the flow of forces by grades of density and permeability.

The design process was comprised of a series of feedback cycles: Finite Element Analysis (FEA) improving the shape and visualizes the flow of forces, geometric analysis, structural space frame analysis and analysis of vistas. Each of these stages allowed going back to any previous stage without losing information (Figure 5.4.10). The final design proposal embodied the synchronization of these chosen parameters represented in a complete dataset.

The design surface (NURBS surface) as architectural approach went through a structural surfaces analysis. The engineers imported the 3D data into their FEM/FEA Software to analyze and visualize the stress distribution. The design was considered and calculated as a continuous meshed skin at that moment. The

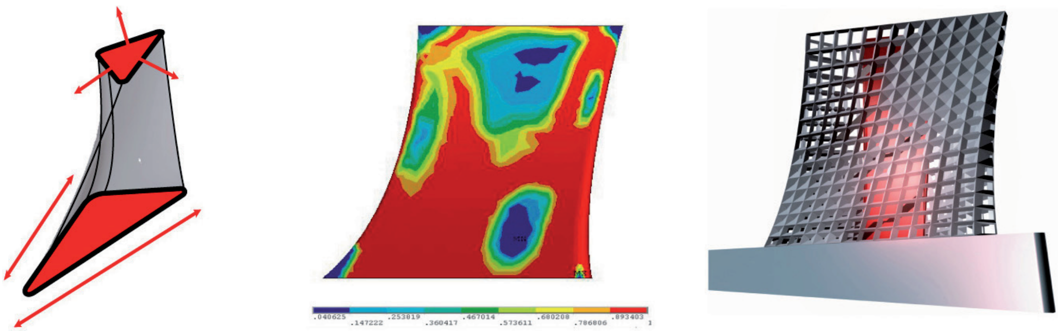



Figure 5.4.11: Skin, FEA plot, façade with adaptive component

analysis was plotted as a false color image and a point cloud with stress analysis values.

Simultaneously a generic component was developed as a basic unit for a space frame structure. The intent was to explore a particular structural system which is relatively simple but carries the potential to vary in its structural performance as well as its permeable performance. The component was set up as a parametric

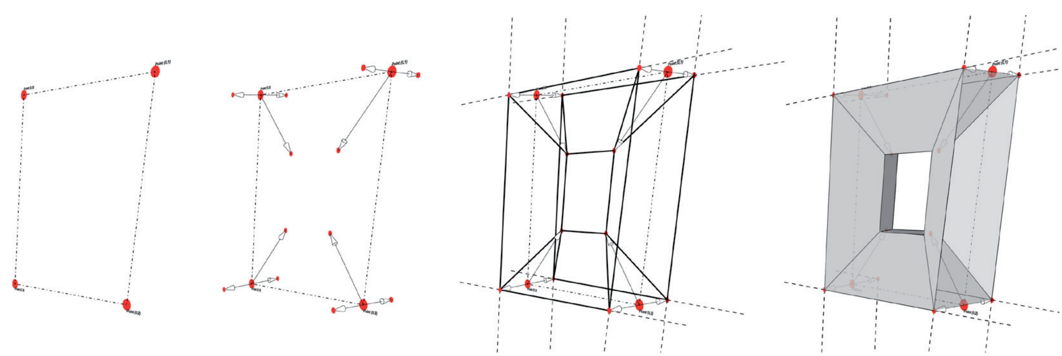


Figure 5.4.12: Parametric module of the space frame

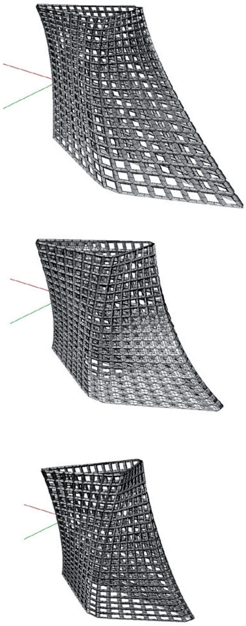


Figure 5.4.13: Parametric components adapted to a sequence of different design surfaces.

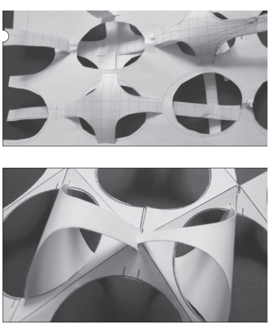


Figure 5.4.14: Conceptual paper models.

model, i.e. single components, their size, position and geometry could be manipulated through variables while all elements could be fabricated from sheet material.

The skin then was used as a reference to populate the parametric components with the help of a script routine and the parameterization of the design surface. Site criteria, visual connection from the building into the city and the stress distribution values derived from the FEA were the driving parameters for the adaptive space frame module. A major achievement was to establish a feedback between FEM surface analysis and space frame population.

The multi definition of the parameter “opening” (structure, view, light) in the space frame component creates conflicting interests. It is precisely these conflicts which provoke creative architectural potential. Instead of treating/designing every opening individually, the team tried to compose the individual interests like a musical score where the different voices change from foreground to background within the structure of the whole composition.

The project proved the potential for collaborative design approaches. Anyway the modes of exchanging, integrating and referencing various kinds of information became a key factor. The technical basis for exchange was already latent in many digital design tools but needed a further refinement. This task was further examined in the subsequent design studios.

## 5.4.3 Design studio 1 – Fabrication constraints

The first studio attempted to integrate constraints into the design process that originate from material systems and fabrication techniques. Scripting was used to describe parametric components that proliferate along a host surface and adapt to their local geometry to form a light modulating screen. The components were fabricated using a laser cutter, so that the digital models had to be augmented by requirements of computer-numerically-controlled fabrication techniques, geometric properties (flat panels, single-curvature, etc.), material properties (bending radius, machinability) and panel sizes to embed rationalization into the design process.

After a one-week tutorial of Rhino Scripting the participants were asked to design a component that could be derived from eight corner points of a non-regular bounding box. Every element of the component had to be laser-cut from sheet material. To embed fabrication constraints from early on the conceptual phase was conducted using physical models made from appropriate sheet materials like paper, acrylic glass and wood. The component was then digitally modeled

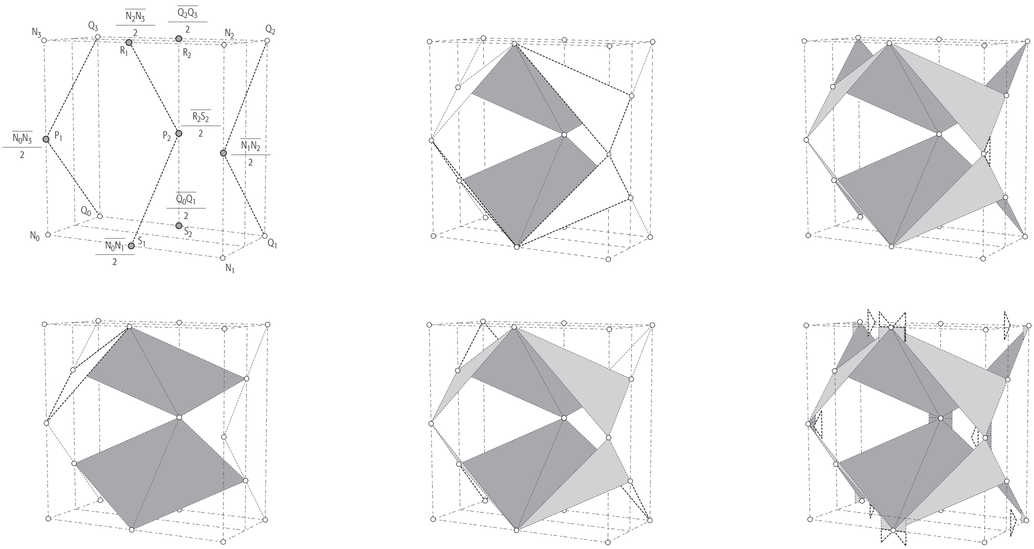



Figure 5.4.15: Sequence of component generation based on eight bounding box vertices, David Seeland. The lower right diagram shows additional flaps which became necessary for connecting components.

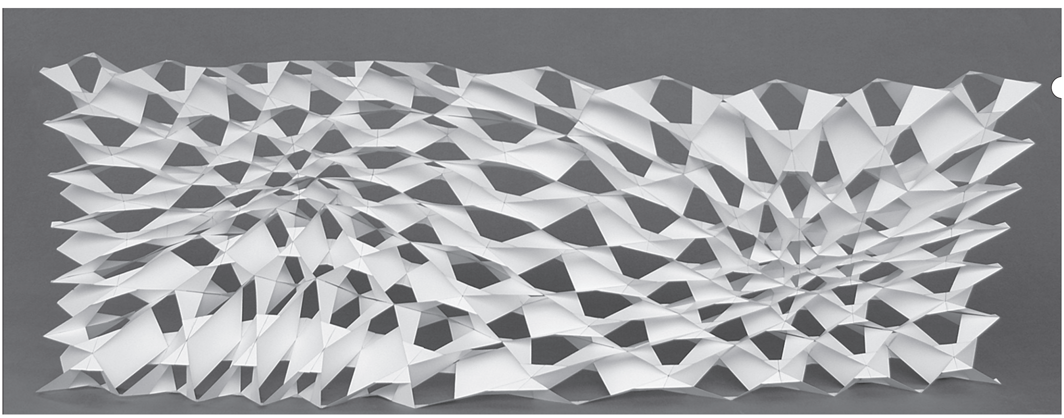


Figure 5.4.16: David Seeland sought to negotiate structural performance with a high level of transparency. The component is comprised of triangular shapes that provide a rigid structure made from planar elements. The overall form of the screen is undulating in the lower area to provide stability. The uv-parameter space of the surface is adjusted to its curvature. In areas with a high degree of curvature the isocurve network is tightened which finally leads to smaller components. The isocurve network directly propagates into the component configuration.

to explore a proper generation sequence and subsequently transferred into an implemented algorithm. Besides the host surface, several participants integrated additional external control parameters. A further reduction of digital draftsmanship could be achieved through the automation of labeling and unfolding the components for laser cutting. The following fabrication and assembly of the physical models allowed no further automation and was accomplished in a time and labor intensive process. Connecting components with each other proved to be delicate due to mere punctiform or linear contact areas. The problem was solved with additional connecting flaps. Many participants experienced this problem. It is not apparent in the digital realm but very obvious when assembling a physical model. The same applies for material thickness, often dismissed when using sheet material.  Those problems emphasize the importance of physical models in the design process. In the studio students got equipped with scripts that tackled the prolif-

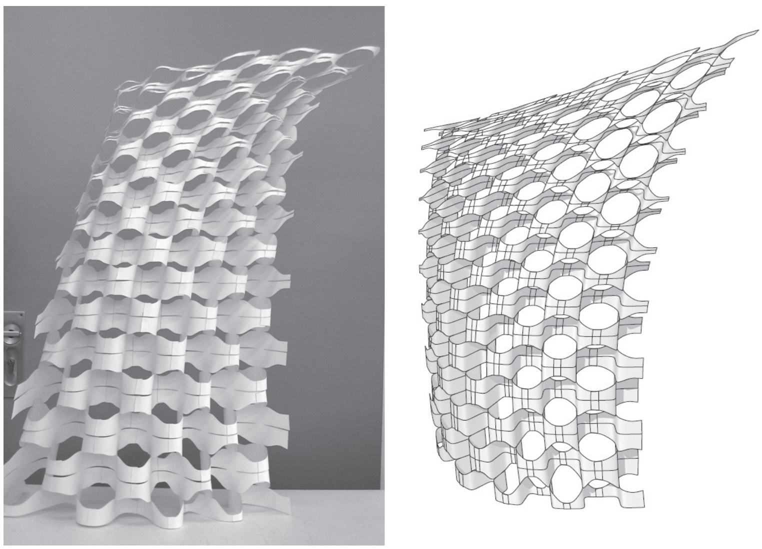
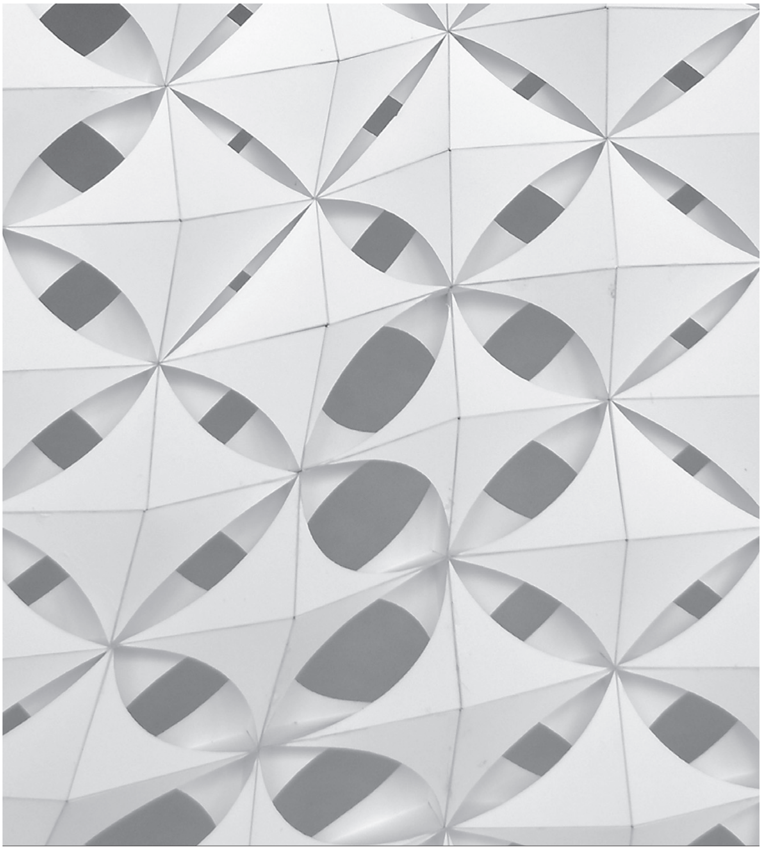


Figure 5.4.17:  Jana Beermann's single curved component blurs its boundaries and merges into an undulating overall form. Large parts of the object could be fabricated in one piece spoiling the component logic but solving the problem of connecting single components. The curvature provided significant rigidity to the cardboard model and allowed large openings in the screen.



