Open systems: approaching novel parametric domains

Marco Vanucci

Some of the most relevant shifts in contemporary architectural discourse and practice are intrinsically connected with evolution in computation techniques and software development.

The novelty in architectural design brought forward by new computational tools is often related to software packages or digital techniques developed in other design fields. Innovations in computational as well as manufacturing processes, in fact, experimented and developed by naval, aero, automotive and products industries have represented seminal undertakings for innovation in the construction industry and, moreover, for experimentation in architectural practice.

The introduction of parametric software packages in the world of architecture and structural engineering, despite being a fairly new paradigm, is already redefining the discipline from within.

Traditional CAD products create lines, arcs, circles and a great variety of geometrical objects; making design changes to a given geometry requires changing all appropriate components in order to make the drawing correct.

A new generation of parametric design systems establishes models defined by a collection of constrained relationship between objects. In other words it allows setting up parametric geometrical arrangements capable to build anticipated variations between objects.

A parameter is a variable to which other variables are related by means of parametric equations: design modification and creation of a family of component parts can be performed efficiently by setting up reconfigurable smart models capturing the underlying logic of the design.

The instrumentation of parametric setups into architectural practice is starting to shift the role of the architect in the design processes: from the design of specific shapes to the determination of those geometrical / algorithmic relationships describing the project and its components. The design shifts from drawing surfaces to setting up rules of interdependency—genotypes—leading to potential differentiation —phenotypes—.[i]

The novelty represented by parametric tools in architectural culture hasn't found architects unprepared to conceptually understand its potential for contemporary practice: the responsiveness by which architects and advanced design firms gathered the resources of associative design has triggered a fast implementation of parametric tools in the software industry as well as an increasing curiosity to apply its potential in contemporary architectural design.

Nevertheless, despite the receptivity of some of the most interesting cutting-edge architectural practices, it is possible to trace certain tendencies concerning different approaches, some limitations and novel developing scenarios.

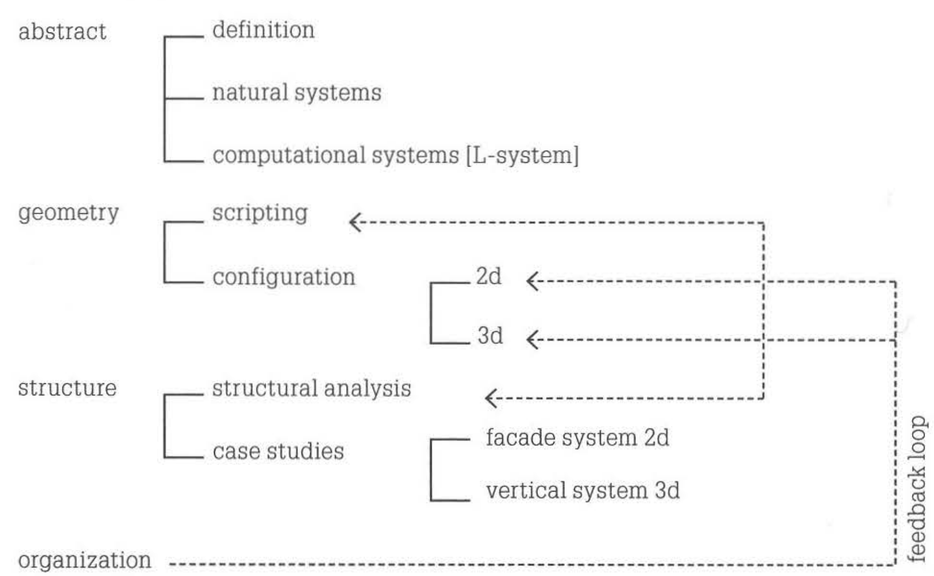
Architecture is ultimately characterized by the need for a coherent design logic between different elements forming a whole constituted by an interiority and an exteriority; quality and meaning are achieved through the rigorous determination of all those elements contributing to the interfacing between the different components and the building in its entirety: facades, detailing, proportions, symmetry, modularity just to name a few. Thus, parametric design is important for that: the possibility to establish intricate system of relations between different objects and their properties fusing the hierarchy between parts and whole.

"So far experimental architects have just jumped from top-down determination of parts to bottom-up determination of wholes." Greg Lynn[ii]

What Lynn points out is the delay by which architects have employed parametric design in the development of bottom-up approaches where the determination of components has been prioritized over the design of the whole. This approach has just represented an extreme case. Nevertheless, reshaping the traditional dichotomy between the building and its parts, new digital parametric tools still leave behind some unexpressed potential for contemporary architecture, particularly in relation to the possibility to define highly modulated wholes together with the determination of differentiated components.

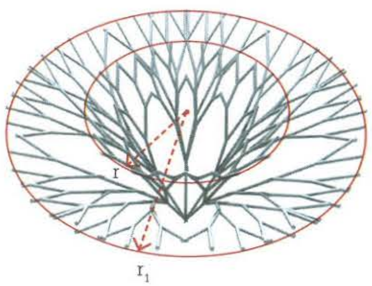
In contemporary construction industry, instead, parametric softwares are often employed in design processes of rationalization and post-rationalization where, given a certain project, the answer to specific problems is required to actualize the desired shape [problem-solving approach].

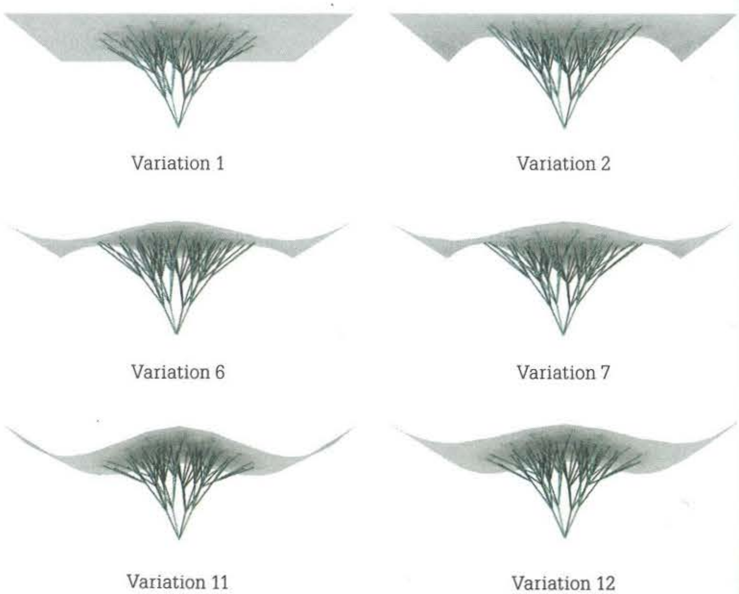
Branching system: the matrix shows parametric variation of the geometry

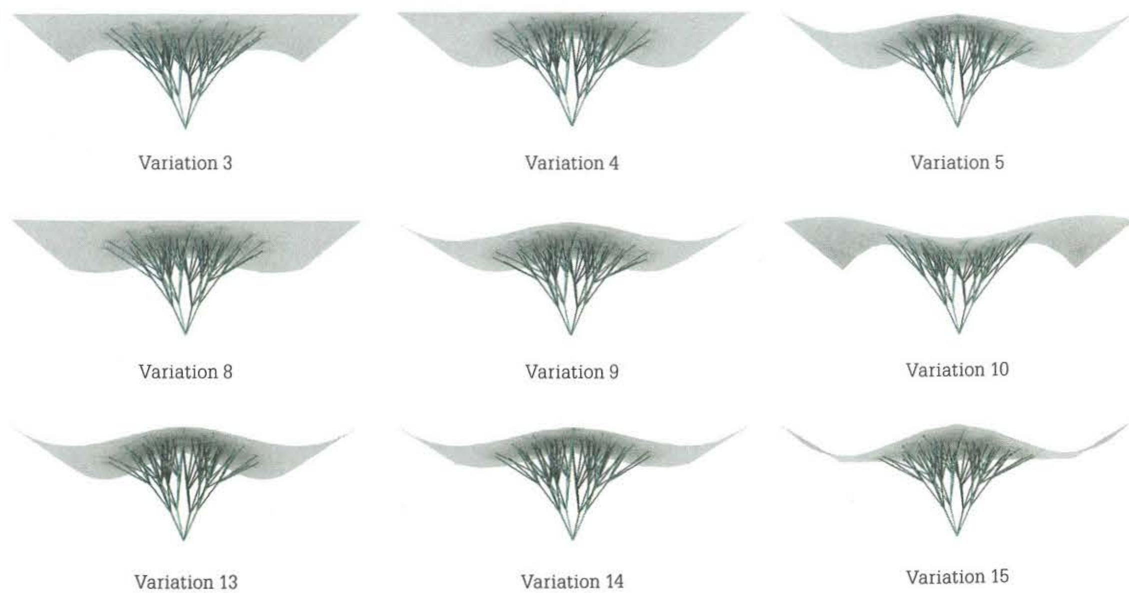


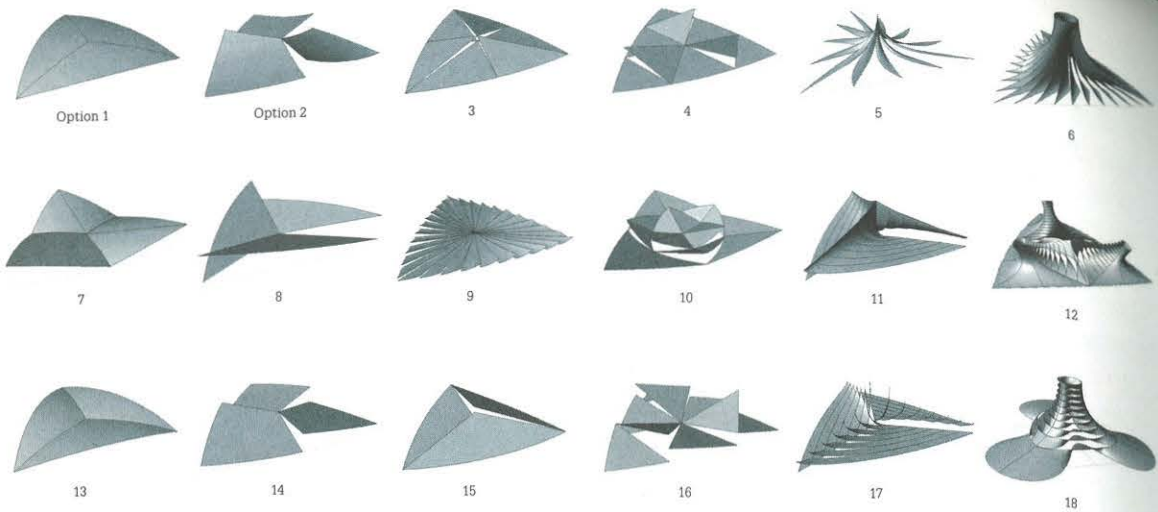
i_Patrick Schumacher – Interview *AJ* 21.12.06
ii_Greg Lynn – *AD Programming cultures*, Wiley Academy, 2006