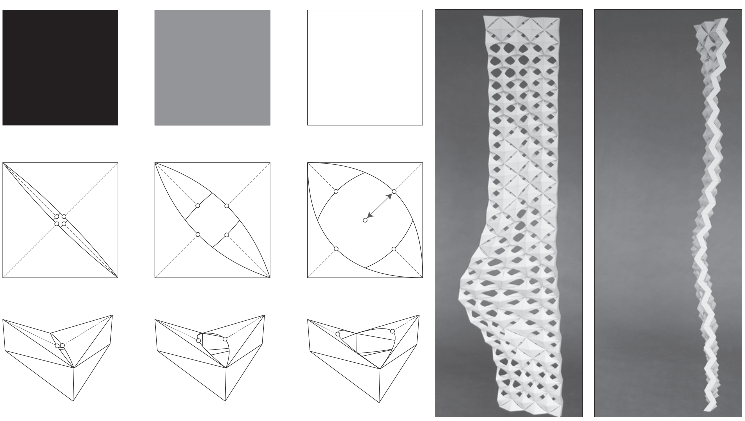


Figure 5.4.18: Johannes Kuhnen developed a lens-like component that is not only driven by the guiding geometry but also by a grayscale image. The component becomes a pixel, able to display 255 grayscale values by altering the size of the lens. The ability of displaying two-dimensional images is superimposed by a curved and distorted host surface.

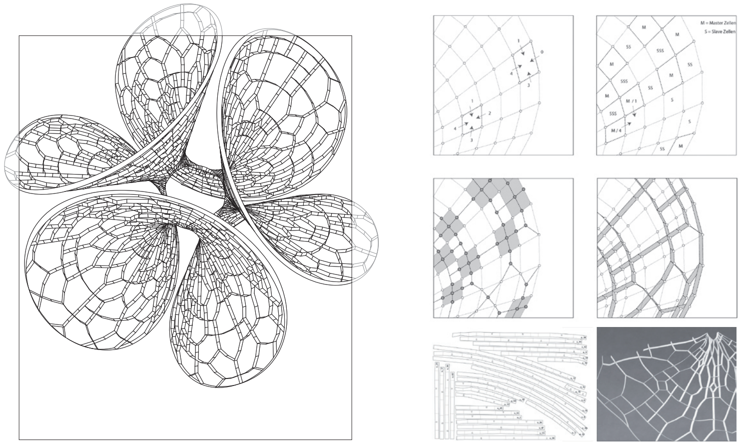
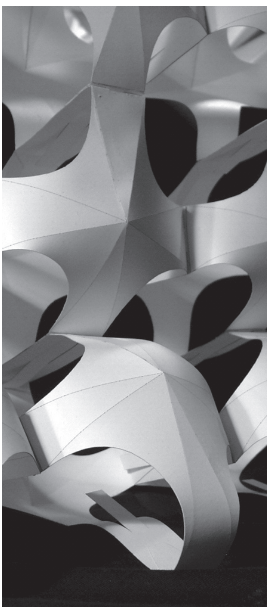



Figure 5.4.19: Instead of a single component Nicola Lammers used a series of components that proliferated in a master-slave relationship along the host surface. The configuration was applied to an Enneper surface and yielded a structure which exceeded the three-dimensional representation of isocurve directions.



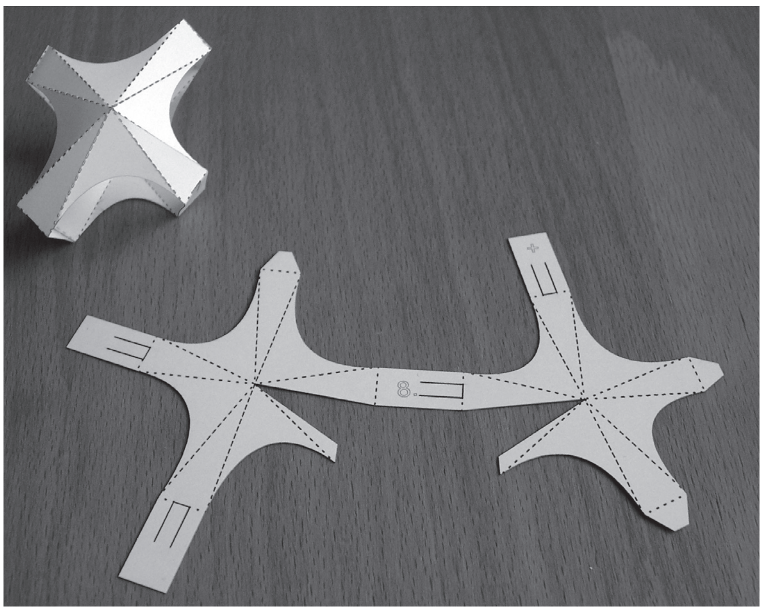


Figure 5.4.20: Hanno Stehlings components could be cut from one sheet of cardboard which accelerated assembly. Unambiguous labels replace shop drawings and assembly guidelines.

Figure 5.4.21 (left): The lowest row of components deformed under the load of the entire model. Material thickness proved to be too thin and the folding of single faces did not provide enough bracing. Many models from the studio suffered deformation for similar reasons hence structural aspects were taken into account in the second studio.

eration of components along the host surface. Individually written component scripts got merged into this larger framework provided by the tutors. The design procedure was very rigorous and allowed only few individual contributions within the overall framework. The overall form was limited to a single NURBS surface.

### 5.4.4 Design studio 2 – Integrating analysis data

While in the first studio the geometric models became increasingly augmented by requirements of CNC fabrication, the second studio aimed to integrate a further crucial aspect of architectural design: the structural performance of building components as design driver from early on. In collaborative design processes of architects and engineers structural design is thus becoming an integrated node within a network of multiple requirements which have to be balanced. Besides questions of embedded rationalization the research explored the use of scripting and programming to blur the realm of quantitative data with qualitative approaches. Building components embrace architectural and structural aspects– from space generating to space demarcating to load bearing.

In the studio participants went through a Rhino© scripting workshop similar to the previous studio. In addition they got equipped with an interface between Rhinoceros© as the modeling environment for architects and Dlubal RSTAB© as the analysis application for engineers. The interface was established using Microsoft Visual Basic 6.0© (VB 6.0). Curves, Surfaces and Solids modeled in Rhinoceros© are translated into meshes, nodes and elements suitable for calculation in RSTAB©. Relevant results of the calculation like deflections and stresses could be fed back into the geometric model.

The students were asked to design a parametric component, comprised of planar or developable elements, which could be derived from the eight vertices of a bounding box. Besides a mere surface representation a center line model for structural analysis was required. Furthermore a three-dimensional guiding system for the population of components comprised of a series of surfaces had to be developed.

The subsequent process of component propagation conducted by the VB 6.0 environment was twofold: In the first iteration a centre line model of the structure was generated and transferred to RSTAB©. For structural analysis a cross section, the material properties, and the load case were assigned. To keep the process feasible only the dead load was taken into consideration. The analysis data was fed back into the second generation cycle. The actual components were

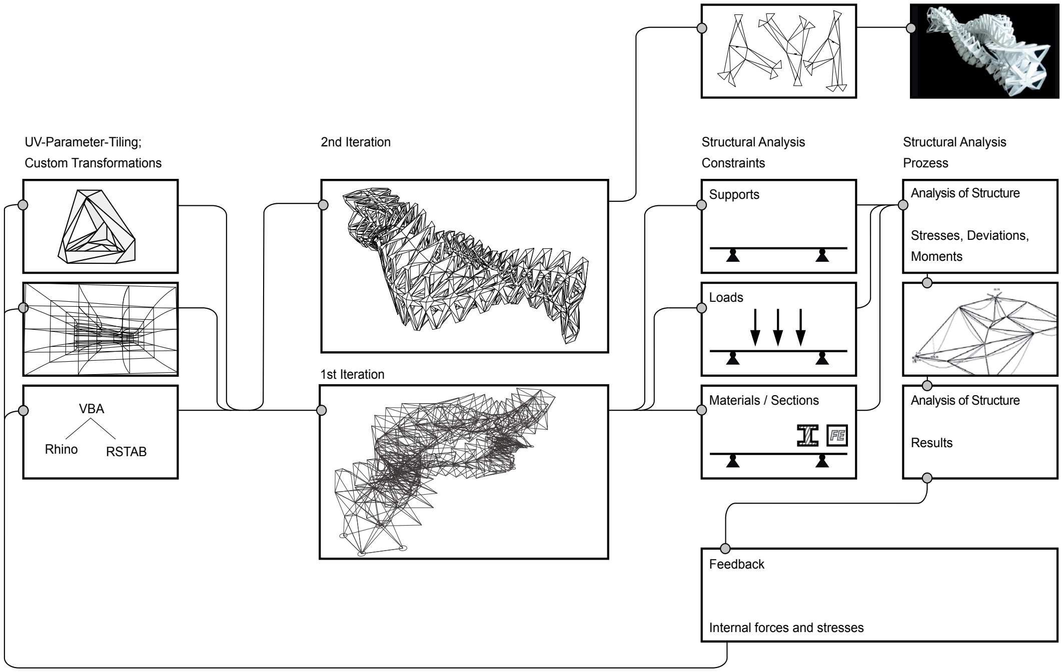



Figure 5.4.22: Flowchart of two-folded generation process

generated, driven by the guiding geometry and the resulting forces present in the members derived from the preceding analysis.

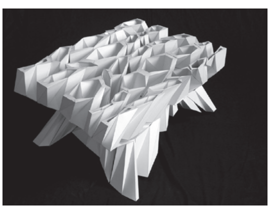


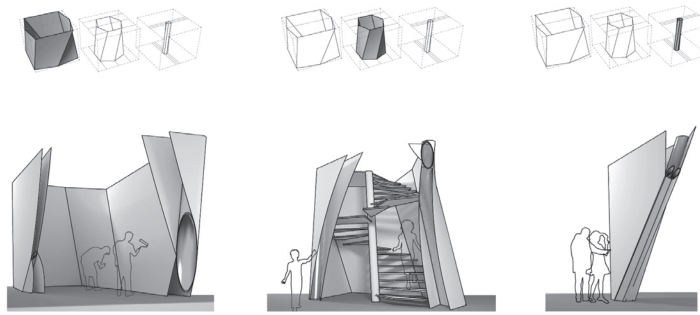
Figure 5.4.23: Prototype model with an array of tubular components.

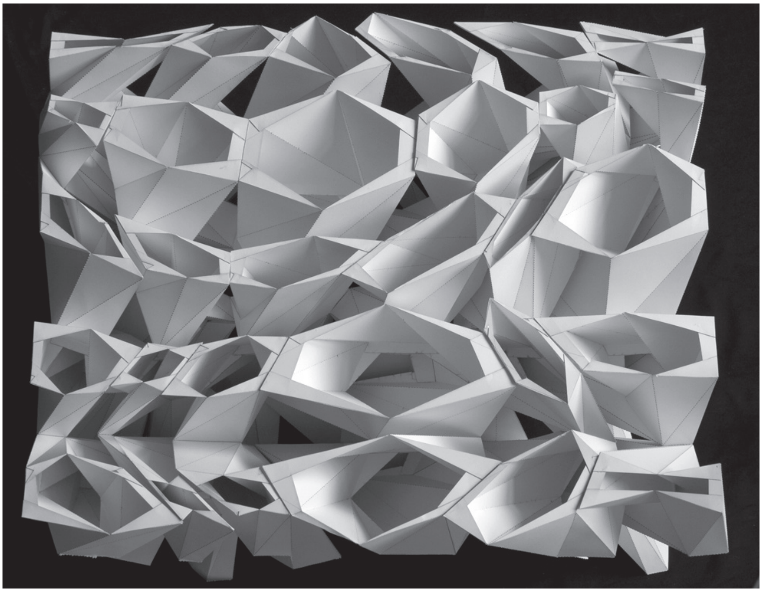
Figure 5.4.24 (right): Repurposing of component function through a change in dimensions.

In the following paragraph several design proposals, developed by the participants, will be presented. Every proposal is stressing one specific research topic

### 5.4.4.1 Integration

Moritz Rumpf developed a prototypical scale model based on a dense packing of





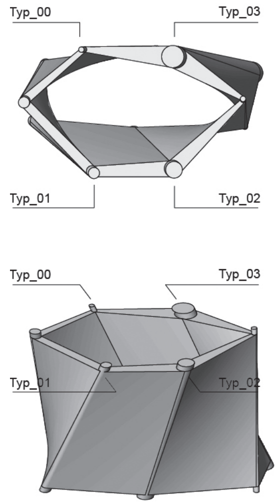



Figure 5.4.25: Top view of the self-similar yet differentiated structure.

Figure 5.4.26 (right): The data received from RSTAB© is used to define the cross sections of edge tubes in the component. Besides a structural optimization the differentiation is reflected into a moiré-like effect of a double-layer membrane.

folded tubular components. The accumulation process of those self-similar components is controlled bi-directional: top-down, by the manipulation of isocurves within the guiding geometry, and bottom-up through the information of every single component through parameters that originate from local geometric properties. The component is comprised of triangular or planar quadrangular faces which suit the fabrication constraints.

The prototype revealed the component's potential for further spatial differentiation by either including space or generating it in-between those elements. Thus, the component serves as a multi-purpose building component. In contrast to the modernist approach of introducing multiple functional layers Moritz investigated an inclusive principle where only one parametric component is constantly instantiated in different contexts and informed through changing parameters. Depending on both, global and local drivers, the instance becomes a mere structural member, a space demarcating wall-like element or a space providing unit. While maintaining the similar topology the behavior is constantly changing.

Figure 5.4.26: The approach was further developed and successfully applied for the design of an exhibition pavilion.