In this case the potential of computational tools is utilized for its higher degree of precision and speed to deliver tailored ad hoc solutions: the parametric modeling is driven by the need to engineer rational solutions in order to fulfill structural, geometrical or fabrication requirements. In this case, in fact, the potentials for a generative approach are set apart in favour of more pragmatic strategies.
At the other end of the spectrum, by contrast, the proficiency of academic research to implement the generative potential of new computational tools is leading architectural experimentation towards unexplored territories where, more and more often, the figure of the (forthcoming) architect is contiguous to the one of the computer scientist. Thus, academia is quickly pushing the boundaries of parametric/algorhytmic architecture towards the definition of novel paradigms, heading towards a higher level of complexity and sophistication marking an increasing disciplinary divergence between research and practice.
The p.art team sets its line of research at the intersection of these two worlds, searching for the definition of an integral approach to parametric design in the endeavor to bridge the gap between architectural design, structural engineering and evolutionary design strategies. The interdisciplinary structure of p.art and its heterogeneous research spectrum describe an open source design structure where the employment of parametric tools represents one of the most fertile lines of investigation.
p.art is increasingly raising interest within the contemporary architectural and engineering realms due to its capacity to create an innovative interface between architectural research and structural engineering opening up opportunities rather than providing answers. p.art operates allowing collaboration between different disciplines and differing expertise in an attempt to create a common ground where it can be possible to formulate novel design strategies. p.art engages its research agenda through the employment of several different digital tools: among others, parametric software such as Digital Project, Gehry Technology's 3D modeling package based on Catia, which it has been used since first the team was set up. The paradigmatic innovation of parametric design originates from its modus operandi: the intrinsic resilience to free-form sketching exercise of Digital Project, in fact, requires a sharper understanding of complex geometry and induces the designer to think through the system logic before even starting to draw a line. In this sense it is projecting desirable perspectives where architectural design is generated from a set of rules and the interdependent relationships between parts governing the manifold aspects of the design. The advent of parameterization increases the complexity of the design task in relation to the necessity to build up not only the model to be designed but also the conceptual structure that guides the parametric variations. From a design point of view it is possible to imagine the advent of design methods based on codified geometrical operations proliferating and interacting to achieve a higher level of complex order: the development of a specific design vocabulary based on parametrically codified instances prefigures a fully integrated design approach where complexity and differentiation emerge from the set-up of coherent and controlled operations.
In this sort of scenario the role of the architect and that of the engineer is contiguous and inform each other in a truly cooperative and generative holistic design process.
So far, p.art's engagement with DP is twofold. In the first instance, in fact, p.art's use of DP has been mainly concerned with the study of complex geometry deploying feasible and buildable solutions: it has been deployed in a "problem solving" approach for specific ongoing projects whereby the mutable nature of the design required an adaptive model. The constant adaptation of the structural arrangement to the changing nature of the building envelope throughout the design process allows, among other things, the iterative computation of structural analysis models, almost in real time.





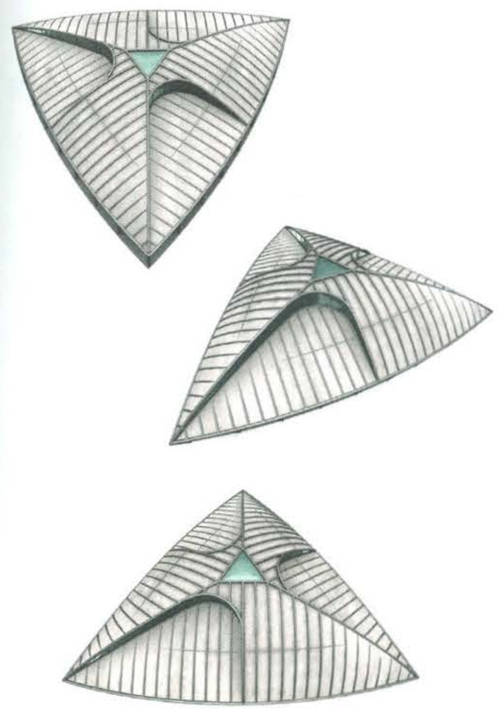




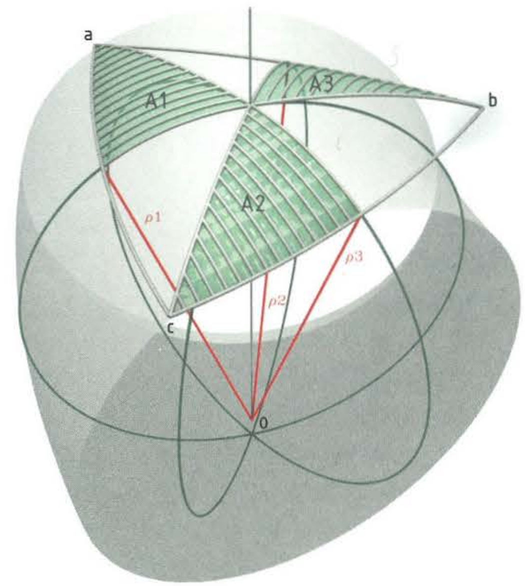
BP Sunbury

Among others, the project for the British Petrol headquarters in Sunbury is an interesting example where parametric modeling has been employed to study the geometrical solution for the roof structure as well as for the delivery of feasible structural system. Numerous geometric arrangements were originally tested to achieve a desirable aesthetic quality and structural viability: the need to provide solar shading to the courtyard below precluded the possibility to utilize translucent lightweight finishes [ETFE]; at the same time, the necessity to provide natural daylight to the suitable levels informed the overall design of the roof and its parts.
By introducing steps within the roof it was possible to introduce vertical glazing through which natural daylight can enter the atrium. The design of the dome shaped roof has been driven by the desire to combine easy fabrication and efficient structural performance. The study of the roof shape has highlighted varying curvature in both lower and higher triangular main panels across the radial directions.
Nonetheless the bespoke triangular panels were extruded from three defined toroids. This allowed identification of planes where structural elements with the same curvature could be defined; in this way, the structure which has been developed presented elements with single curvature for both the lower and the higher roof panels. The structure of the panels was organized between primary beams along the curved edge and secondary beams arranged at 1.5 m spacing perpendicular to the edge ring beams. This methodology created a specific logic around the study of the geometry in order to optimize the fabrication of the elements with identical curvature hence simplifying the fabrication process and increased economy. In turn this methodology allowed easy rationalization of analysis thanks to the selection of few steel sections with similar stress and deflection patterns. The need of fewer number of sections optimized the design time required, providing an efficient result that ease cost saving in the overall design/construction stages of the project.

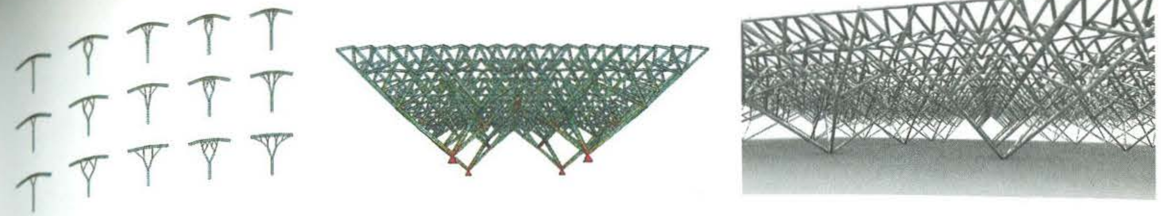
This type of operation seems, at a first glance, fairly straightforward but it represents a certain level of intricacy in the setting up of the model and its constraints; after a first analysis, in fact, the 3 dimensional model was set up in Digital Project following simple yet rigorous parametric logics.
The main problem concerned the opportunity to establish a simple and efficient set of relationships between parts so that the model could be easily updated in each single geometry as well as in its entirety. The overall geometry of the roof has been simplified and rebuilt starting from the geometrical definition of the toroids to which all other components are related and derived from: indeed, changing the radius of the toroids, the curvature of the roof surfaces are altered determining the adaptation along the surfaces of those lines determining the roof structural beams. This model allowed for reconfiguration of the overall structure and fast adaptation to various and unpredictable design stimuli during the design process (i.e. the need to increase the distance between higher and lower roof surface to increase light penetration).
Traditional program packages— i.e. Rhino—can initially develop quick and precise 3D models; at the same time any occurring change would imply rebuilding the model over and over again until a fixed determination of the design and all its aspects.
Digital Project, on the contrary, despite the more complex and, to a degree, time consuming developmental logic, offers greater advantages: from accommodating unpredictable changes happening during the process to extracting precise data for structural analysis or fabricators.

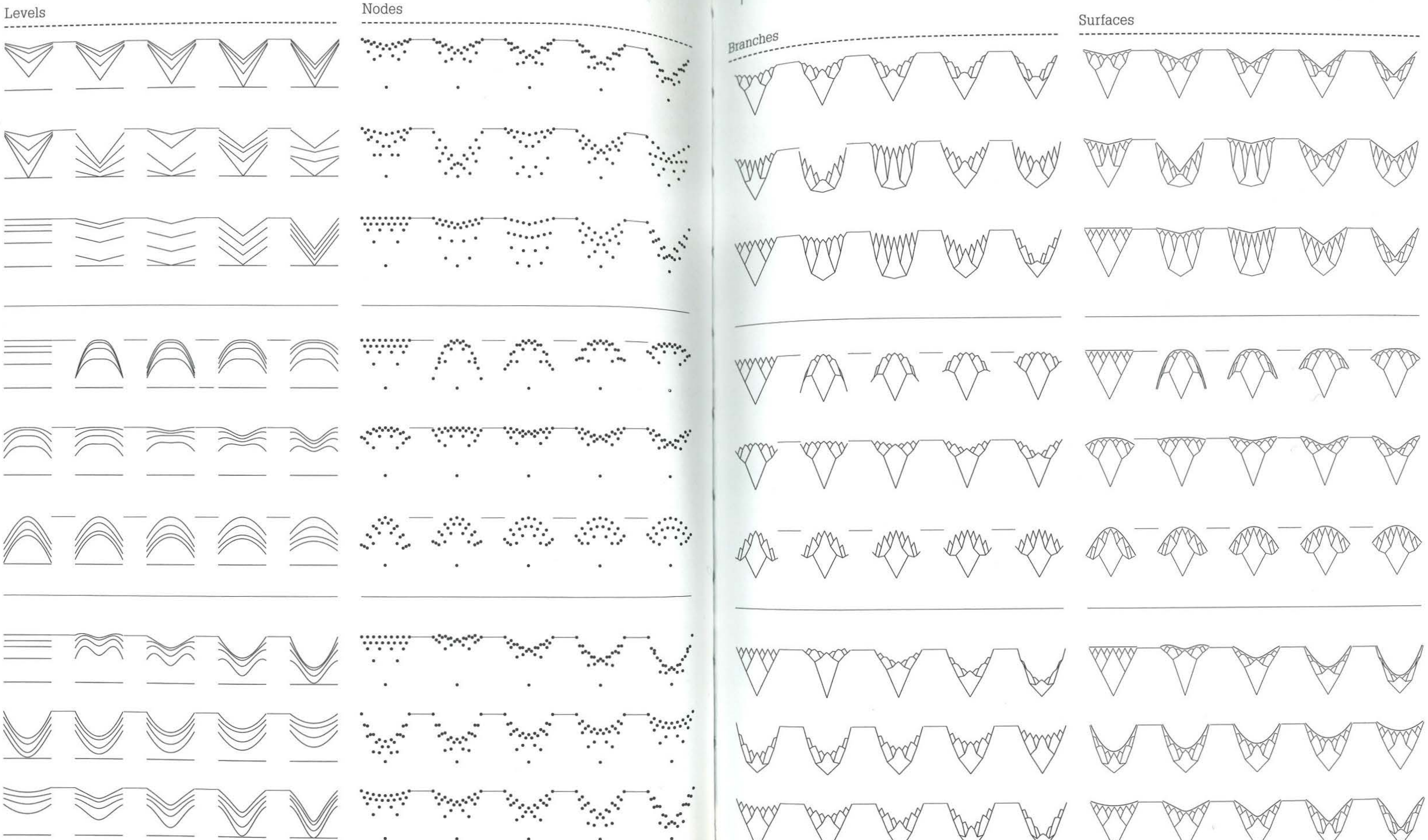


BP Sunbury: the diagram shows the geometrical principle from which the ovel geometry was parametrically generated: three toroids are drawn; the tree geometries forming the roof are sections of the toroids. The angle of curvature of such surfaces is determined by the parametrized length of the radiuses of the toroids.



Branching system: the matrix shows parametric variation of the geometry

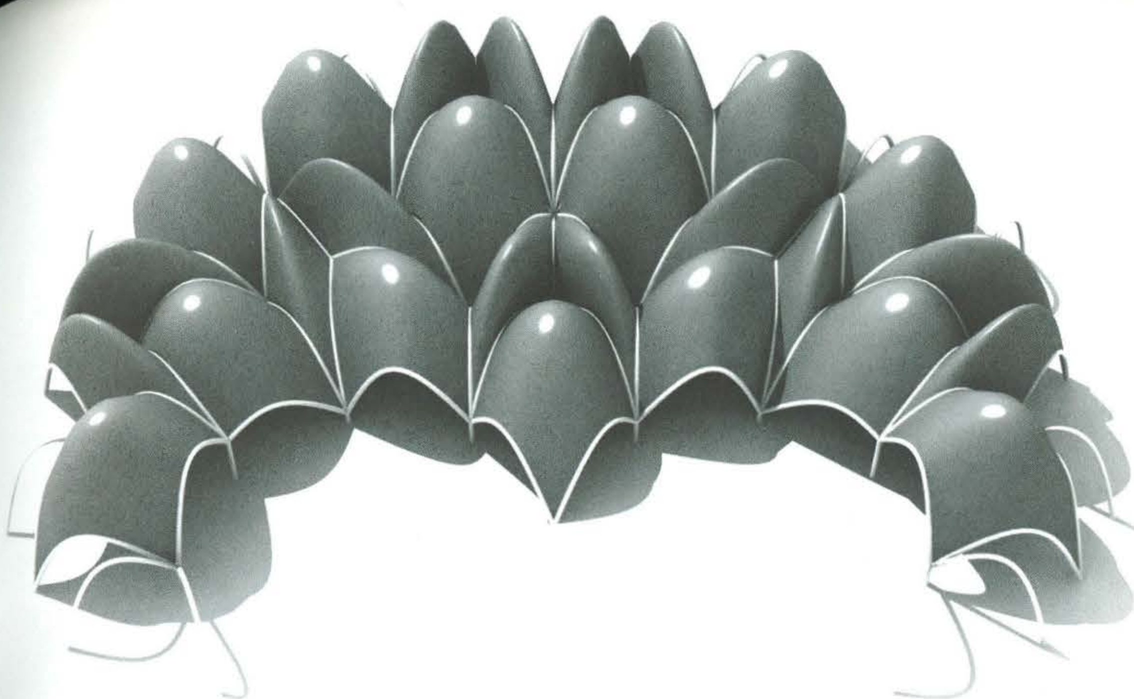


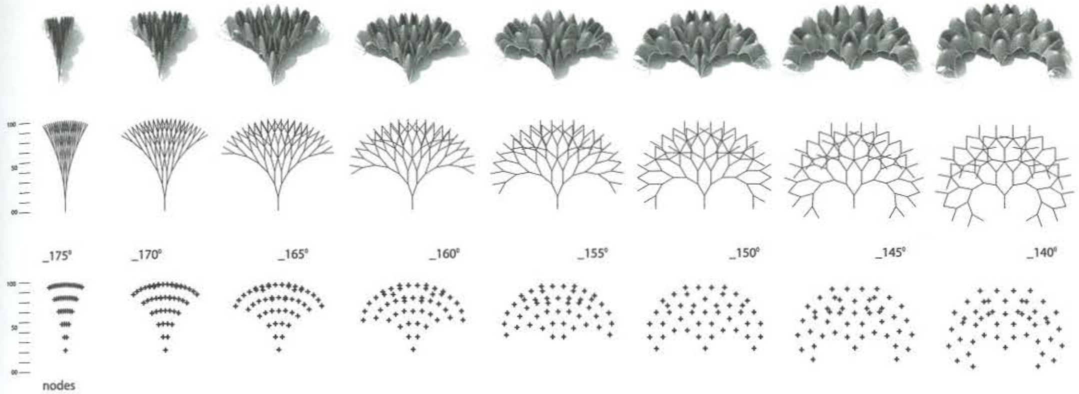


Open system: branching structures

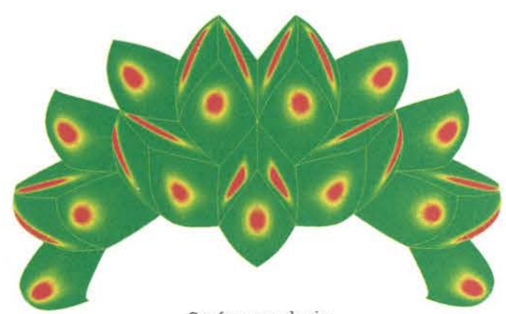
A second approach towards parametric design is represented by the attempt to build up a deeper understanding of structural systems as multi-performative design set-ups. Moving away from the homogeneous standardization of the Modern paradigm, this research, through the generative use of parametric tools, is seeking to investigate open systems as multi-performing, differentiated organizational systems.
In line with the experimentation on branching structures developed by Frei Otto, the research unfolds through a series of exercises aiming to open up a generative approach to parametric design: specificity is achieved through iterative differentiation, adaptation through redundancy, robustness through structural-geometric interdependency. Understanding architectural design as a process of formation leads to the exploration of a pre-material state of given systems: namely, the state prior to the crystallization into a specific design form is explored. In this way, open systems act as virtual machines prior to the actualization into a given design scenario. Methodologically, different paths are followed in an attempt to open up potentials for inclusive performance:

Organizational logic: branching is explored as an organizational system. Different network topologies are analyzed and compared.
Geometrical logic: the geometrical logic of branching is created and developed through parametric tools: Digital project is employed to generate the geometrical structure; in addition differentiation is achieved by the instrumentalization of the defining principle: angle between branches, number of branches, length, displacement of the nodes in space… An intricate matrix is then emerging from the proliferation of differentiated geometrical operation.
Structural logic: the structure and the stability of the various configurations is analyzed through finite element analysis software [FEA]. Thus running structural analysis necessitates specifying a range of parameters to set up likely structural scenarios. Running structural tests on differentiated geometrical arrangements is possible to detect certain general behavioral patterns happening during the process of extracting precise data for structural analysis or fabrication.
The possibility to establish interdependent relationships between different system logics contributes to the redefinition of common fitness criteria: each system logic, instead of responding to a specific optimized scenario, informs each other towards a multi parametric performing whole. Geometrical arrangements, spatial affects, structural performance and organizational logic contribute to the formation of the system and its performance-based logic. p.art develops its research in the endeavor to shift the architectural paradigm from a problem-solving to a problem-caring approach where integral design logics contribute to the coherent employment of novel design method.