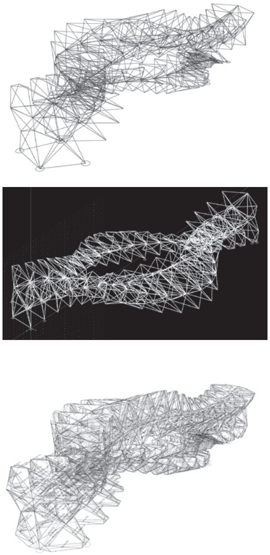


Figure 5.4.27: Sequence fro the generation process: Center line model, analysis model, component model

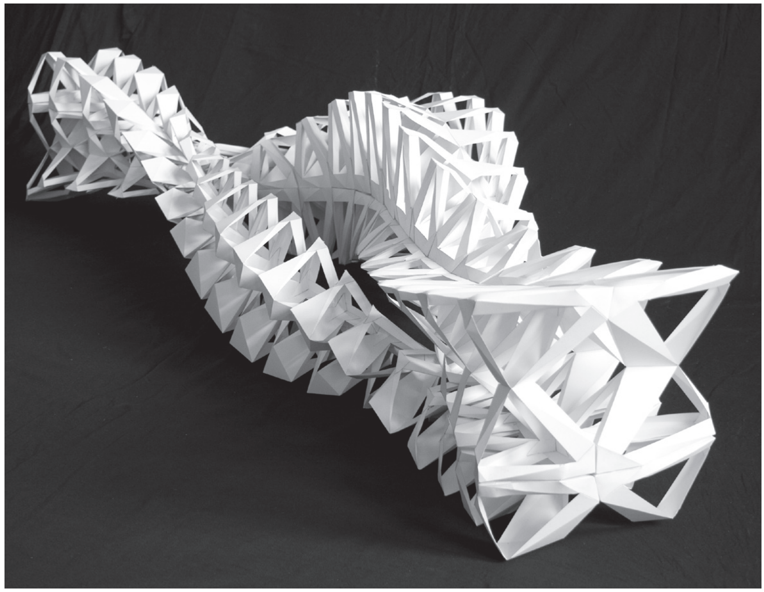


Figure 5.4.28: Cardboard model by Marina Leifels. A series of design surfaces allowed the complex topology of bifurcating and twisting component arrays. Unlike in the first studio the spatial guiding systems are not distinguishable anymore.

### 5.4.4.2 Differentiation

A modular configuration always implies a certain quantity of its components. Their differentiation emerges during instantiation when exposed to external parameters or through manipulation of the spatial host geometry to which they are aligned. Marina Leifels thoroughly employed both concepts. She introduced multiple spatial guiding systems. These stacks of surfaces continuously merge into each other and host different arrays of components. The approach was not envisioned during the tool-making process thus a multiple execution of the script was necessary. Nevertheless the result proved successful because it increased the complexity of modular configurations. Furthermore the immediate visual relation of guiding geometry and component alignment is blurred. The project exemplifies the notion of novelty generation due to the use of tools in a way not intended by the tool maker. A prescribed problem-solving procedure is replaced by an explorative process. A further differentiation is achieved through the parametric manipulation of single faces within the component. The system constantly oscillates between a surface-active and a vector-active system. In addition to the laser cutter a 3D printer was utilized to fabricate a second scale model. The extra degree of geometric freedom is reflected in a double-curved solid component.

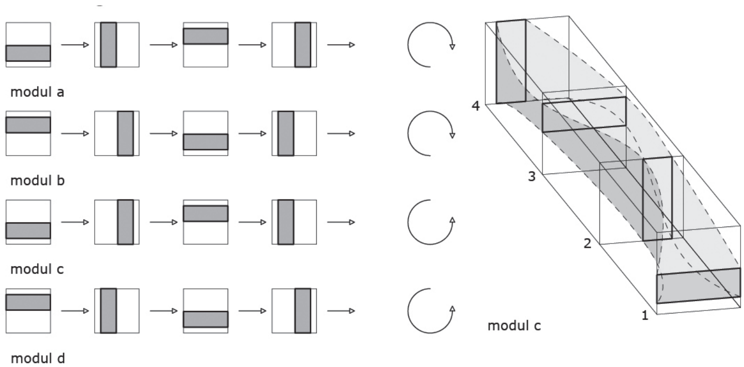



Figure 5.4.29: Rectangular profiles define the tubular module.

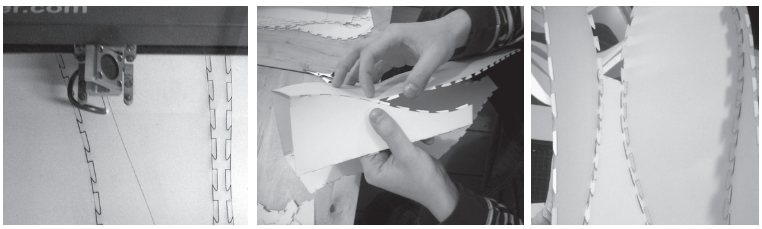


Figure 5.4.30: Laser cut fabrication and manual assembly of sheet material

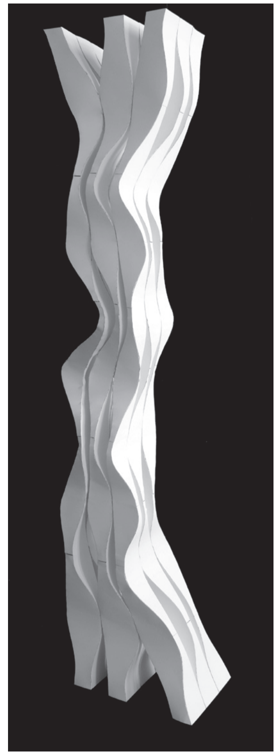


Figure 5.4.31: Final cardboard model

### 5.4.4.3 Assembly

The use of programming in combination with CNC fabrication allows for the development of connection details which would be hardly possible to craft by hand. Due to the replacement of standardization and fixed dimensions by topological description of relationships connection details can be customized for specific positions within the larger context. The geometry of those details has to merely fulfill the constraints of the fabrication technique. The actual shape can vary as long as the required functionality is provided.

Felix Wurst examined the creative potential of this technological shift and extended the principle of topological equivalent but geometrical differentiated components to a different scale by applying it to a saw-tooth connection detail. His tubular component is derived from a loft along a series of rectangle profiles that vary in proportion in accordance to the guiding geometry. Adjacent components alternately share a common surface area that provides stability and subsequently bifurcate to open an in-between space. Those lofted tubes do not incorporate any material logic that would help to connect the single surfaces with each other. The 3D model is merely representing polysurfaces with zero-thickness. Only the geometric constraint of single curvature, which provides developable surfaces, is implemented in the digital model so far. The aim in this project was to derive a hidden connection detail from the surfaces that suits the design intent. Thus Felix developed a custom-written script which generates saw-tooth shaped flaps aligned along the edge of the unrolled surfaces. Differentiation becomes a necessary means to adapt the saw-teeth to the local geometry. Therefore the curve tangent vector at a specified t-parameter is extracted and an instance is rotated by 90°. Those vectors define the alignment; a tooth-shaped tip effects the interlocking of the surfaces. The assembly is a sequential process which yielded the overall form of the components. But exercising the interlocking proved to be a cumbersome task. The material put under tension tends to buckle, thus the intended shape is deflected. A further testing of saw-tooth size in relation to shape and material thickness is necessary.

### 5.4.4.4 Recursive Growth

A central concept in programming is circularity. The linear configuration of cause and effect is replaced by feedback loops where the effect becomes the new input for the successive iteration. Recursion establishes circularity by defining functions in which the defined function is called within itself. Inside such procedures complex problems are broken down into less complex ones until a previously defined base case or a certain number of iterations is achieved.

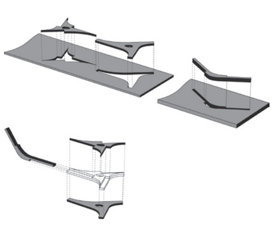


Figure 5.4.32: Create three-dimensional components from sheet material through revolving the assembly orientation.

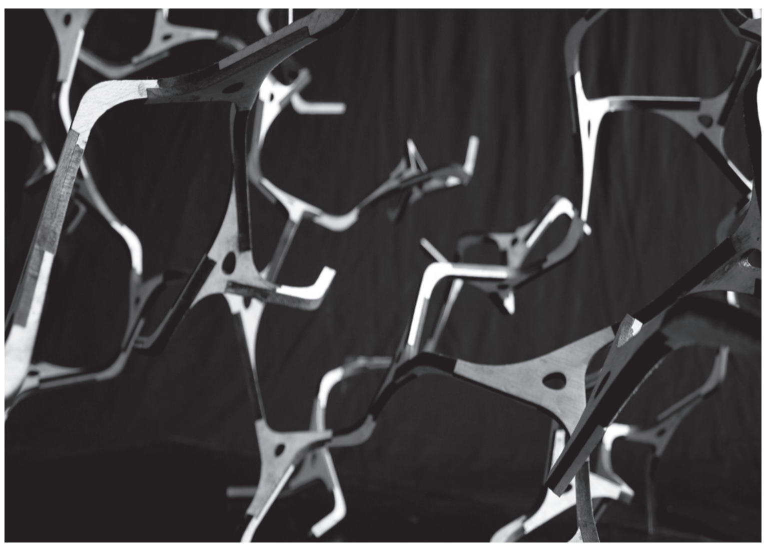


Figure 5.4.33: Laser-cut model of a branching structure by Johannes Kuhnen

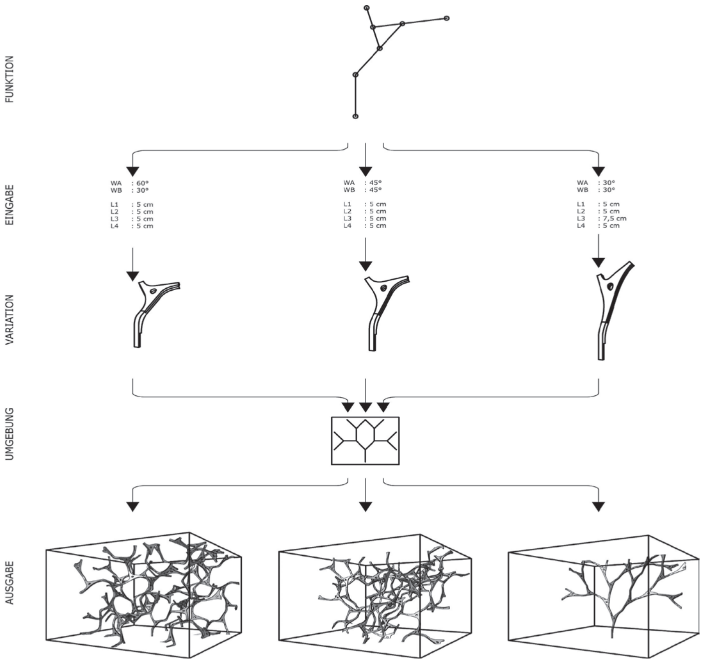



Figure 5.4.34: The branching structure is transferred into a parametric component and subsequently proliferated into a predefined bounding box.

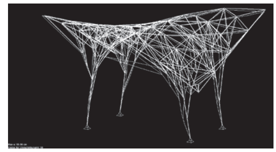


Figure 5.4.35: RSTAB© model with displayed deflections

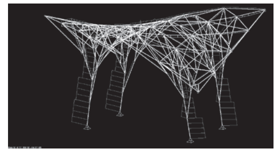


Figure 5.4.36: RSTAB© model with displayed normal forces

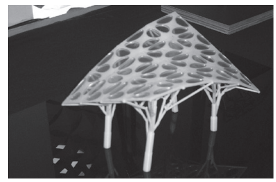


Figure 5.4.37: 3D Print of the structure

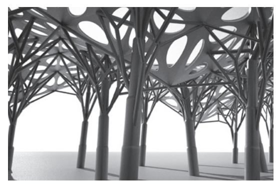


Figure 5.4.38: Elements are sized according to the RSTAB© data

L-systems or Lindenmayer systems are formal grammars which can easily be expressed by using recursive algorithms. They are famous to model the growth processes of plants. As a result L-systems yield self-similar and fractal structures.

Johannes Kuhnen implemented an L-system which proliferates within a bounding box. Besides tackling those re-writing rules systems within a 3D modeling environment, the pursued aim was to employ the approach in terms of parametric design. The component thus rather incorporates the limits that come along with laser cutting then mimicking plant-like structures. Sheet material is used in two layers with revolved orientation to achieve growth in three dimensions.

A second version of the script improved the control of growth direction by assigning an origin point and a goal surface towards the structure is growing. The initial center line model is transferred to RSTAB© and exposed to its dead loads. The resulting forces were fed into the geometric model as parameter for element cross sections. The geometric instantiation depended on the chosen fabrication procedure. Tubular elements formed solids for 3D printing, while friction locking branches could be cut from sheet material.

### 5.4.4.5 UV space

The concept of the design surface is based on the uv-parameters of NURBS surfaces. Proliferating components along a surface can be perceived as a three dimensional texturing. One means to exceed the mere thickening of surfaces could be achieved through a spatial guiding system comprised of stacks of surfaces as exemplified in this studio.