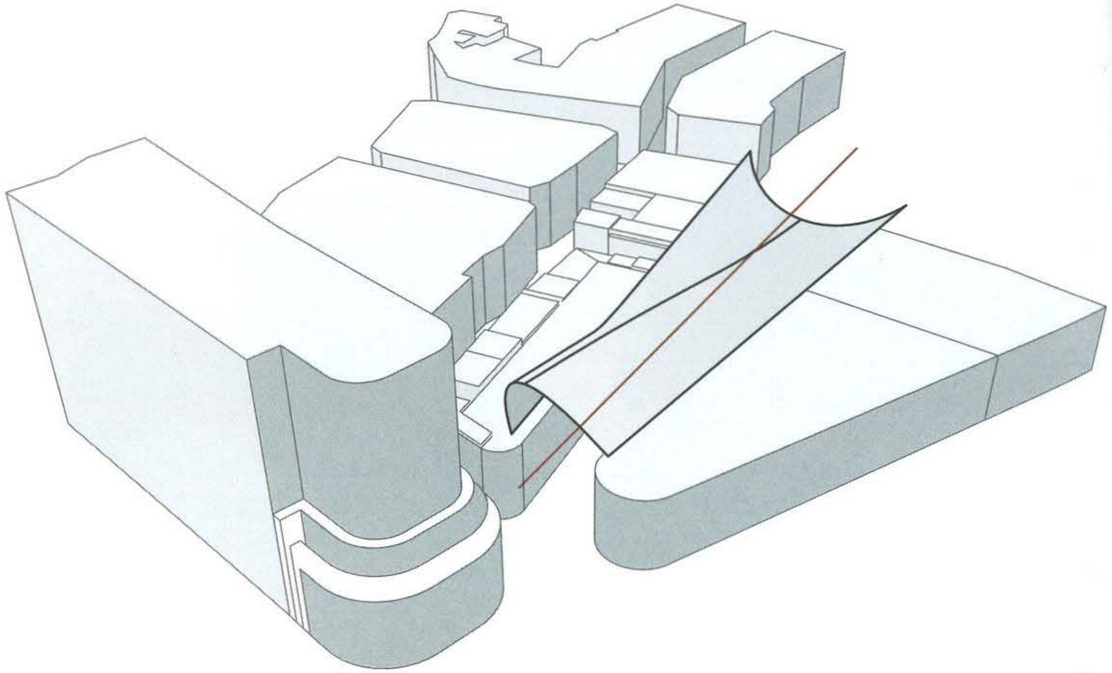
Surface analysis

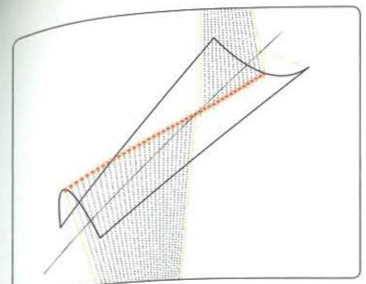


Surface analysis

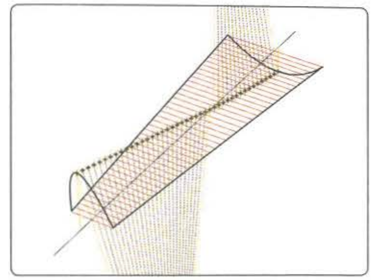
Barnsley market roof

The geometry was defined by the architect—it rises at one end by 20m and dips at the other end by 9 metres, both edges cantilevered/angles outwards.
Structural concept of a rib structure fabricated from riveted metal plates. The structure is clad by a single ETFE strip pillow between two ribs. The entire structure is also to be supported by the the adjacent buildings.
The ribs were extracted from the architects model for structural analysis. This enabled us to define limits and constraints to begin refining the geometry of the roof.
Parametric model was set up based on fixed length of roof and heights of either ends and that the roof must be symmetrical. The number of ribs were determined by the standard ETFE span. Alterable factors are the angles of cantilever at each edge, which defines the longest length hence defining the orientation of each plate.
We were able to generate several options for analysis.
Through sofistik analysis, it was determined that the maximum angle for the edge cantilever/overhang is 20 degrees. There needs to be a single rib whose orientation was perpendicular to the ground, to ensure structural integrity. Cable ties are to be employed to tie the whole thing together. Calculations also determined minimum plate widths for the ribs.
There are 2 types of ribs, the concave and the convex. It became apparent through analysis that the width at the quarter length point of the rib was more important than supporting ends, due to buckling patterns. With a set of figures as requirements, the next task would be how to accommodate them and develop them into a set of continuous aesthetically logical (and pleasing) steel plate profiles.

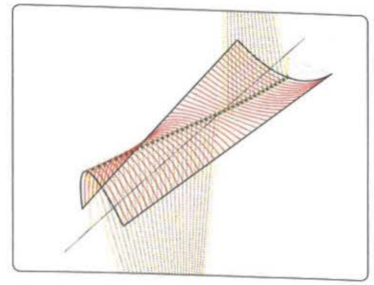




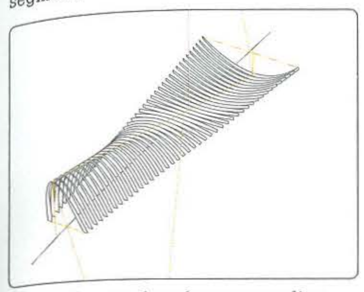
Adhering to spans between 3-3.5 meters to accomodate standardised ETFE panel dimensions, the middle line of the surface was divided longitudinally into 42 segments of equal spans (43 points).



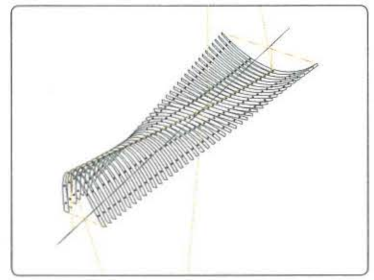
Having established the 43 points on the middle line, the boundaries dictated by the adjacent buildings were also divided into the same number of segments.



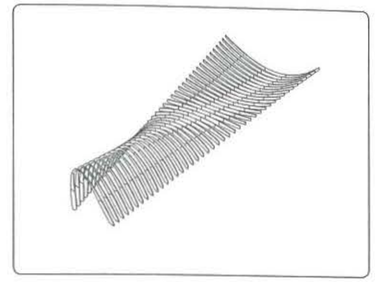
All 43 profiles were then extracted from the surface. The geometries were then structurally analysed to determine the dimensions of the structural members.



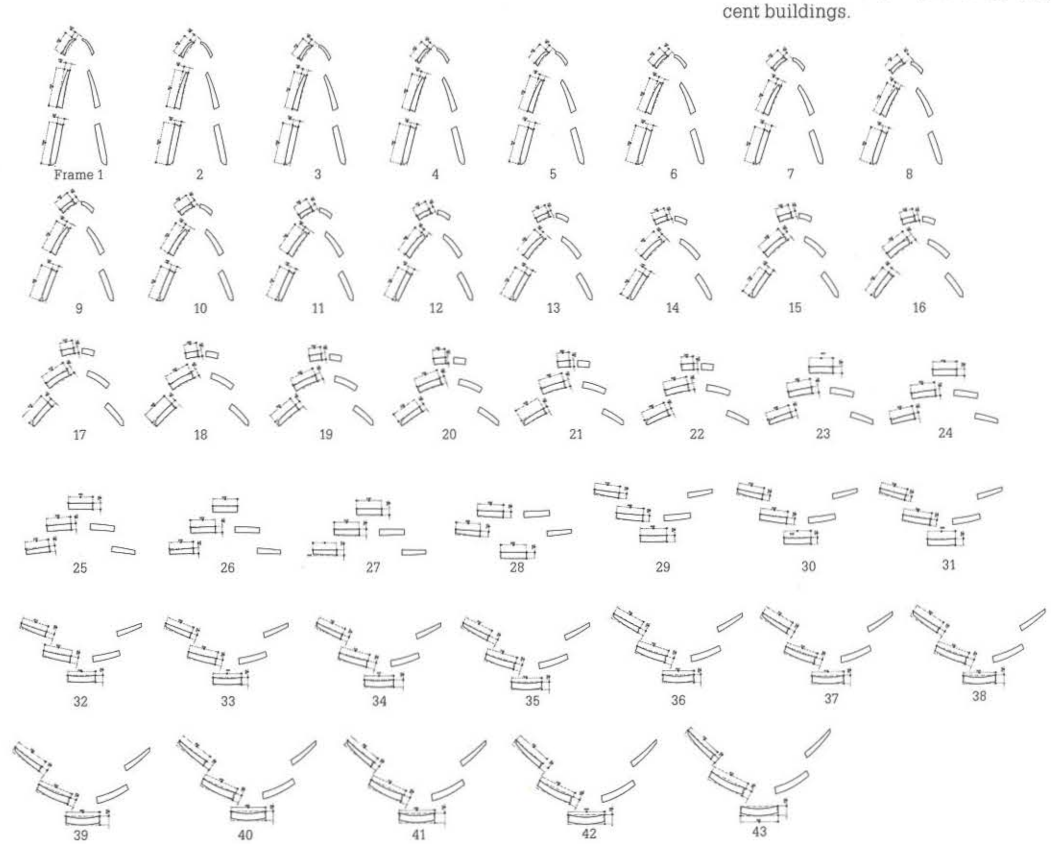
Rib profiles are then drawn according to the sizing provided from the analyses with the material being steel plates.