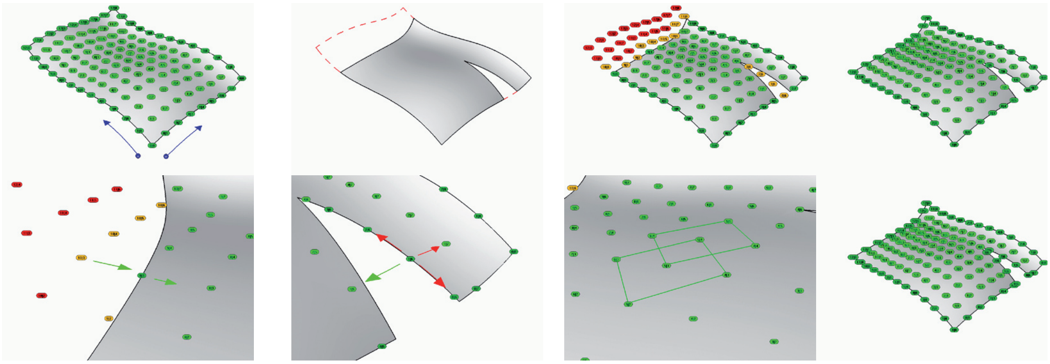


Figure 5.4.39: Reallocation of points along a trimmed surface

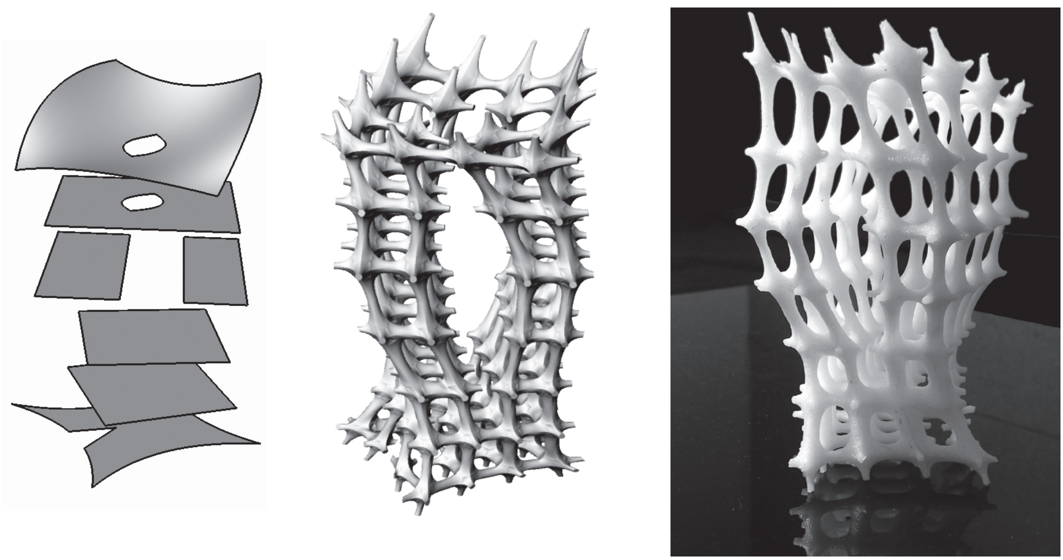


Figure 5.4.40: Stack of design surfaces, digital and physical model of proliferated components

Another technical flaw is that the process of component proliferation ignores any kind of surface trimming. Holes or cut away areas of NURBS surfaces are hidden in the graphic display. However the surface remains unaffected which can be revealed by displaying the control polygon. The same applies for any component placement. Furthermore any kind of bifurcations or surfaces with more than four edges are technically not feasible.

To defeat this shortcoming Hanno Stehling is analyzing the surface for trimmed areas before placing components. Therefore the isocurves of a surface are decomposed into a network of curves. Trimmed holes lead to more than one curve per surface isocurve. Cut away areas can be identified by curves which are shorter than the initial isocurve. After spotting trimmed areas the point grid that formerly followed the isocurves is rearranged along the trimmed surface. In order to achieve an equally spacing every change in position of one point has repercussions on the entire grid. A hole in the surface requires a doubling of point; a single point is replaced by one point ahead and a second point after the hole.

As proof of concept a node-like component is proliferated along a stack of trimmed and untrimmed surfaces. The dimensions of the elements and nodes are driven by the previous analysis of the structure in RSTAB©.

### 5.4.4.6 Results

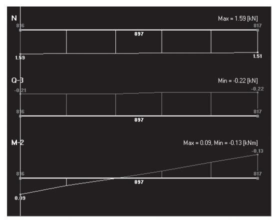



Figure 5.4.41: ‘Ergebnisverlauf’ - diagram in RSTAB© showing the gradient of forces and moments present in one single element. The data could be exposed in dimensions of modular components.

A significant increase in quality and complexity of design proposals could be achieved from the first to the second design studio. The major reason for this development is seen in the shift from a tool user to a tool maker. The participants underwent this changed and yielded better results and increasingly customized tools.

Exposing the quantitative data derived from RSTAB© yielded highly aesthetic physical models. By embedding structural analysis data this rationalization procedure became a driver for the design.

# 6. Conclusion

***The following chapter comprises the results and findings of the three case studies and hints towards potential future research. Furthermore the author draws a conclusion about the aim of the thesis to integrate structural design procedures and analysis data into the architectural design process.***

The three case studies represent different approaches towards collaborative design procedures. The case study 1 – Surface Structures sought to broaden the integrative character of form-finding procedures. Additional design criteria represented by the initial NURBS surface beyond mere structural issue such as formal intent of the architect, program, light etc. were negotiated with structurally driven shapes. The case study 2 – Space Frames utilizes an evolutionary procedure. The cybernetic concept of circularity is used to integrate an analysis application into a generative process. The seeming contradiction of determined formal systems and their unpredictable results is explored as a means to overcome generic structural typologies by balancing multiple criteria. The case study 3 treats the quantitative data of engineers in a qualitative architectural fashion. Differentiation, made possible through computer-aided manufacturing, is achieved by feeding analysis data into the generation process of parametric modules. The procedure pursues an integrative approach. Results of the parametric modules comprising of various sub-elements oscillate between ornament and structure. Furthermore the last case study offered the opportunity to observe tool users becoming tool designers.

## 6.1 Case study 01

The experiment pursues a geometric approach towards modifying an initial design intent in respect to structural performance. A NURBS surface serves as a representative of the initial design intent.  Improvement is achieved through a change in shape almost independent from material properties. The design procedure simulates hanging models in a digital environment. Instead of generic shapes an initial design intent is already inscribed before the shape is exposed to its dead loads. The design procedure yields solutions which incorporate a compromise between different requirements. Without changing their initial design intent the surfaces are structurally improved, by incremental translations of node points within constraint limits. Deformations under dead load are reduced significantly.

### 6.1.1 Broaden the range of shapes

The design procedure is assumed to be helpful in explorative design phases when an overall form needs to be established. The repertoire of shapes is not limited to the outcome of common from-finding procedures which makes the method attractive to architects who pursue a personal formal agenda. The shape manipulation can be limited to certain regions of a form while others maintain their initial expression. The magnitude of change can furthermore be controlled through an interface like a slider bar and multiple versions are rapidly produced. From a structural point of view those shapes are far from being optimized regarding the total elimination of bending moments in the surface. Only idealized symmetric barrels, domes, and vaults a free from bending forces. Those forms however exclude design criteria which do not originate from structural aspects.

### 6.1.2 Embed structural performance

Digital tools in architectural design unleashed the formal repertoire of design proposals and buildings. “Free-from” became the buzzword of the early millennium but was often accompanied by a certain disillusion due to a complete lack of embedded fabrication intelligence. The freedom of the form is lost when construction demands impose their constraints on a design proposal. Therefore the integration of fabrication constraints into the design process was explored in recent years.

Informing a geometric model with structural performance can be regarded as a further enhancement within the design process. Furthermore the behavior of a form under dead load becomes a design driver instead of a problem that has to be solved later in the process. Architectural design exploration is predominantly conducted and represented by geometry. Thus the instant qualitative feedback of the form-finding is transferred back into the geometric model which fosters the integrative aim of the design procedure. The resulting surface can be treated in the same way as the initial one. The impact of different supports positions and mesh topologies can be quickly explored and has a major impact on the deformation of the form.

### 6.1.3 Future research

The use of NURBS surfaces proved successful in providing a robust and easy to use interface. Three-dimensional modeling is predominately conducted on the basis of NURBS. Thus structural intelligence could be implemented without changing the medium for the designer. Translating those surfaces into meshes to generate structural models by sampling the uv-parameter range is an easy means for interfacing analysis and modeling applications. The procedure could be enriched in future research by implementing polysurfaces and meshes as representatives of design intents. Those constructs would broaden the range of feasible shape and topologies.

The transformation of surface points into mesh nodes and back into surface points creates buckling in regions with a change of curvature direction. The disturbance is not induced by structural behavior but rather originates from the mathematical properties of NURBS surfaces. Integrating discrete surface representation into the procedure would enhance its field of application. The discrete surface approach was impressively exemplified by Chris Williams in his development of the roof for the British Museum in London by Fosters and Partners in collaboration with Buro Happold (Leach et.al., 2004). Many surfaces contain regions which cannot be improved through geometric changes. Vertical areas, for instance, are identifiable with the current tool. A further refinement in defining regions and magnitude of influence of geometric manipulation could be another objective of further research.

## 6.2 Case study 02

An EA is utilized in the second experiment to balance multiple requirements. A space frame structure which forms a roof and at the same time incorporates spaces became the objective of a multi-parameter improvement. The negotiation between different and even conflicting aspects yields solutions which are improved during the generative process instead of being post-rationalized afterwards. In the case study the procedure serves as a collaborative design exploration tool for architects and engineers focusing on the structural system which has to embrace architectural design intents. The collaborative design process could be improved by evaluating structural and architectural criteria simultaneously. The equally ranked requirements of maintaining the overall morphology, intermediate spaces and minimal deflections of the space frame could be satisfied.

### 6.2.1 Improving structural systems through EA's

From the structural perspective the procedure proves successful. The space frame follows double-curved surfaces and is comprised of both, cantilevering and spanning regions. Spaces which should be free from structure further disturb the structure. A generic structural type with repetitive topology would not be a suitable answer to the task. Generating a system in the conventional way by anticipating the behavior of the system and insert structural elements would be a time consuming trial and error procedure. The manipulation of any single element may have repercussions on the entire system.

The EA in contrast engenders diversity without directed intention. It is not until evaluation that the quality and performance of a solution is revealed. The space frame thus gradually evolves towards a solution which adapts to local requirements. The procedure offers the chance to exceed preconceived notions of structural typologies. To achieve this goal one has to accept a shift in control. The act of steering a design towards a certain direction is relocated from directly envisioning a solution to the definition of selection criteria. The procedure is collaborative because architectural design intents, like the spaces free from any structure, contribute to the ranking of the structural system. The capability of the method to simulate physical behavior is used to turn the analytical tool into a generative one by circularly linking analysis results to generative procedures.

### 6.2.2 Design exploration

The procedure furthermore embodies an explorative character which is not only interesting for optimization but also in the search for novelty. It is a powerful method to generate diversity within a predefined solution space.

As described in chapter three Jane Drake observed that designers tend to approach a complex problem by generating a relatively simple idea to narrow down the range of possible solutions and construct and analyze a first scheme accordingly (Drake, 1978). The quality of a design cannot be anticipated in advance and not all given constraints can be considered in the first proposal. However the early solution contributes to the understanding of the problem itself.

Using an EA in the explorative part of the design process bears some similarities but also differences. One major difference is the need for quantifiable selection criteria. When discussing, sketching or modeling first ideas the goal is mostly uncertain. Changing the media even broadens the range of formal possibilities and always proved helpful in the personal work of the author and when working with students in design studios.

A common notion is seen in the initial generation of early concepts which are far from satisfying solutions. Solutions evolve during a process. The same applies for every design development. Many successful architectural practices are known for their huge amount of scale models build to investigate different versions and variants of one design proposal. Of crucial importance is the difference of a version and variant. Different versions always refer to one initial model or framework. Different variants, in contrast, constitute different ways to approach a design problem. While versions embody a difference in degree variants embody a difference in kind. When it comes to versions of a design proposal the EA is able to outscore conventional design procedures by the sheer quantity. An initial model or framework can be described as a parametric model. In the particular case a parametric model of a space frame structure. Even though this framework will not be exceeded the process of becoming, which yields the series solutions can never be skipped.

Technically speaking this is obviously a matter of the predefined solution space. In practice, however, it sometimes proves difficult to explain the difference between version and variant to collaborators not experienced in the use of algorithmic design procedures and parametric models. The remark points towards issues that certainly exceed the framework of this thesis. Nevertheless, when exploring collaborative design procedures those issues quickly appear in practice. Limits and potentials have to be clearly stated. Evolving quantitative factors by digital means is a congenial partner of human generative capacity as long as both complement one another. Such task sharing in the man-machine 'partnership' is regarded by the authors as the most promising approach.

### 6.2.3 Exceeding formal frameworks

Heinz von Foerster claimed that we can only decide the undecidable questions. Whenever a question is asked within a specific framework of a formal system the answer is already implied. Regarding the use of EA's von Foerster's dictum is not that unambiguous. Unpredictable solutions can evolve during the procedure. Space frames, for instance, evolve by adapting their structural behavior to extrinsic forces. A space frame thus incorporates a multitude of structural systems which gradually merge into each other. Shell-behavior is established in double curved areas while planar regions act as a series of girders or a spatial system. The solutions resemble some of the early bridge designs presented in the second chapter. Those bridges were not exclusively based on analytical procedures but also incorporate evolved knowledge of early engineers and their predecessors. The author claims that there is a certain similarity between these processes and the design methods of the aforementioned master builders, who developed their structures through experience and observation of constructed buildings. This can also be understood as an evolutionary method, one that is not limited by the availability of calculation and analyses methods. Contemporary digital methods make it possible to simulate such processes and thus enable us to refer back to empiric methods of previous generations.

One the other hand EA's will never exceed the framework they operate in. In the space frame experiment the genome controls the topology of nodes and elements. The design procedure does not enable an evolution from a vector-active to a surface-active system. In this specific case the limitation is caused by the use of RSTAB© which cannot calculate surface structures. However, every EA operates within a specific solution space. Its size defines the level of unpredictability and therewith the level on which EA's can be used for design exploration. When programming and implementing an EA the designer has to anticipate the range of solutions already. The extensive use of EA in the field of optimization enforces this assumption. An optimization process always implies a well-defined or 'tame' problem with a clear goal.

### 6.2.4 The abuse of biological metaphors

Besides all analogies to biological systems it is important to keep in mind that EA's operate in a technical environment constructed by man. Only few principles are borrowed from natural evolution and transferred into a digital environment while other aspects a completely dismissed. The programmer establishes a model through abstraction, formalization, and mechanization. The real phenomenon and its model are not isomorph (structurally identical). The process of individual growth within a specific environment, for instance, is not regarded in an EA. However D'Arcy Thompson's work stresses the importance of environmental forces acting on the phenotype besides the genome as its blueprint (Thompson, 1942).

Regarding morphogenesis, biological systems do not necessarily suit as a role model. Structural systems have to unfold their load bearing capacity when completed. While being under construction they are usually supported by scaffolding or temporary structures. A tree-like column serves as structural element when connected to a roof or girder which is needed to generate a coherent structural system. Unlike a tree supporting its branches to collect sunlight from early on the tree-like column unfolds its capacity when integrated into a larger system. Although often claimed in the architectural discourse all the current form generating and evolving design procedures work on the level of improvements of initially envisioned design proposals. Morphogenesis in a biological sense is currently not taking place in the architectural design context even so biological terms are borrowed and migrated into the architectural realm.

### 6.2.5 Future research

One possible means to broaden the solution space lies in the encoding of form in a genome. NURBS surfaces allowed the representation of continuous surfaces but come along with many other restrictions like very limited possible topological variation.  Polygon models on the other hand can represent a broader range of shapes while being discretized in single faces. Complexity in shape thus comes along with a huge amount of information to encode. An interesting approach to encode complex geometrical and topological shape with a finite set of information is pursued by Haresh Lalvani. Lalveni patent anmelden which is comprised of the following idea:

> *This invention deals with an integrated morphological system, herein called a morphological genome (morph genome), for design applications. This is the genome that encodes all form and is similar in intent to biological genome that encodes all living things by its genetic code. The morph genome comprises a finite set of morphological genes, each gene specifies a distinct*

*group of transformations, each group of transformations is defined by a group of independent topological, geometric or other parameters. The morph genes and their parameters are mapped within an integrated higher-dimensional framework, with each parameter being represented along a vector in higher-dimensional Euclidian space. (Lalveni, 2007)*

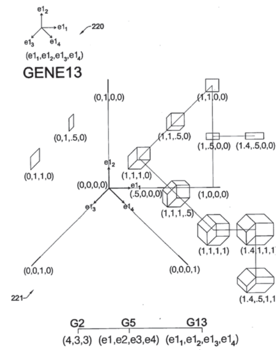



Figure 6.1 : Encoding geometric information, Haresh Lalveni, 2007

Encoding form in such a way and use it as a genome in an EA is regarded by the author as a promising approach for further research. The approach would require suitable applications for representation and analysis of those forms. The principle mimics the biological genome which generates variety from a limited set of four bases.

EA's can be perceived as cybernetic machines. Cybernetics is not interested in the material the machine is made of but rather in the way the machine works and the kind of output it creates. Algorithms are made of strings of symbols in a specific syntax. Predefined rules define how operators manipulate operands. In the space frame experiment the bit strings which defines the genome and therewith the space frame topology is the operand. The bit string is manipulated by operators that swop 0's and 1's to cause mutation. Furthermore crossover is conducted by a different set of operators. The fact that operators and operands are represented as strings of symbols implies the possibilities to exchange their roles. Genetic Programming (GP) is a procedure that seeks to conceptualize this change of relations. The genome is a string of symbols which represent fragments of a programming language. The EA recombines those elements in various ways and creates implemented algorithmic procedures as phenotypes. The rank the individuals the algorithms are executed and ranked by the efficiency they fulfill predefined tasks. The genome being the operand manipulated by the EA becomes the operator for a different task. Genetic Programming exceeds.

## 6.3 Case study 03

Developing a design procedure and provide it as a design tool to a third-party proved to be a successful to test the envisioned concepts. While the first studio yielded results anticipated by the author the second studio motivated students to switch from tool user to tool maker. This process is reflected in the subsequent conclusion followed by a critical observation of the integration of analysis data into the architectural design process.

### 6.3.1 Structural data as design driver

The interface between the 3D modeling software and the structural analysis application was used to automatically generate a structural model based on the geometrical model and subsequently feedback the resulting forces and stresses within the members. No optimization or form-finding procedures were implemented. The aim was rather to expose analysis data in the architectural context.

The part-to-whole relationship of parametric components is different from the modernist notion. Hierarchy is predominant in modern architecture. A building is composed of multiple layers with different functions and scales, like the structural system, façade, cladding etc. Every elements used in this system has a predefined function and the complex requirements of a building are broken down into less complex compartments.

When proliferating parametric components within a spatial configuration every single component and every single element within it gains its meaning when placed in a specific context. This notion is precisely described in the book ‘Atlas Of Novel Tectonics’ by Jesse Reiser (Reiser, 2006), which carries at lot of conceptual ideas served to inspire the author to implement them into the digital working environment of architects and engineers.

This approach could be successfully implemented through the interface between Rhino© and RSTAB©. The analysis of forces and stresses did not automatically lead to an improved or optimized structure; this step requires the thorough interpretation of data by an engineer. Nevertheless a framework was developed which served as an architectural tool in the design studios blurring the line between structural and architectural elements within a building. Whereas a column is always predefined to be a structural member, the meaning and function of an element within a component can change from load bearing to space demarcating, from vector-active to surface-active, from ornament to structure. Meaning is assigned by the analysis output which becomes a design driver. The amount of the calculated normal or shear force of a specific element is dynamically transferred from the center-line model to the parametric component. Type of force, magnitude and effect correlated by the designer/tool-builder in the creative process.

### 6.3.2 Customizing design procedures

In both design studios the author developed a design procedure and the corresponding tools. Participants were thoroughly trained to use those tools correctly. Unlike many other design procedures in architecture, programming and scripting prohibit any kind of ambiguity. Only the correct use of syntax and arguments leads to a successful results. The act of envisioning a concept was extremely limited in comparison the subsequent implementation of those ideas into the prescribed formalized system. The component itself could be defined by deriving points, lines and surfaces from a bounding box and the host geometry could be modeled within the CAD software. This tight set-up led to remarkable results in the first studio. Nevertheless none of the participants tried to exceed the predefined limits of the design procedure. Every result suited the previously articulated requirements and the design procedure itself is not further developed through its use.

Therefore in the second design studio the intent was to further introduce participants to the underlying principles of the procedure. In addition the procedure was supposed to provide a more spatial approach instead of a mere ‘3D texture mapping’ which suits an architectural articulation much better. Individual goals which did not necessarily suit the prescribed procedures should be pursued . The previously envisioned concepts should gain more importance than the design procedure and its tools. To achieve the envisioned goals the tools either have to be used in a way not intended by the tool maker or the participants have to turn into toolmakers themselves, upgrading the tools by required functionalities. The results of the second studio prove the success of the enriched approach by displayed a broader range of concepts many of them not anticipated by the author as the initial tool maker.

In the first studio the relation of toolmaker and user resembled more the relation of commercial software developer and client. The products of conventional software development rather address an abstract average user. Any kind of individuality is eliminated from the product to provide functionality for a broad range of tasks. In the case study the tools provided by the tutors take the role of such a generic product. It does nothing but deliver vertices from a surfaces in a predefined sample rate. Everything else which finally leads to a cardboard model is up to the designer.  He or she has to envision a module which takes the vertices as input parameter. Furthermore the generation process has to be implemented in RhinoScript.

Commercial software usually works as a black box with a graphic user interface. The user is not allowed and enabled to look behind the curtain or even change the inner state of the software. In the case study in contrast the provided tool and its functionality was exposed to the user. Furthermore it was encoded in the same language then the one which was used by the designers to implement their modules. Nevertheless the utilized application programming interface (API) is still a fairly high level interface to the compiled application

Nevertheless it became possible to adjust the previously generic tool to personal needs. If, for instance, further vertices from the design surface were required the tool was reprogrammed. Another designer needed to know whether a module is placed at the corner, the edge or the inner field of the design surface. Thus a customized ‘navigation’ tool was written and added to the initial tool. This bidirectionality between tool use and tool design significantly improved the results of the second design studio.

The author observed that those modified tools at a certain point exclusively served the individual toolmaker. Hence when tool-making migrates into the design process the resulting tools loose their generic character. Those tools become specific and individualized. The reason for this development is seen by the author in the difference between problem solving (‘tame’ problems) and design exploration. The latter often lacks clearly stated goals or is confronted with moving targets which make permanent adjustments and recalibration of tools necessary.


Figure 6.2: RhinoScript.org initiated by Johannes Kuhnen and Hanno Stehling. The platform is supposed to enable knowledge exchange. (http://www.rhinoscript.org)

The above described observations are not an issue for professionally trained programmers but the ongoing use of scripting in the field of architecture provides those tools to ‘amateurs’ who pursue aims different from those of problem-solvers. But more important than becoming professional programmers was the intent to explore strategies of improvising, hacking existing scripts, and share newly acquired knowledge. As a great success the author therefore regards the launch of the website. rhinoscript.org by participants of the studio. The idea is to provide a platform for knowledge and code exchange expressed by the website subtitle “bringing open source to architecture & design” (http://www.rhinoscript.org). Scripting is one tool amongst many other in the design practice and the majority of architects will not become experts. The author will follow the development of those tools in the coming years with interest.

## 6.4 Conclusion

Algorithmic means proved to be successful as an interface for collaborative design procedures between architectural and structural design. On a general level it proves to work as a productive method for embedding knowledge/rational into the design process. Structural analysis integrated into generative processes as a specific aspect of embedded knowledge/rational enriched architectural design exploration. The three case studies investigated collaborative procedures on different levels:

Geometry – the form-finding experiment in case study 1

Typology – the space frame experiment in case study 2

Sizing – The parametric module experiment in case study 3

The benefit of the procedures oscillates between rationalization and exploration as well as between both disciplines. The first and the third case study tend towards the explorative part of design whereas the second case study refers to rationalization and optimization. Nevertheless, the author strongly believes that procedures such as the ones developed in this thesis help to blur those disciplinary and conceptual demarcations. They are more than mere problem-solving devices but rather contribute to the establishment of algorithmic design procedures in a collaborative explorative design process of architects and engineers.

# 7. Kooperative Entwurfsverfahren für Architekten und Ingenieure

***In dieser Arbeit sollen neue Ansätze erforscht werden, Werkzeuge, Methoden und Ergebnisse der Tragwerksanalyse in den architektonischen Entwurfsprozess zu integrieren.***
***Der konventionelle lineare Ablauf, bestehend aus Synthese, Analyse und Evaluierung, soll durch eine Schleife ersetzt werden, die die Generierung mit der Analyse verbindet. Rationalisierung findet dann innerhalb des Entwurfsprozesses statt und nicht im Anschluss. Die Erkenntnisse der Tragwerksanalyse werden auf diese Weise zu formgebenden Parametern im Entwurfsprozess statt zu einer reinen Post-Rationalisierung.***

Die Tragwerksleistung soll Entwurfsparameter unter vielen verschiedenen und oft widersprüchlichen Anforderungen darstellen. Ziel ist ein Gleichgewicht aller dieser Parameter. Die Arbeit zielt also auf einen Formfindungsprozess ab, der nicht ausschließlich durch tragwerksrelevante Kräfte gesteuert wird. Für das gemeinsame Arbeiten von Architekten und Ingenieuren sowie das Installieren einer Generierungs-/Analyse-Schleife ist die technische und methodische Schnittstelle von entscheidender Bedeutung. Sie muss in der Lage sein, Informationen in beide Richtungen transferieren und interpretieren zu können. In dieser Arbeit sollen solche Schnittstellen entwickelt werden, um mit ihnen den gemeinschaftlichen Entwurfsansatz und das Einbinden von Tragwerksanalyse in den architektonischen Entwurf zu erproben. Dies geschieht aus der Perspektive eines Architekten in enger Zusammenarbeit mit Ingenieuren. Prototypische Schnittstellen zwischen verschiedenen Softwareanwendungen sollen im Hinblick auf neue Entwurfsverfahren entwickelt werden.

**Persönliche Motivation und Hintergrund**

Der Autor hatte Gelegenheit, gemeinschaftliche Entwurfsansätze von Architekten und Ingenieuren in der Praxis zu erleben und als Architekt im Büro Coop Himmelb(l)au aktiv mitzugestalten. In Anschluss daran entstanden in interdisziplinären Teams eine Reihe von eigenen Wettbewerbsbeiträgen, bei denen stets versucht wurde, die Tragwerksplanung als treibende gestaltende Kraft einzusetzen. Dieser Ansatz erfordert leistungsfähige Schnittstellen in technischer und methodischer Hinsicht. In der vorliegenden Arbeit sind Themen der gemeinschaftlichen Entwurfsarbeit genauer untersucht und erforscht worden.

**Schlüsselbegriffe und –konzepte der Arbeit**

Die folgenden Begriffe sind für die Arbeit von entscheidender Bedeutung.

**Entwurfsverfahren**

Ein Entwurfsverfahren besteht aus Werkzeugen und Methoden, die es erlauben, erdachte Konzepte zu visualisieren, kommunizieren, evaluieren und auch zu rechtfertigen. Eine Methode ermöglicht weiterhin die Reproduzierbarkeit von Ergebnissen, indem bestimmte Handlungsabläufe in der richtigen Reihenfolge, Art und Weise ausgeführt werden.

**Formale Systeme**

Formale Systeme (Kalküle) bestehen aus den folgenden Teilen:

- Ein Alphabet mit einer endlichen Anzahl an Symbolen (Operanten).
- Formationsregeln, die festlegen, wie man aus den Operanten wohlgeformte Formeln zusammensetzt.
- Transformations- oder Deduktionsregeln, die definieren, wie wohlgeformte Formeln zu neuen Formeln umgeformt werden.
- Axiome, also Objekte, die ohne weitere Begründung oder Ableitung bestehen können.

Die Differential- und Integralrechnung, aber auch Spiele wie Schach stellen formale Systeme dar. Sie ermöglichen die Erlangung von neuen Erkenntnissen und Situationen, die sich in einem deduktiven Verfahren aus bereits bekanntem Wissen ableiten. Die Tragwerksplanung bedient sich in der täglichen Arbeit Formalismen und Methoden, um Sicherheit und Vorhersagbarkeit von Tragstrukturen gewährleisten zu können. Formalisierung bedeutet, dass Denkprozesse in Handlungsprozesse überführt werden. Eine Reihe von Regeln stehen zur Verfügung, die die Handlungsalternativen einschränken und bereits geleistete Verständnisarbeit funktionalisieren. Einmal gewonnene Erkenntnis ist theoretisch für jedermann erlernbar und gehört zum ‚öffentlichen Denken'.