Points were extracted from each rib for the location of cable ties, all of which were of equal distance along the rib profile.



Each rib plate is then divided into 5 segments of equal length. Each rib is made up of a set of 12 plates which are riveted together; Plates are needed to fix the structure onto the parapets of the adjacent buildings.



SIMPLEXITY

Sawako Kaijima, Michalatos Panagiotis

Simplexity is a term in system science which describes the emergence of simplicity out of intricate and complex sets of rules.

In recent years there is an increasing trend in architecture to exploit the ability of algorithmic design to produce complex forms by implementing relatively simple and easy formulas. This often results in the addition of unnecessary layers of complexity to a project just for the sake of production of seemingly more complex forms. This in turn can degenerate to computational decoration and after taking into account all the layers of information, the resulting algorithms seem little different than a complicated random number generator.

In contrast there is a whole class of algorithms that deal with simplification which are usually more complex and difficult to implement. This is partly the result of the fact that multiplication and proliferation can be easily implemented via iterative function calls and local simple operations over parts of a system. However, simplification in a way that produces meaningful results and renders the complex system more accessible to human thought and intuition or more efficient is harder to achieve. This is because omitting elements, filtering, reduction, selection and abstraction are procedures that require intelligent and responsible choices as well as some way to refer to and operate on the totality of the system. This implies that the designer needs to have a more or less clear idea as to what she wants to achieve and in addition take full responsibility of the choices made. A deeper understanding of the system on which operations are carried out is required. A lot of these algorithms are hidden within commercial software packages that designers employ in order to realize their projects in the first place. They are the little workers that do not produce spectacular results but guarantee consistency.

Let's take for example an algorithm that iteratively copies a set of points applying some transformation matrix. If the matrix is a contraction this results in the often organic looking Iterated function system imagery. The amount of elements increases exponentially but the algorithm just applies the same transformation mechanically over and over. On the other hand an algorithm that will take a vast amount of points and attempts to reduce them or extract some information like density, shape or skeletal structure will be a rather more complicated story. It will have to scan the totality of the system over and over and then compare, classify, seek spatial relationships like clusters, implied boundaries etc. It will probably require the introduction of more complex data structures both to partition space (e.g. octrees) and to hold derivative elements that describe implied or imposed relationships within the point set (lines, clusters, areas, boundaries etc.). So while the first algorithm only needs to know one type of object, a point as a triplet of numbers, the second algorithm will have to describe points and their relationships using objects of a higher level of complexity.

Another way to see this contradiction is through decision paths. A proliferation algorithm will try to follow all possible paths and avoid making any choice between them. A simplification algorithm will try to find a single more or less optimal path within the constraints of the problem. This implies also that the second requires a well defined problem and hence a better understanding of both the problem and the algorithm's behaviour on the part of the designer.

As we will demonstrate in the following examples simplexity is not just a simplification of form. The simple might arise in different invisible layers of the design and formal regularity (repetitiveness, symmetries, etc.) might actually decline as a result of the application of such algorithms.

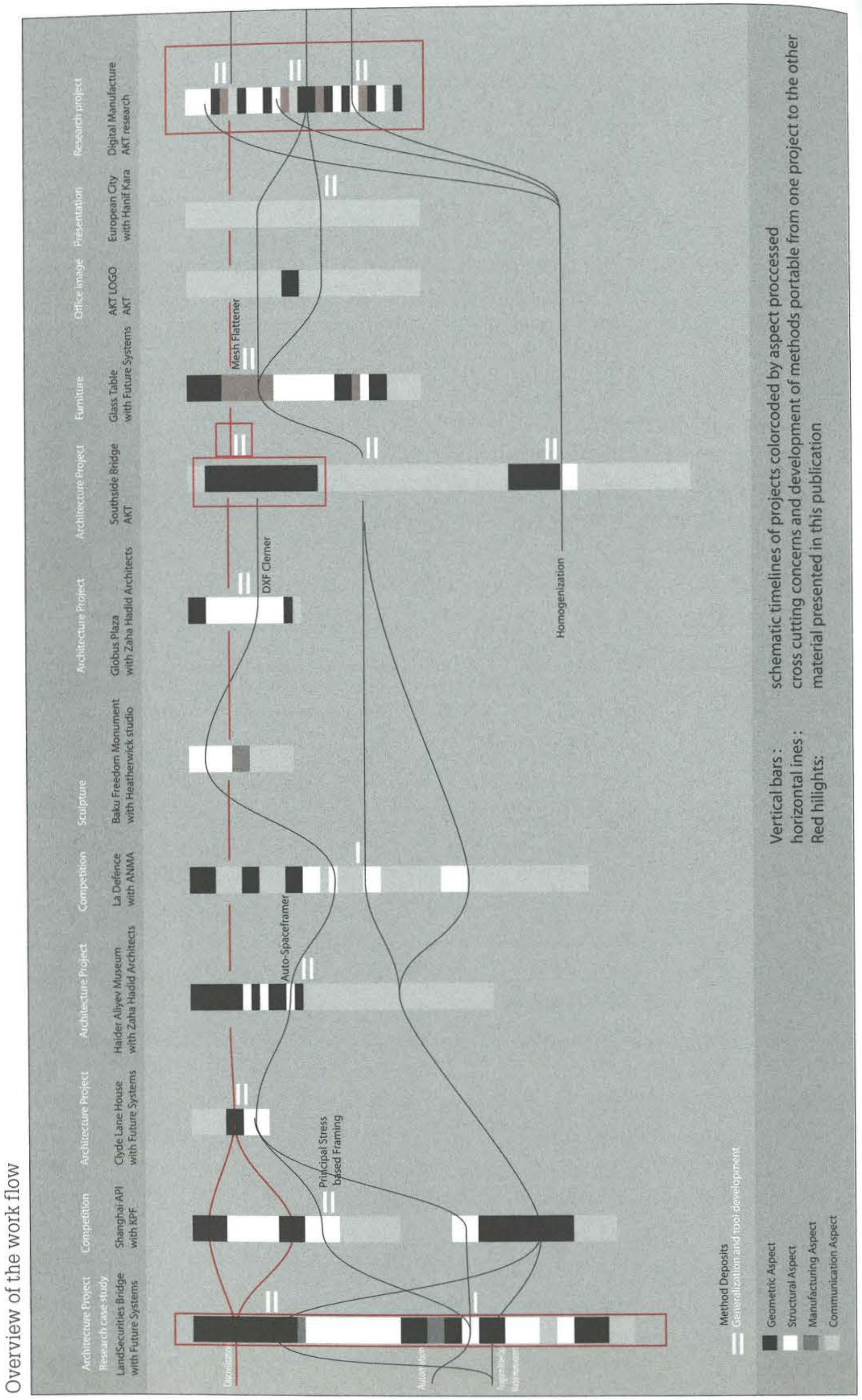
Another point we will try to make is that simplexity algorithms are not only employed in the post processing of a given geometric object (rationalization, quantization etc.) but also can be the generating mechanism as well.

Design aspects

From the perspective of the application of computational techniques in design and within an engineering firm we can observe that we are always presented not with whole projects but aspects of them. The involvement into fragments of projects often means that one has to carry out similar operations on different projects. One example of such a cross cutting concern we are going to present is discretization where a project is presented as a continuous manifold and has to be converted to a frame solution or cladding solution taking into account different manufacturing, design and engineering considerations. In the following pages we will present a series of methodologies and the corresponding software tools developed. As the diagram shows below we start with discretization which is a cross cutting concern and appears in a host of projects hence lending itself to generalization. Next we will present a case study of a combination of discretization and optimization within a single project. The third section is concerned with development of a tool by which one can setup an initial environment for a project by placing constraints and design intentions in the form of vector field affectors. Finally we present a project that integrates tools and techniques developed in other projects in order to reconstruct a sense of totality of the project out of its fragments, trying to combine design engineering and manufacturing concerns through computation.

Fields

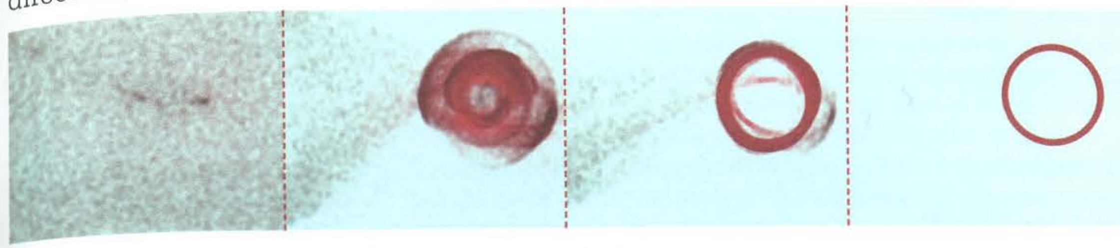
A recurring theme in the following pages is the field. Fields are mathematical objects defined over manifolds (be it a surface or a 3D portion of space) which enrich these manifolds with spatially varying properties. The introduction of fields allows for a treatment of space as non homogeneous and non isotropic. They help us establish a spatial condition which is variable and multidimensional. Many problems can be raised temporarily to this higher level of complexity and then tools can be used to interrogate the structure and topology of the constructed fields (degenerate points, seperatrices etc.) in order to reach some simpler design solution.