**Formfindung**

Bei der Formfindung werden physische Modelle einer äußeren Kraft ausgesetzt. Die Form, die sich durch die Krafteinwirkung einstellt, ist die Reaktion des Modells mit dem Ziel eines Gleichgewichtes von inneren und äußeren Kräften. Eine Seifenhaut in einem Rahmen beispielsweise formt sich zu einer Minimalfläche, eine Kette stellt sich in der bekannten Kettenlinie ein, in der ausschließlich Zugkräfte herrschen. Die gefundene Form hat aufgrund ihrer Geometrie günstige statische Eigenschaften, die auf den Originalmaßstab von Gebäuden skaliert werden können. Antonino Gaudi, Frei Otto und Heinz Isler sind bekante Architekten und Ingenieure, die ihre Projekte mit Formfindungsmethoden entwickelt haben.

**Optimierung**

Optimierung nähert sich dem Problem von der entgegengesetzten Richtung. Eine bereits bestehende Lösung wird hinsichtlich möglicher Verbesserungen untersucht. Bei der Topologieoptimierung beispielsweise sind ein Volumen, die einwirkende Kraft und mögliche Kraftweiterleitungspunkte (Auflager) definiert. In einem iterativen Prozess wird dann überall dort Material entfernt, wo nur geringe Kräfte oder Spannungen vorherrschen. Nach und nach entsteht eine Form, deren Materialaufwand minimiert ist. In dieser Arbeit werden evolutionäre Optimierungsverfahren verwendet, die einen Entwicklungsprozess mit Individuen, Populationen und vielen Generationen simulieren. Dem Diktum ‚der Stärkste überlebt' folgend, werden die besten Lösungen in einem Lösungsraum aufgespürt.

**Vielfalt**

Vielfalt hat seit der intensiven Nutzung digitaler Technologien und algorithmischer Konzepte in der Architektur eine andere Bedeutung gewonnen, als ihr in der Postmoderne innewohnte. Während die postmoderne Collage eine Komposition aus vielen unterschiedlichen Dingen erstellt, bedeutet Vielfalt in dieser Arbeit eine selbstähnliche und parametrische Vielfalt. Variation entsteht durch das Einspeisen unterschiedlicher Werte in die gleichen Variablen. Die kundenspezifische Massenfertigung im Produktdesign nutzt dieses Prinzip, um Produkte nach Kundenwünschen anzupassen. Während diese Produkte gestreut und auf viele Kunden verteilt werden, können sich diese selbstähnlichen Objekte in der Architektur an einem Ort befinden und dort eine Gesamtkomposition ergeben. Die Knoten eine Raumfachwerkes beispielsweise sind bei einer freien Großform an jedem Punkt unterschiedlich. Dieses Prinzip ist bekannt und technisch beherrschbar. In vielen Beispielen wird es jedoch ‚versteckt' angewendet, um Homogenität zu erzeugen (Hofüberdachung British Museum, Foster and Partners mit Buro Happold, London). In dieser Arbeit wurde das Gestaltungspotential von relationaler parametrischer Vielfalt untersucht. Dabei dienten architektonische und tragwerksplanerische Daten als treibende Kraft für Variation. In drei Fallstudien wurden die Konzepte Formfindung, Optimierung und Vielfalt in gemeinschaftlichen Entwurfsverfahren untersucht

## 7.1. Entwurfsverfahren

Zu den Entwurfsverfahren gehören Modelle. Modelle sind Repräsentation von realen Phänomenen, die auf die wichtigsten Aspekte des Phänomens reduziert sind. Architekten nutzen Modelle, um ihre Konzepte in einem kleinen Maßstab zu präsentieren und kommunizieren, oder auch um an ihnen zu entwerfen. Aber auch mathematische Berechnungen zum Verhalten von Tragstrukturen werden in diesem Kontext als Modelle bezeichnet.

Die Modelle der mittelalterlichen Baumeister, die die Berufe Architekt und Ingenieur in einer Person vereinten, nutzen Modelle und Verfahren, die auf Geometrie, Proportionen und Harmonien basierten. Die griechischen und gotischen Prinzipien dienten sowohl der wohlproportionierten Fassadengestaltung als auch zur Dimensionierung tragender Bauteile wie Brückenbögen.

Seit der Renaissance ist zu beobachten, wie die wissenschaftlichen Methoden zunehmend in die Ingenieurspraxis migrierten. Damit wurden mathematische Modelle präziser, und das Tragverhalten physischer Systeme konnte exakter vorhergesagt werden. Im 19. Jahrhundert vermuteten führende Ingenieure, dass Sicherheitsbeiwerte bald überflüssig sein würden, da die neuen Modelle Tragverhalten originalgetreu vorhersagen würden. Die Ingenieure hatten Newtons Ursache-Wirkung-Prinzip verinnerlicht. Gleichzeitig bestimmten die Rechenmethoden, welche Tragwerke konstruiert wurden, nämlich solche, die berechenbar waren. Karl Culmanns ‚Grafische Statik‘ (1866) beispielsweise definiert klare Regeln und basiert auf den Erkenntnissen seiner Forschung. Ihre Anwendung erfordert ganz bestimmte Rahmenbedingungen und dient ausschließlich zur Berechnung vektor-aktiver Tragsysteme. Damit sind der gesamte Ablauf der Berechnung, der Lösungsraum und die Tragwerkstypologie determiniert. Tragwerksplanung im Geiste dieser rationalistischen Tradition hat zu Tragwerkstypologien geführt, die durch ihre formalisierten Rahmenbedingungen determiniert sind. Der Computer diente später in diesem Zusammenhang lediglich als ein besserer Rechenschieber.

## 7.2. Entwurfsverfahren im Zeitalter der Kybernetik

Im 20. Jahrhundert wird der Determinismus durch die Relativitätstheorie, die Unschärferelation und später die Chaosforschung widerlegt. Außerdem bieten Systemtheorie und Kybernetik alternative Denkansätze zum linearen Ursache-Wirkung-Prinzip. Die Kybernetik beschäftigte sich mit dem Wirkgefüge komplexer technischer und biologischer Systeme. Grundlegend anders war die Betrachtung von komplexen Systemen und ihren Funktionsweisen im Vergleich zur bisher üblichen Zerlegung komplexer Systeme in einfache, voneinander losgelöste Systeme. Hinzu kam das für die Kybernetik zentrale Prinzip der Zirkularität. Die Ergebnisse eines Prozesses dienen wieder als Startbedingungen für eine erneute Iteration eines Prozessdurchlaufs. Dieses Prinzip ermöglicht das Erreichen von Gleichgewicht in dynamischen Systemen. James Watts Dampfmaschinen sind frühe Beispiele kybernetischer Systeme. Das Prinzip der Zirkularität begegnet uns nun auch bei der Nutzung des Computers im Entwurfs- und Planungsprozess. Der Einsatz des Computers verändert die Arbeit des Ingenieurs zunächst durch schiere Quantität und Geschwindigkeit. So war das formale System der numerischen Rechenverfahren zur Behandlung von umfangreichen linearen Gleichungssystemen, wie sie bei der Finite-Elemente Methode zum Einsatz kommen, schon lange vor den 1960er Jahren bekannt. Lediglich der Mangel an leistungsfähigen Rechenmaschinen verhinderte ihren Einsatz.

Der Computer ist jedoch nicht nur eine Rechenmaschine, denn seine formalen Systeme sind nicht der Hardware eingeschrieben und damit unveränderlich, sondern sie liegen sprachlich formuliert als Zeichenketten vor. Scripting und Programmierung ermöglichen den Zugriff auf diese Beschreibungsebene, auf der der Algorithmus (die Rechenmaschine) und die Daten, die verarbeitet werden, mit den gleichen Symbolen und Zeichenketten repräsentiert werden.

Speist man nun die Ergebnisse einer Analyse in den Prozess zurück, können diese Daten eine treibende Kraft im Entwurfsprozess werden. Statt nur den Ist-Zustand zu analysieren, dienen die Daten in einem zirkulären Prozess als Information, in welche Richtung sich ein Prozess weiterentwickeln muss. Die pure Menge der Daten kann in Zusammenhang mit sehr einfachen Regeln komplexe emergente Phänomene hervorbringen. Celluläre Automaten, evolutionäre Algorithmen und nichtperiodische Flächenparkettierungen sind einige Beispiele, die im Entwurfskontext von Architektur in den letzten Jahren aufgetaucht sind. Dabei handelt es sich um formale Systeme, die zwar in ihrer Funktionalität determiniert sind, ihre Ergebnisse jedoch sind nicht vorhersagbar. Damit verkompliziert sich Heinz von Foesters Diktum von entscheidbaren und unentscheidbaren Fragen.

Die Kybernetik zweiter Ordnung verweist auf das Problem der Kybernetik, dass Systeme meist bereits Abstraktionen von realen Phänomenen sind und damit der Beobachter bereits eine Wertung vorgenommen hat. Dem Beobachter wichtige Aspekte des Phänomens werden in das Modell übernommen, scheinbar unwichtige werden ausgeklammert. Selbst wenn der Beobachter imstande sein sollte, vollkommen objektiv zu entscheiden, so ist seine Wahrnehmung doch definiert durch seine Sinnesorgane und sein Gehirn. Die Kybernetik zweiter Ordnung und der radikale Konstruktivismus verweisen darauf, dass Druck- und Lichtwellen erst von unseren Gehirnen zu Musik und Bildern konstruiert werden. Damit ist der Mensch determiniert durch die Struktur seines Körpers. Die Schlussfolgerung der Vertreter dieser Denkrichtung ist, dass es keine objektive Welt ‚dort draußen' gibt, sondern jeder seine Welt in seinem Gehirn konstruiert. Der Eindruck von Objektivität entsteht, wenn viele Menschen Welten mit großer Kohärenz konstruieren. Diese Vorstellung wird in den systemischen Ansätzen von Hort Rittel und Marvin Webber aufgegriffen, um Entwurfsprozesse zu erklären. Die Wissenschaftler unterscheiden ‚zahme' und ‚bösartige' Probleme. Zahme Probleme haben klare Ziele und ein formales System, mit dem die Aufgabe bearbeitet werden kann (Rechenmodell, Werkzeug etc). ‚Bösartige' Probleme sind bösartig im Sinne von verzwickt. Die eigentliche Problemformulierung ist bereits schwierig und hängt von der Perspektive ab, von der man das Problem betrachtet. Eine eindeutige Lösung des Problems existiert genauso wenig wie ein formales System, das zur Lösung des Problems eingesetzt werden kann. Eine hervorgebrachte Lösung ist nicht falsch oder richtig, sondern gut oder schlecht. Auch diese Bewertung hängt von persönlichen Bewertungskriterien ab. Rittel und Webber nennen als Beispiel das Problem der Straßenkriminalität. Polizist, Stadtplaner, Sozialarbeiter und Lehrer würden dieses Problem sehr unterschiedlich angehen. Abhängig von der beruflichen Perspektive, den vorhandenen Mitteln und den gewünschten Zielen sind ganz unterschiedliche Problemlösungsstrategien wahrscheinlich. Persönliche Aspekte spielen auch beim Architekturentwurf eine große Rolle, da es hier nicht nur um das Lösen von Problemen geht. Neben einem Raumprogramm und einem Grundstück spielen auch die persönlichen Methoden und der Stil des Architekten eine entscheidende Rolle.

## 7.3. Entwurfsverfahren entwerfen

Bei Entwurfsaufgaben, für die es noch kein formalisiertes Entwurfsverfahren gibt, müssen zunächst solche Verfahren entwickelt werden. Diese Situation tritt ein, wenn ein Architekt eine Form entwickelt hat, die mit den gegebenen Methoden des Ingenieurwesens nicht berechnet werden kann. Beim Sydney Opera House von Jørn Utzron oder der Philips Pavillon von Le Corbusier und Iannis Xenakis war dies der Fall. Andererseits haben Ingenieure wie Pier Luigi Nervi, Felix Candela und Heinz Isler ihre ganz eigene Entwurfsmethode zur Formfindung entwickelt. Isler ist ein Beispiel für einen entwerfenden Ingenieur, der sich jenseits formaler Systeme bewegt. Seine in Gips getränkten Gewebe werden als Hängemodelle für die Formfindung von Betonschalen genutzt. Die materielle Ähnlichkeit von Formfindungsmodell und gebauter Form erwies sich als erfolgreiches Entwurfskonzept.

Mit digitalen Werkzeugen entstand die Hofüberdachung für das British Museum in London. Der asymmetrische Grundriss des Bestands und seine beschränkte Lastaufnahmefähigkeit definierten die Randbedingungen der Dachform. Der beratende Ingenieur Chris Williams entwickelte eigens für diese Form eine mathematische Formel, die die gesamte Form beschreibt. Anschließend kam ein Algorithmus zum Einsatz, der mittels dynamischer Relaxation die verwendeten Stablängen vereinheitlichte, um ein homogenes Tragwerk zu bilden, das in der gleichen Ebene wie die Glashaut liegt. Für beide Entwurfsphasen mussten die Methoden und Werkzeuge eigens entwickelt werden.

## 7.4.Fallstudien: Formfindung, Optimierung, Dimensionierung

### 7.4.1 Fallstudie 1 – Flächenaktive Tragwerke

In dieser Fallstudie geht es um die Entwicklung eines Entwurfsverfahrens, das digital simulierte Formfindung in RSTAB© in den architektonischen Entwurfsprozess integriert. Formen, die bereits vom Architekten gestaltet wurden und damit ein Entwurfskonzept repräsentieren, durchlaufen einen Formfindungsprozess. Damit wird die ursprüngliche Form nicht vollkommen verändert, sondern in Bereichen, die extrem ungünstig für das Tragverhalten sind, innerhalb vorgegebener Toleranzen manipuliert. Ziel ist ein Verfahren, das die Formfindung als Entwurfsparameter mit anderen Gestaltungsprinzipien vereinigt.