Overview of the work flow

1. The circle

The circle was a small program that we were developing for fun while experimenting with particle systems. At that point we stumbled upon the concept of simplexity even before we knew this term existed. The particle system is composed of thousands of particles moving within a force field. Given time all the particles will converge to a single perfect circle at the point where attractive and centrifugal forces balance. Of course you can draw a circle directly by plotting its parametric equation or by any other optimal algorithm well studied in the field of computer graphics. However this is not just any circle but it has a strong connection to the whole system that generated it. The radius of this circle tells something about the underlying force field in a very direct way.



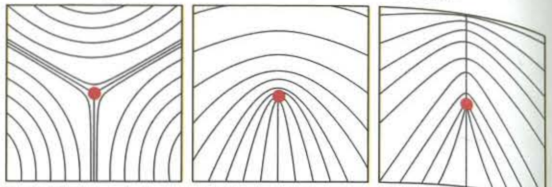
2. Discretization (continuity discontinuity)

A problem that persists in the interface or gap between architecture and engineering practice is discretization. By this we mean the necessity to decompose continuous geometric objects into discrete elements. This is something that is done anyway in visualization programs and FEM analysis packages with each employing algorithms to fit its own set of requirements (well behaved quad element meshes under a given analysis algorithm or minimization of number of facets for visualization purposes). We are concerned with discretization as a design process which takes a continuous domain and lays down elements over which an engineering solution can be built.
One particular case of discretization is when given a continuous smooth manifold as the ones that are mass produced with the proliferation of software based on free form modelling. For the engineers it is often necessary to generate a discrete graph over this manifold, a wireframe model that could suggest ribs of a shell, or a three dimensional frame structure etc. There are many ways to achieve this of course with the most often employed is operating in the ambient space of the given object and partitioning it accordingly (e.g. projecting a grid on a given surface, where the grid is not intrinsically linked to the surface's geometry).
We present here some attempts at developing software tools for interactively interrogating the surfaces in order to construct framing solutions that express intrinsic properties of the given surface. We try to achieve results that look a little less forced and reduce clashes with the underlying geometry.

For demonstration purposes we will use a case study shell. We also make 4 variations of different support conditions for this shell (support at intersection with the ground, linear support along the median axis, dual cores and single big core).


Perspective view of a case study shell

The basic types of first order 2D degenerate tensors

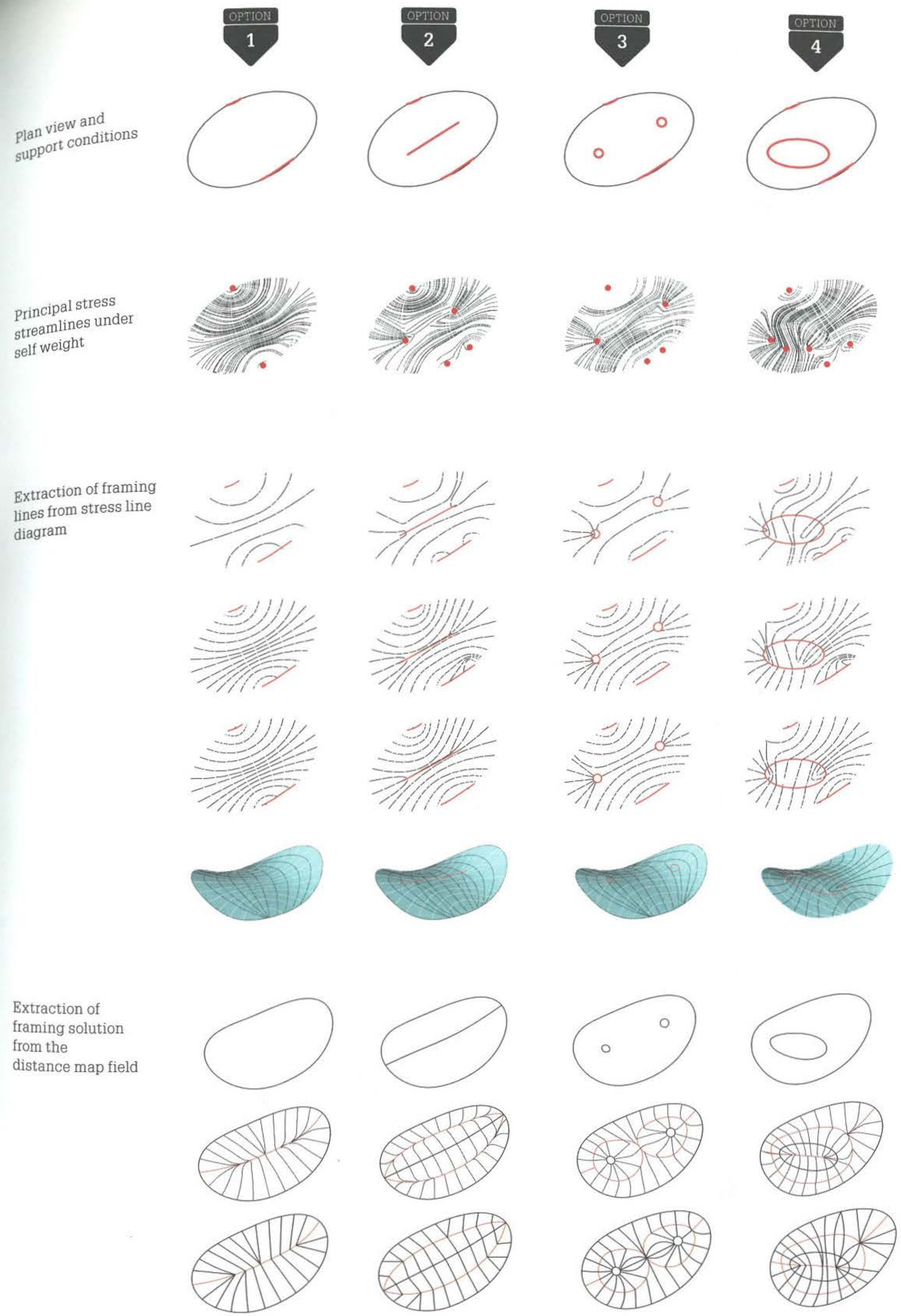

Trisector Single wedge Double wedge

Option 1: Rank
For this method we took the advice of engineer Oliver Bruckermann who suggested that a starting point for figuring out a framing solution might be to try to align members with the principal stress directions. So as a starting point we analyze a given surface as if it was a shell with given boundary conditions and then use custom software to selectively extract the stress tensor's streamlines. From the network of curves we can detect the singular points which can be used as guides in the development of a framing solution.

Option 2: Rank
Using scalar fields defined over the given surface. Scalar fields are particularly attractive because they are easy to define and manipulate in real time as well as superimpose using techniques with which many people are familiar through image processing programms. In the above example we chose a scalar field which is intrinsically linked to the geometry and is the distance map.
The distance map assigns a distance value at every point on a surface according to its geodesic distance from the closest boundary edge.

Option 3: Rank
Another intrinsic tensor field to the surface is its curvature field. The streamlines are aligned with the two principal curvature directions and it gives rise to natural looking networks of curves on the surface. Singular points and curves arise in the areas where H^2+K=0 that is where the surface is locally spherical.

Option 4: Mapping
In the cases where a surface is given as a NURBS we can use its parameter space to produce tilings. These tilings can be further optimized by using some iterative algorithm in order to meet different criteria. By desribing these criteria as a vector field over the surface we can very easily superimpose them. Such criteria might have a manufacturing or cost effect (making elements similar sizes) or as we will see in the next example (the land securities bridge) might have structural requirements (contractions near areas of high stress).



3. Densification field (The land securities bridge case)

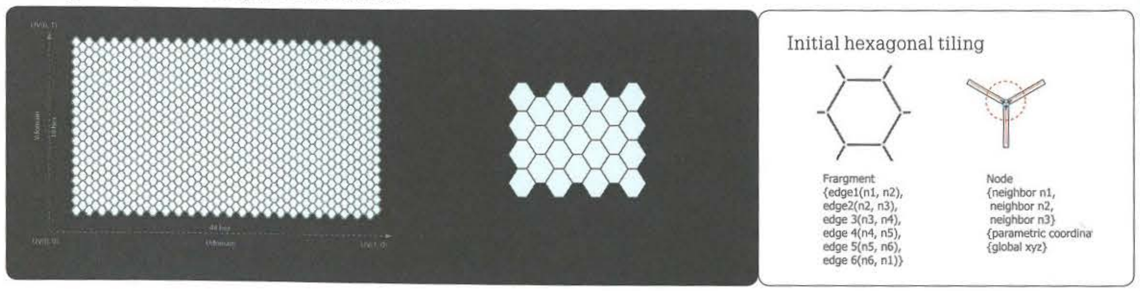
Continuing on the previous theme of discretization we now present a related real project. The case study of the Land Securities Bridge was developed by focusing on the feasibility study undertaken by Adams Kara Taylor in supporting the design concept by Future Systems for Land Securities. The Land Securities Bridge is designed as a free-form envelope that twists around a pair of paths connecting two floors of the office buildings with a hexagonal mesh forming its cladding system. The complex structure is realized as a lattice of nodes and struts supporting light weight polycarbonate panels. Guidance from the fabrication industry suggested that the number of nodes in the frame would be the biggest cost factor, as the connections will be fabricated one by one, welding a machined spherical piece to standard cut tubes.

From observing the geometry, one could easily understand that all the members of the frame are acting differently from one another due to the complex bridge-form. However, during the structural analysis of the model the majority of the analysis results are ignored in favour of a few singular values which resulted in applying more or less constant cross sections to the whole structure. Even though this type of simplification is one of the most conventional operations when designing a structure, in the case of a non-rectilinear design, we can identify that this approach often leads to over structuring of the form as well as clashes with the geometry and the architectural intentions behind it. The “densification” process was implemented as an attempt to optimize the structural solution within its constraints (hexagonal tiling of constant number of nodes over given skin). At first glance, it seems that this has little to do with simplexity since the end results have a higher diversity of panel sizes and shapes than the original more regular mesh. However the algorithm basically operates on the stress distribution diagram within the parametric space of the surface. The emergent irregularity of the mesh is a reaction to the algorithms attempt to simplify and equalize the stress diagram.

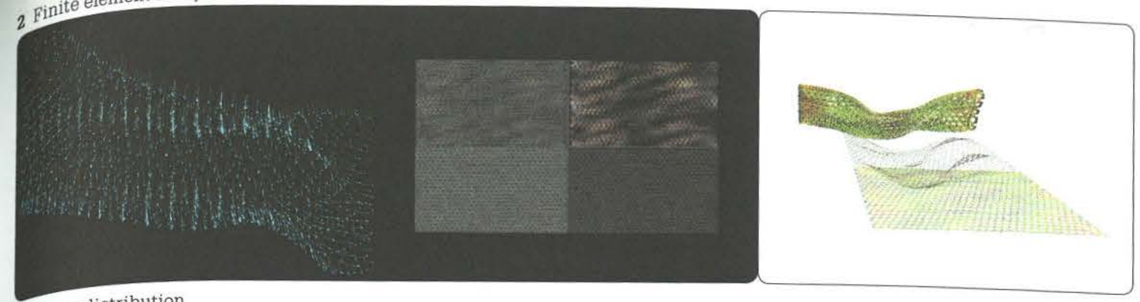
Input

The skin was provided by the architects as a twisting NURBS surface and the hexonal pattern was specified to be the structural framework. The conversation with the fabricator informed us that the number of nodes would decide the construction cost to a large extent. Therefore, we chose an approach that tries to introduce small changes in the structural frame that would improve its structural performance and conformity to the envelope's geometry respecting the inputs.

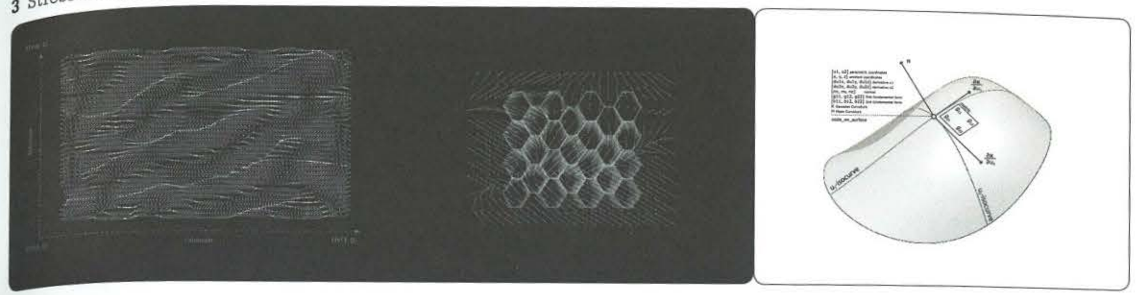
1 Tiling of the parametric space of the surface



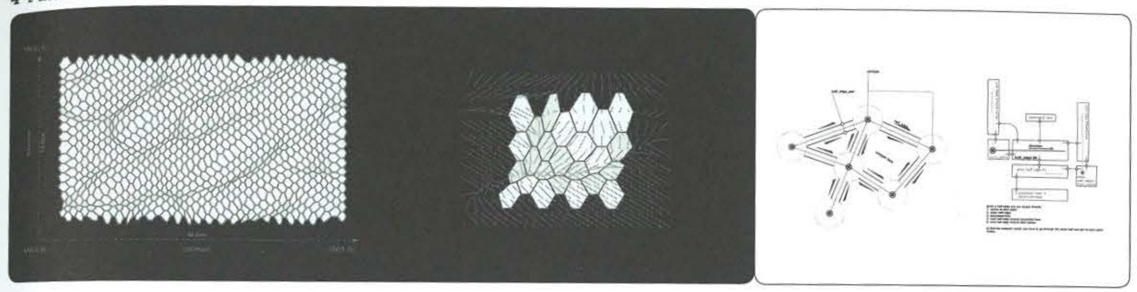
2 Finite element analysis



3 Stress distribution



4 Pattern densification using the stress distribution

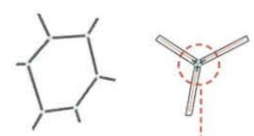


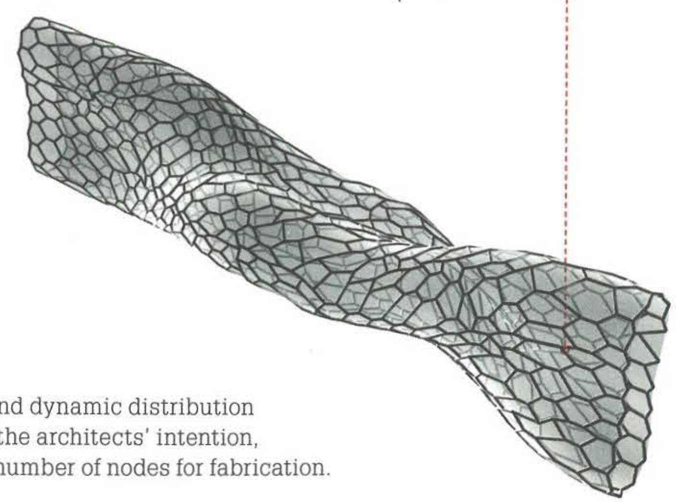
5 Evaluation

The performance and the esthetics was evaluated in each step and if the result was not satisfactory, we repeated the process from the step 2 FEM analysis.

6 Generalization

After the case study, we focused our effort on generalizing the process and made an integrated software tool that allows us to explore the same process for any given surface. We also considered using other patterns, flattening the cladding elements by introducing triangles in the pattern. In addition along with the gradient of the stress field used for the densification, other force fields can be superimposed that drive the geometry towards different goals (e.g. equalization of member lengths, areas or angles) and all these requirements can be superimposed to achieve a compromise between them.





Output

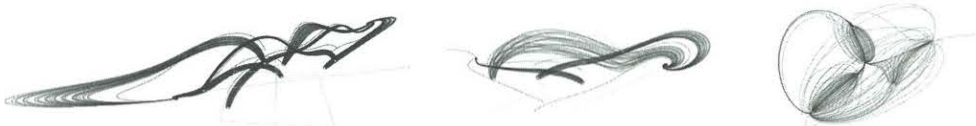
The resultant form shows a more organic and dynamic distribution of hexagonal patterns, that is more true to the architects' intention, with simpler stress distribution and same number of nodes for fabrication.

4. Constructing fields (Field designer tool)

The field designer project challenges the form generating process using digital computation, which initially was conceived as a tool development to help us design a pedestrian bridge over a highway.

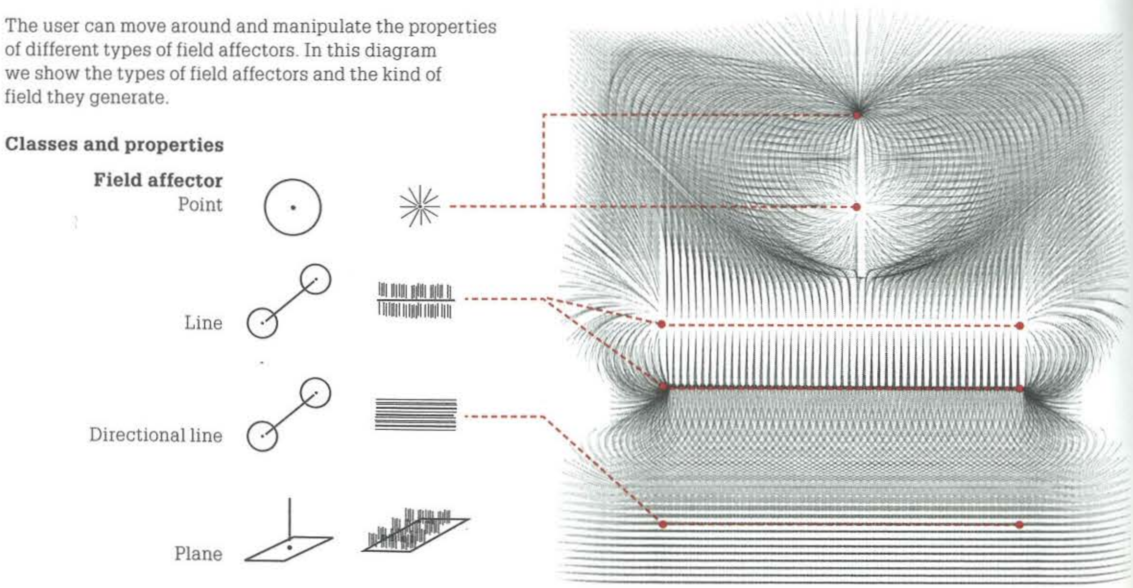
Generally, architectural design starts from generating a form and then it is slowly developed to meet the complex design considerations and requirements. However, in this project we present a process that allow us to evolve design without preconditioning the outcome by formal biases.