Architektur ist das Produkt einer Teamarbeit und so kann auch eine Schale einer ganzen Vielfalt von Anforderungen dienen, die über das reine Tragwerk hinausgehen. Das Projekt „Rolex Learning Center“ des japanischen Büros Kazuyo Sejima + Ryue Nishizawa / SANAA auf dem Campus der Ecole Polytechnique Fédérale Lausanne (EPFL) besteht beispielsweise aus einen aufgewölbten eingeschossigen Gebäude. Dadurch werden verschiedenste Raumsituationen geschaffen. Das Gebäude soll mit einer Zentralbibliothek, Studienräumen, Einrichtungen und Dienstleistungen zum Wissenserwerb sowie mit Ausstellungsräumen, Konferenzsälen, einer Cafeteria und einem Restaurant zum Mittelpunkt des zukünftigen Campuslebens werden und das Erscheinungsbild des Campus entscheidend mitprägen.

Eine homogene ideale Schale ist aus der Sicht des Ingenieurs elegant, weil sie die Kräfte ohne Biegespannungen ableitet und damit extrem dünn hergestellt werden kann. Doch schon das Einfügen einer Türöffnung in solch eine ideale Form kann strukturelle und formale Probleme schaffen. SANAA‘s Landschaft integriert Patios, Blickbeziehungen und unterschiedlichste Raumqualitäten und resultiert aus einem Entwurfsprozess, bei dem Überlegungen zum Tragwerk nur ein Aspekt unter vielen anderen waren.

Für die Ingenieure war die Aufgabe also das Auffinden lokaler Schalen- und Bogenwirkung innerhalb der globalen Geometrie, sowie deren vorsichtige Modifizierung in Absprache mit den Architekten. Das Finden von Form wird ersetzt durch das Aufspüren von Qualitäten in einer vorhandenen Form. Das Tragverhalten einer solchen Landschaft ist unterschiedlich, so dass es keine Bereiche gibt, die eine alleinige Tragwerkstypologie repräsentieren.

Was hier beispielhaft an einem Projekt aus der Praxis erläutert wurde, sollte mit Hilfe digitaler Werkzeuge vereinfacht und mit automatisiertem Datenaustausch realisiert werden. Dafür wurde vom Autor in Visual Basic 6.0© ein Programm geschrieben, das folgende Arbeitsschritte automatisiert: Eine in Rhino© modellierte Fläche wird ausgewählt. Diese wird anschließend vermascht und als Stab- und Knotenmodell an das Analyseprogramm RSTAB© übergeben. Die Netztopologie ist dabei vom Benutzer wählbar. Außerdem werden im Geometriemodell die Auflagerpositionen bestimmt. In RSTAB© werden Materialien und Querschnitte zugewiesen und die Struktur unter Eigenlast gesetzt. Auf die resultierenden Verformungen wird dann differenziert reagiert. Verformungen zwischen Auflagern werden, wie bei der klassischen Formfindung, umgekehrt. Auskragendende Bereiche werden leicht angehoben, so dass verjüngende Querschnitte entstehen. In vertikalen Bereichen erfolgt keine Modifikation, da eine geometrische Veränderung nicht hilfreich ist. An einer Testfläche wurde das Verfahren erprobt. Das Resultat wurde dann in einer zweiten Analysesoftware als Flächenstruktur untersucht. Das Ergebnis der Formmanipulation überzeugte durch reduzierte Verformung des flächenaktiven Tragwerks unter Eigenlast.

### 7.4.2 Fallstudie 2 – Raumfachwerke

In der zweiten Fallstudie kommt ein vom Autor, in Zusammenarbeit mit Markus Schein von der Kunsthochschule Kassel, eigens programmierter evolutionärer Algorithmus zum Einsatz, um ein Raumfachwerk hinsichtlich tragwerksrelevanter, aber auch architektonischer Parameter zu verbessern. Ziel ist nicht die Optimierung eines Parameters, sondern vielmehr eine Balance zwischen den unterschiedlichen und manchmal auch widersprüchlichen Anforderungen.

Der Begriff Evolutionary Algorithms steht als Sammelbegriff für vier Kategorien von Algorithmen: Evolutionary Strategies, Genetic Algorithms, Evolutionary Programming und Genetic Programming. In Detail und den Anwendungsgebieten unterschiedlich, basieren diese Algorithmen alle auf dem selben Prinzip, das der natürlichen Evolution entlehnt ist. In einem Initialisierungsvorgang wird eine Anzahl zufälliger Individuen erzeugt, die eine digitale Repräsentation möglicher Lösungen sind. Sie basieren meist auf einer definierten Struktur, aber zufälligen Werten. Die Individuen werden Fittnesstests unterzogen und das Ergebnis bewertet. Auf Grundlage dieser Bewertung wird nach einem bestimmten Selektionsverfahren und über die Verwendung genetischer Operatoren (Mutation, Crossover, Inversion) die nächste Population erzeugt, wobei die besseren Ergebnisse eine höhere Fortpflanzungswahrscheinlichkeit haben. Die Individuen der neuen Population werden wieder bewertet, und so fort. Der Prozess endet, wenn ein vorher definierter Fitnesswert erreicht oder eine bestimmte Anzahl von Generationen durchlaufen ist. Diese Art Algorithmen sind vor allem für Problemstellungen geeignet, bei denen rechnerische Methoden zur Optimierung nicht verfügbar sind und multimodale Zielfunktionen erfüllt werden sollen. Evolutionäre

Optimierungsmethoden gehören zum Standardrepertoire der Ingenieurwissenschaften und werden beispielsweise in der Strömungsmechanik häufig genutzt, etwa zur Optimierung der Form von Tragflächen, Schiffsschrauben oder Rohrkrümmern (Rechenberg, 1994). In der Automobilindustrie werden sie verwendet, um z.B. die optimale Anzahl und Verteilung von Schweißpunkten und -nähten an einer Karosserie zu ermitteln.

Bei evolutionären Algorithmen werden Zeichenketten erzeugt und manipuliert, die die Genotypen, also die Baupläne ganzer Populationen von Tragwerken repräsentieren. Solche Blaupausen dienen der Erzeugung von Strukturen (den Phänotypen), die anschließend auf tragwerksrelevante, aber auch architektonische Parameter untersucht werden. Jeder Parameter wird gemessen und auf einer normierten Skala beschrieben. Dies eröffnet die Möglichkeit, solche Tragwerksindividuen nicht nur nach ihren Spannungen und Verformungen zu bewerten, sondern auch quantifizierbare Faktoren anderer Disziplinen abzuwägen. Das Ziel ist also weniger eine Optimierung, sondern vielmehr ein Gleichgewicht zwischen unterschiedlichen Faktoren zu erzeugen. Die Individuen werden nach dem Grad des erzeugten Gleichgewichts auf einer Rangliste angeordnet, die, vereinfacht gesagt, die Wahrscheinlichkeit definiert, mit der ihr Genotyp als Ausgangskonfiguration der nächsten Generation dient. Das beste Ergebnis einer Iteration dient also als Startpunkt einer erneuten Schleife dieses zyklischen Prozesses. Die neue Generation basiert auf dem Genpool der vorangegangenen, wird neu kombiniert (Crossover) und unterliegt einem gewissen Grad zufälliger Mutation. Natürlich sind solche evolutionären Algorithmen ebenfalls formale Systeme, die wohl definierte Aufgaben mit klar abgesteckten Rahmenbedingungen und Zielvorgaben bewältigen können. Eine Lösung ist jedoch nicht gebunden an bestimmte Tragwerkstypologien, sondern verkörpert ein Tragwerksindividuum, das sich am besten an eine spezifische Situation angepasst hat. Das Ergebnis geht aus einem Prozess hervor, der zwar strengen Regeln unterliegt, jedoch stets in voller Länge ablaufen muss, da sein Resultat nicht absehbar ist. Die Determinierbarkeit des Algorithmus impliziert also nicht die Kenntnis aller möglichen Endzustände.

In der Fallstudie werden Tragwerke innerhalb von Hüllgeometrien generiert. Außerdem werden Bereiche definiert, die möglichst frei von Tragstruktur bleiben sollen. Mit Hilfe eines evolutionären Algorithmus wird nun eine Vielzahl von Raumfachwerken erzeugt, deren exakte Stabverteilung in einem Genom kodiert ist. Das Ziel ist ein Raumfachwerk, das mit möglichst wenigen Stäben eine minimale Verformung erfährt und dabei gleichzeitig der architektonisch definierten Hüllgeometrie folgt und die vorher definierten Bereiche meidet. Diese widersprüchlichen Parameter müssen in dem evolutionären Prozess miteinander verhandelt werden, so dass am Ende ein Gleichgewicht entsteht.

### 7.4.3 Fallstudie 3 – Vielfalt

Die dritte Fallstudie beschreibt zwei Entwurfsprojekte mit Studierenden der Universität Kassel. Den Teilnehmern wurde digitale Werkzeuge in Form kleiner Scripts und Programme zur Verfügung gestellt, die vom Autor in Zusammenarbeit mit Markus Schein programmiert wurden. Beide Studios starteten mit einem RhinoScripting Lehrgang. Die Teilnehmer erlernten, wie man parametrische Komponenten programmiert, deren Dimensionen sich von acht Eckpunkten einer kubischen Hüllgeometrie ableiten. Im ersten Studio standen die Rahmenbedingungen einer computergestützten Fertigung der Module aus Karton mit Hilfe eines Laserschneiders im Vordergrund. Planarität oder Abwickelbarkeit der Komponenten musste gewährleistet sein. Im zweiten Studio kam die Einbindung von Tragwerksanalysedaten in diesen Prozess hinzu. Es ging um die Fragestellung, welchen gestalterischen

Einfluss die quantitativen Daten der Tragwerksanalysedaten haben können. Die Dimensionen der Komponenten sind durch externe Parameter steuerbar. Diese Parameter sollten aus der Tragwerksanalyse abgeleitet werden.

**Flächen**

Die immaterielle unendlich dünne Fläche ist ein elegantes Medium in digitalen Architekturentwurf. Sie entsteht aus Liniennetzen und Punktewolken oder beliebigen Kurven, die Bewegungen im Raum beschreiben und dabei Flächen aufspannen (Abb. 01), denen diese dynamische Kapazität eingeschrieben ist. Flächen verkörpern Kontinuität und graduellen Wechsel, sie sind Oberfläche und Raum zugleich. Die Oberfläche ist die äußerste Begrenzung eines Körpers, die unmittelbar an seine Umwelt oder einen anderen Körper angrenzt. Diese Fläche besitzt zwei Dimensionen, die sich eben oder gekrümmt, begrenzt oder unendlich im Raum entfalten. Zugleich beschreibt die Geometrie jeden Punkt auf einer Fläche mit Hilfe von x, y und z Koordinaten und damit in drei Dimensionen also räumlich. So ist die Fläche ein Paradoxon, weil sie gleichzeitig oberflächlich und räumlich ist. Ein Körper ist nur noch seine äußerste Begrenzung. Die Masse eines riesigen Schiffsrumpfes wird in dieser Vorstellung auf seinen außen liegenden Farbmantel reduziert. Das Objekt liegt dann nicht mehr innerhalb oder außerhalb einer Begrenzung sondern ist die Begrenzung selber In der digitalen Welt stellt dieser Widerspruch kein Problem dar.

Im Modellierprogramm kann die Fläche direkt oder über sein Kontrollpolygon manipuliert werden und ist greif- und kontrollierbar. Texturen simulieren Materialien und Tiefe und lassen die Flächen als Objekte erscheinen. Sollen solche Flächen jedoch in gebaute Realität überführt werden wird der Widerspruch von Oberfläche und Volumen deutlich.

**Flächen und Module**

Diese Unvereinbarkeit von digitaler Fläche und physischem Objekt tritt überall dort zutage, wo die uneingeschränkte digitale Kontinuität mit dem architektonischen Maßstab und Techniken wie Fügung und Elementierung konfrontiert wird und dieser Arbeitsschritt nicht Teil des Entwurfes ist. Ein möglicher Ausweg aus diesem Dilemma ist die Strategie der „Design Surface“ (Kilian, 2006). Die Fläche wird dabei weiterhin als zentraler Bestandteil der entwurflichen Arbeit genutzt, jedoch auf eine komplexere Weise instrumentalisiert und damit der physischen Realität näher gebracht. Jede NURBS-Fläche kann über das Verändern erzeugender Elemente und ein assoziiertes Kontrollpolygon präzise modelliert werden und besitzt ihr eigenes zweiachsiges Koordinatensystem, das es ermöglicht, Punkte, Kurven, Krümmungen und Richtungsvektoren an jeder Stelle der Fläche eindeutig zu identifizieren. Diese Informationen werden genutzt, um Module entlang von Flächen zu positionieren.

Die Fläche dient nun als Repräsentation einer dreidimensionalen Großform und gleichzeitig als eine Leitgeometrie für ein konstruktives System.

Ihre eingeschriebenen Eigenschaften steuern Objekte in einem anderen Maßstab, die nicht nur der Geometrie folgen, sondern auch auf Rahmenbedingungen von Materialien und Fertigungstechnologien reagieren. Diese feinere Organisationsstruktur ist in der Lage Geometrie und gebautes Objekt stärker zu verknüpfen und reagiert auf die Tatsache, dass Architektur nie in einem einzigen Material, System oder einer Fläche realisiert werden kann.

### Modul und Serie

Ein Modul entsteht zunächst als ein dreidimensionales Diagramm, das die Topologie seiner Bestandteile beschreibt und definiert. Dieses generische System wird erst in dem Moment spezifisch, wenn es auf der Fläche positioniert und dort von lokalen Parametern der Fläche informiert wird. Die seriell auftretenden Module werden graduell differenziert. Eine solche Transformation wirkt also auf alle Elemente in der Gruppe und ist auch erst ab einer kritischen Menge von Einzelelementen wahrnehmbar. Das Einzelne ist nicht mehr Unikat sondern Teil einer selbstähnlichen Struktur. Dieses differenziert repetitive System verarbeitet mannigfaltige Anforderungen, die sich aus Programm, Geometrie, Struktur, Material und Fertigungsmethoden ergeben. Das Ganze entsteht durch ein Zusammenwirken einer Serie von Einzelteilen. Interaktion und Rückkopplungen wirken in beide Richtungen: Vom Ganzen zum Modul und vice versa. Eine Modifikation der Leitgeometrie variiert die Geometrie der Module. Strukturelle oder materielle Anforderungen wirken auf jedes Modul und damit auch wieder auf die Gesamtkonfiguration.

### Serialität und Differenzierung

Konrad Wachsmann beschreibt 1959 das Prinzip der Industrialisierung als „ identisch mit dem Begriff der Massenproduktion“. Die vollautomatisierte Fabrik ist erst durch die Produktion „einer großen Anzahl identischer Teile wirtschaftlich“. Dieses Prinzip unterscheidet die Fabrik von der Werkstatt und verändert die Bedeutung des Begriffes Werkzeug, das nicht mehr allgemeines Hilfsmittel für eine Vielzahl von Aufgaben ist, sondern eine spezifische Form-, Stanz- oder Schneidevorrichtung in einer Maschine. Das formgebende Werkzeug ist somit das einzige Original im Produktionsprozess und indirekt auch das fertige Produkt. Jede Instanz des Produktes ist nur noch eine Kopie. Im Gegensatz zu handwerklichen Produkten wird ein unverrückbarer Standard definiert, dem die Produkte folgen. Das dazugehörige Ordnungsprinzip beschreibt Wachsmann als modulare Koordination, die sich auf Punkte, Linien, Flächen und Körper bezieht. Ziel sind einheitliche, räumliche Messwerte, integriert in einem einzigen System, das auf einem Grundmodul basiert. Jedes Einzelteil innerhalb des Systems ist in sich selbst und in Beziehung zu allen anderen Teilen eindeutig bestimmt. Darauf aufbauend synchronisiert und hierarchisiert ein Universalmodul verschiedene Modulkategorien wie Geometrie, Bewegung, Toleranzen, Konstruktion etc.

Ist diese Logik des industriellen Bauens implementiert, entsteht einerseits verlässliche und wiederholbare Qualität, andererseits wird nur das gebaute Realität, was sich dieser Systematik fügt. Die Industrialisierung „kann nicht als Hilfsmittel missbraucht werden, um frei erfundene Konzeptionen zu verwirklichen. Sie kann nur als direkte Ursache für die Entwicklungsbestimmung irgendeines Produktes verstanden werden, das als Teil oder in Kombination mit anderen die Ausdrucksform bestimmt“. Diese euphorisch vorgetragene und notwendige Entwicklung im Bauen stellte seinerzeit eine Innovation dar und bildet den Grundstein für viele technische Entwicklungen wie den Mero Knoten sowie die Möbel- und Architektursysteme Fritz Hallers.

Andererseits erlaubt serielle Fertigung keinerlei Art von Singularität. Jedes System ist reduziert auf einen Idealtypus, der stets den Startpunkt jeder Entwicklung definiert. Variation ist dann eine Abweichung des Idealtyps, die aber immer auf die Ausgangsform zurückgeführt werden kann.

Betrachtet man mit dieser Strategie eine Honigwabenstruktur, dann kann daraus nur die ideale hexagonale Zelle abgeleitet und tausendfach gefertigt werden. Lokale Besonderheiten der Struktur, die auf den spezifischen Kontext reagieren, werden nicht Teil des Systems, sondern als Anomalie verworfen. Für die Natur jedoch ist die pure geometrische Form eine Abstraktion, oder aber ein Sonderfall unter vielen. Die Industrialisierung des Bauens wie Konrad Wachsmann sie beschreibt, zeigt eine Reihe von Parallelen zu aktuellen Entwicklungen der Digitalisierung des Bauens auf. So wird die damalige Ausbildung von Architekten hinterfragt und „anonyme Teamarbeit“ als Ersatz für Autorenschaft vorgeschlagen. Das Materielle, Technische und Methodische steht im Vordergrund und löst empirische und traditionelle Bauweisen ab. Die gleiche Euphorie verspürt man in den Publikationen der letzten Jahre, die davon berichten, dass computergesteuerte Maschinen hunderte unterschiedliche Teile in fast gleicher Zeit und demselben Aufwand herstellen wie eine Serie immer gleicher Teile. Diesen technischen Vorteil kann man sich jedoch nur zunutze machen, wenn man auch Techniken in Entwurf und Planung entwickelt, die diese neue Strategie verinnerlichen. Natürlich „ist es der Maschine egal, ob sie eine Kurve oder eine Gerade schneidet“, aber Geometrieerstellung, Logistik der Identifizierung von Bauteilen, Montageabläufe und Materialverbrauch müssen ebenfalls Teil der neuen Systematik werden.

Ein kontinuierlicher digitaler *Workflow* ist nötig als eine Fertigkeit oder Technik, die Architekten auf konzeptioneller und technischer Ebene entwickeln müssen. Dabei tauchen die gleichen Elemente auf, die bereits Wachsmann in seiner Forschung beschreibt und analysiert, nur müssen diese an die neuen technischen Möglichkeiten angepasst werden. Im konkreten Fall, der in diesen Buch beschriebenen Projekte gibt es eine modulare Koordination, die zwar repetitiv ist jedoch gleichzeitig differenziert wird. Das Bezugssystem leitet sich aus vier Flächennormalen ab, die nicht zwangsläufig parallel sein müssen, wichtig ist allein die korrekte Topologie, also ihre Beziehung untereinander. Wie bei Wachsmanns Universalmodul leiten sich alle weiteren Kategorien von diesen geometrischen Informationen ab. Die im Raum gekrümmte Fläche wird zum Leitsystem der modularen Koordination.

Das formgebende Werkzeug bzw. das Original, ist der digitale Datensatz eines jeden Bauteils. Diese Daten werden genutzt, um daraus Derivate ganz unterschiedlicher Natur zu erzeugen: Zweidimensionale Abwicklungen, dreidimensionale Visualisierungen, Datensätze für Laserzuschnitt oder 3D Druck sind Instanzen der digitalen Informationen. Damit erfolgt eine Trennung von Struktur und Form. Von entscheidender Bedeutung ist die Struktur, die das System aus einzelnen Elementen organisiert und erhält. Die tatsächliche Form ist davon losgelöst. Auch auf dieser Ebene paart sich zur Serialität die Variation. Jedes Modul kann geometrisch unterschiedlich ausgeformt sein, entscheidend ist die relative Beschreibung seiner Elemente untereinander und die geometrischen Rahmenbedingungen der geplanten Fertigungsmethode.

Das bedeutet gleichzeitig, dass es keinen Idealtypus des Moduls gibt von dem ausgehend Variation entsteht. Jedes Modul wird auf der Fläche positioniert und dort in sein zugewiesenes Koordinatensystem implementiert und von lokalen Parametern der Leitfläche informiert. Wollte man eine Typologisierung dieser Module vornehmen würde diese durch alle auftretenden Instanzen definiert werden und sich mit jeder neuen Instanz verschieben.

Die dreidimensionalen Muster der hier gezeigten Projekte entfalten sich im Prozess der Entstehung als Resultat der vorher definierten Regeln. Singularitäten entstehen durch Reaktion auf den lokalen Kontext, dessen Eigenschaften wechseln können. Die pure additive Anordnung immer gleicher Elemente wird ersetzt durch Module, die mit ihrem Kontext interagieren. Im Projekt wurde diese Tatsache auf unterschiedlichen Ebenen deutlich.

Bevor man die Module auf der Leitgeometrie platzierte, war eine Einschätzung des Ergebnisses nur bedingt möglich. Der Prozess der Generierung kann nicht übersprungen werden. Ist dann aber eine Lösung gefunden, die auch die physische Produktion durchlaufen hat, ist bei sorgfältiger Identifizierung aller Module kein zusätzlicher Bauplan nötig. Allein die Wiederholung des Generierungsprozesses in derselben Reihenfolge lässt die Großform in einem Bottom-Up Prozess entstehen.

**Scripting**

Diese Differenzierung innerhalb der Serie ist bekanntermaßen nur durch den Einsatz von Computern möglich. Große Mengen an Daten können exakt und automatisiert abgearbeitet werden und das in viel größerer Geschwindigkeit, als der Mensch imstande ist, es zu tun. Eine neue formale und technische Qualität entsteht also zunächst durch schiere Quantität. Damit verschiebt sich die Aufgabe für den Entwerfenden vom Erzeugen digitaler oder physischer Objekte hin zum Definieren und Steuern von digitalen Prozessen, die dann in beliebig vielen Iterationen ablaufen können. Eine Technik, die dies ermöglicht, ist seit geraumer Zeit in die Welt der Architektur migriert: Scripting, eine vereinfachte Form der Programmierung, erlaubt es, große Mengen der repetitiver Modellierarbeit automatisiert ablaufen zu lassen. Scripting ist eine Form von Programmierung, die zwischen einer Anwendung und ihrer API (Application Programming Interface) angesiedelt ist. Geschriebene Befehle, die sich hinter Icons auf der grafischen Schnittstelle der Software verstecken, können mit einem Script ausgeführt werden. Darüber hinaus ist die Ausgabe von Werten nach Abschluss einer Operation möglich. Diese Informationen können an die nächste Operation weitergegeben werden. Der Einsatz von Variablen, Schleifen, Bedingungen und Funktionen erweitert das Anwendungsspektrum zusätzlich. Das „Scripten“ (oder „Macro-Scripten”) ist damit ein Werkzeug, mit dem regelbasierte, repetitive Aufgaben effizient bearbeitet und evaluiert werden können. Diese Technologie schließt eine Lücke, die vormals in der digital kontinuierlichen Prozesskette bestanden hat, und erfordert gleichzeitig das Entwickeln neuer Techniken für Architekten und Designer, wenn sie nicht auf eine reine effizienzsteigernde Automatisierung reduziert werden soll. Ein großes, bislang wenig erforschtes Potential bietet die Implementierung von Analysedaten unterschiedlichster Herkunft in den generativen Prozess.

**Tragwerksanalyse**

Die geometrischen Daten eines Modellierprogramms können in ein Analysemodell überführt werden. Im konkreten Fall kam eine Software zur Errechnung von Stabwerken zum Einsatz. Aus diesem Grund wurden Achsmodelle der Komponenten aus dem Geometriemodell an die Analyseanwendung übergeben. Die Schnittkräfte in jedem Stab wurden ermittelt und dynamisch in das geometrische Modell zurückgeschrieben. Die Daten konnten dann für die Dimensionierung der Komponenten genutzt werden.

# 7.5. Fazit

### 7.5.1 Fallstudie 01 - Formfindung

In der Fallstudie 1 wird der gestalterische Rahmen von Formfindungsmethoden aufgeweitet. Dabei entstehen Formen, die architektonische und der tragwerksrelevante Aspekte werden miteinander ins Gleichgewicht bringen. Aus architektonischer Sicht ist interessant, dass freie Formen durch einen zunächst beschränkenden Parameter informiert und gestaltet werden. Weitergehende Forschungsarbeiten könnten die Art der Flächenbeschreibung erweitern. Neben den kontinuierlichen NURBS-Flächen wären auch Netze als Grundlage für den Prozess denkbar. Damit könnte eine höhere topologische Vielfalt erreicht werden.

### 7.5.2 Fallstudie 02 - Optimierung

Das Ergebnis der Studie kann als Erfolg gewertet werden, da nach 280 Generationen ein Raumfachwerk hervorgebracht wurde, das mit einer stark reduzierten Stabanzahl eine geringe Verformung aufweist. Die vorher definierten Räume sind fast frei von Stäben. Das entstandene Tragwerk folgt keiner vordefinierten Typologie, sondern paßt sich an die lokalen Gegebenheiten an. Das determinierte System des evolutionären Algorithmus bringt ein unvorhergesehenes Ergebnis hervor. Es entsteht wieder ein Raumfachwerk, aber die Stabanordnung ist so ausdifferenziert und angepaßt, dass sie in einem manuellen Prozeß nicht entstanden wäre. Zukünftige Forschungsfelder liegen in der Weiterentwicklung der Geometriebeschreibung, eine Art DNA für Geometrie, die unterschiedliche geometrische Typen (Linie, Fläche, Volumen) zulässt, so dass beispielsweise über einen evolutionären Prozeß aus einem vektoraktiven System ein flächenaktives System werden kann.

### 7.5.3 Fallstudie 03 - Dimensionierung

In der Fallstudie sind die Werkzeugbenutzer zu Werkzeugbauern geworden. Teilnehmer, die anfangs lediglich ihr eigenes Modul programmiert haben, begannen im zweiten Entwurfsprojekt das Werkzeug (das von den Betreuern zur Verfügung gestellte eigens entwickelte Programm) an ihre individuellen Bedürfnisse anzupassen. Die allgemeingültigen Prozeduren wurden zu maßgeschneiderten Anwendungen, die eher an das Entwurfskonzept angepasst wurden als umgekehrt. Desweiteren wurden die quantitativen Daten aus der Stabwerksanalyse als treibende qualitative und gestalterische Kraft im Entwurf eingesetzt.

### 7.5.4 Fazit

Algorithmische Werkzeuge erwiesen sich als eine produktive Schnittstelle für das gemeinschaftliche Entwerfen von Architekten und Ingenieuren. Tragwerksrelevante Aspekte konnten in das Modell des Architekten übernommen werden und informieren damit die Geometrie. Die Stärken der drei Fallstudien bewegen sich zwischen Rationalisierung und forschendem Entwerfen und Entdecken. Der Autor ist der festen Überzeugung, dass solche Verfahren helfen können die professionellen Grenzen zu verwischen. Sie sind nicht nur ‚Problemlöser‘ sondern Werkzeuge zur Erforschung neuer Entwurfs- und Lösungsräume.

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This book argues for novel strategies to integrate engineering design procedures and structural analysis data into architectural design. Algorithmic procedures that recently migrated into the architectural practice are utilized to improve the interface of both disciplines.

Architectural design is predominately conducted as a negotiation process of various factors but often lacks rigor and data structures to link it to quantitative procedures. Numerical structural design on the other hand could act as a role model for handling data and robust optimization but it often lacks the complexity of architectural design. The goal of this research is to bring together robust methods from structural design and complex dependency networks from architectural design processes. The book presents three case studies of tools and methods that are developed to exemplify, analyze and evaluate a collaborative work flow.

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