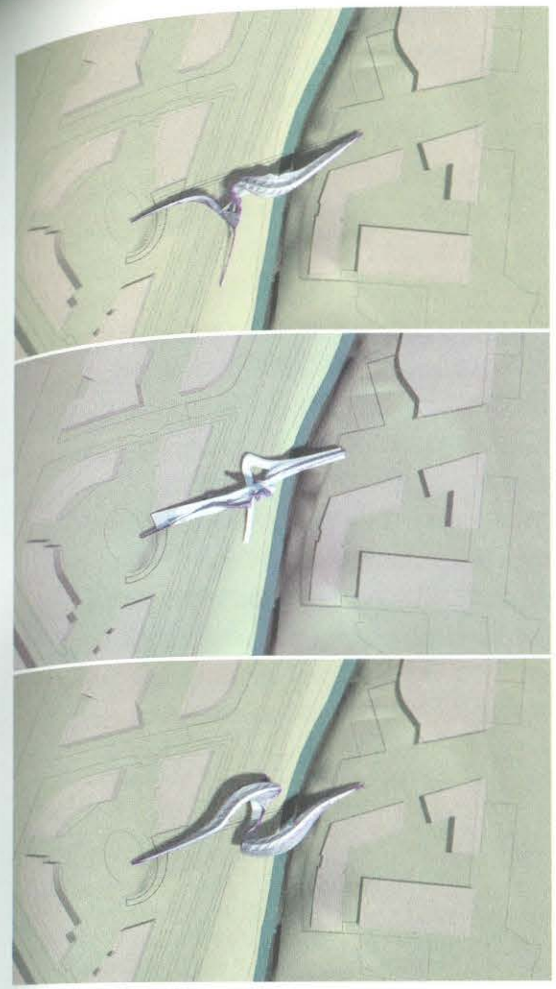
In most design interfaces, the space is considered homogeneous and isotropic where as in reality and in a design space it is not (e.g. gravity, area of interests). The idea for us was to generate a vector field that the designer could affect and calibrate according to the design intentions and project constraints, thus the design space would be treated non-homogeneous and anisotropic. As an affecter of the field, we developed elements that attract or repulse the field representing primary view point or areas that need to be cleared. We also developed functions to regulate the transition of the field, which, for example, accommodates the inclination requirements for the bridge. To reduce the complexity, we introduced trajectory generators within the field which renders more tangible paths and allow us to detect boundaries within the field. These intermediate bundles of point strings are not fixed to a single representation and can be interpreted in multiple ways. As a result, we are able to generate geometries from the field that is sculpted by multiple considerations related to the design project.



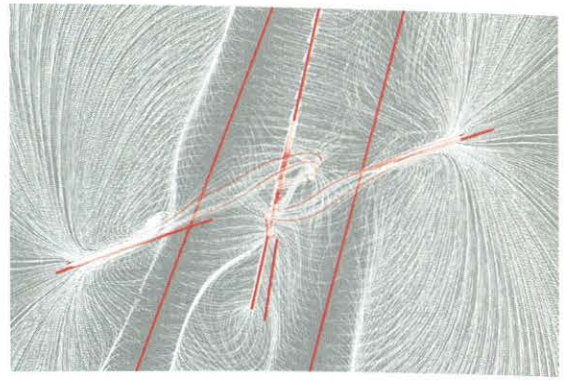
Simplified software structure

The user can move around and manipulate the properties of different types of field affectors. In this diagram we show the types of field affectors and the kind of field they generate.

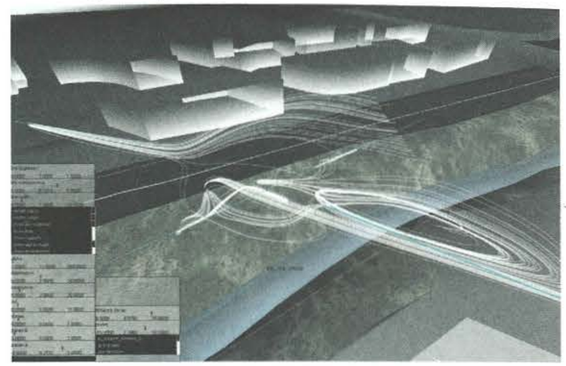




Variations and selection



Input of problem description as field affectors—case study—bridge.



Screenshot from the version of the software developed for the Southside bridge project.

Constructing a material density and stress field according to the method described in the next section where the selected trajectories become applied loads within the material volume

5. Constructing and interrogating the stress tensor field. Digital manufacturing

Our aim in this ongoing project is to construct a methodology for design developing an integrated software tool in parallel that will allow us to combine structural and manufacturing information with design intentions. As a case study we took to design a light support, however the same methods and software tools developed can be extended to handle larger and more complex projects. In agreement with previous examples we first establish a tensor field over a region of space from which we can gather information to aid us in our design. We want this field to reflect the materiality of the result and chosen manufacturing technique, yet still be indeterminate enough not to imply a singular solution. For this reason, we chose to construct the field out of the simplest known conditions, that is the outer material boundary, the support conditions, and the position of the light bulb and shade that appear as applied loads. From these conditions, we can construct a volume of variable material density endowed with a stress field, which yields a variable coordinate system at each point within the volume. To do that we used a variant of the well documented homogenization method. This is a method which is very elegant in its simplicity. One starts with the assumption of a volume of material with arbitrarily placed loads and supports. Then iteratively we analyze and reassign material densities in the volume until some desired convergence has been achieved.

Initial input

Problem description as volume of material with applied loads and boundary conditions

Start of analysis loop

The problem is described as a 3D finite element volume with varying material density per element.

→ Analysis results processing

Results are read back and matched to the inital problem domain.

→ Restart loop

Von Mises stress determines new material density value for each finite element in the volume.

→ Terminate loop

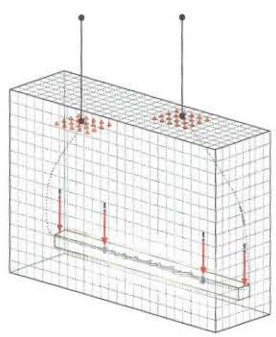
If the maximum number of iterations have been reached or the material distribution does not change significantly terminate loop.

Software layer

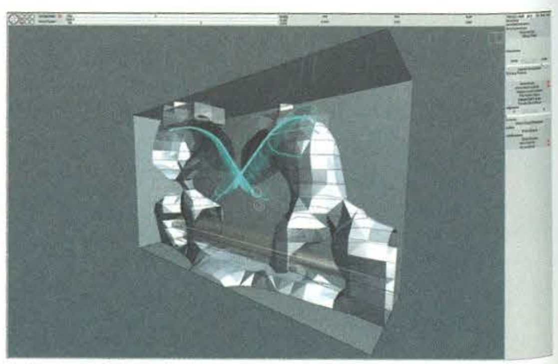
User interface to graphically set up the problem and prepare for the iterative structural analysis.

Write Special file ready for the analysis software with full material, load and support description. Call the external structural analysis software.

Read the database of the analysis results and update stress values in the custom software.



Initial input of problem description



Screenshot of software interface

To start the project we developed a software interface where we can interactively describe the domain of the problem whose parameters include resolution of voxels, dimensions, supports and placement of lights in the form of concentrated load. The software automatically builds a file compatible with the structural analysis program we used (in this case sofistik) and goes through the iterations required. In the end, it allows the extraction of level set surfaces of the Von Mises stress field or selective extraction of the streamlines of the stress tensor field. The interface allows the designer to develop a tactile relation to the field and consequently an intuition of the material behaviour by interrogating the conditions around specific locations.

For the particular object presented here we placed the supports at the top of the volume as the light will be hanging. Applied loads are generated at the endpoints of the hypothetical light location and the light-shade's support points.

By observing, an overview of the field we can see that as expected the major stress direction traces curves roughly linking supports to loads forming nearly vertical bundles. The minor stress direction is predominantly in compression and its absolute value is small relative to the major stress's absolute. Excluding the regions around singularities, it tends to form rings wrapping around the major direction's bundles. Another feature of the bundles of the major principal stress direction is that they form two distinct groups: an outer one wrapping around supports and light-shade support points

→ Interrogation of the results

Try to understand the behaviour of the material in the initial volume and suggest solutions. Custom software helps the designer develope an intuitive relation to the behaviour of the field. Design intentions are fed back to the software as new features.

→ Design decision

After deciding a general configuration use information from the inital field for every decision. Every direction, every pattern density, and every thickness is extracted from the inital field thus investing with some consistency the final result.

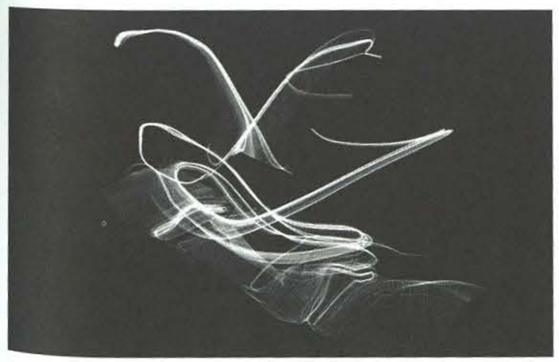
→ Manufacture

Send information to manufacturer of chosen material and method.

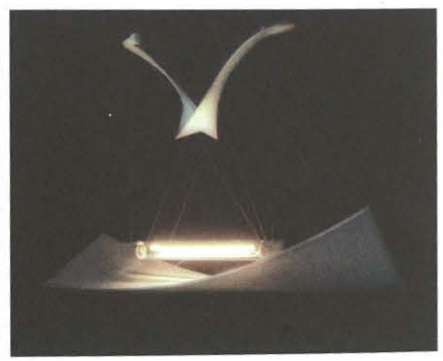
Software layer

Custom software allows visualization of local and global properties of the material and stress distribution in real time. The designer can interactively extract bundles of principal stress streamlines or patterns whose density reflects the material density suggested by the underlying field. As the software was developed in parallel to the project new ideas and possibilities of interpretation of the tensor field were implemented gradually as features or classes of parametric objects.

Generate appropriate files for the chosen manufacturing method, taking into account tolerances and other constraints.



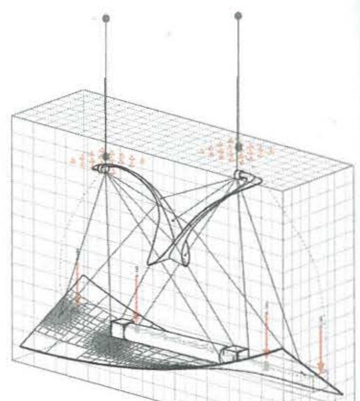
Selective extraction of streamline bundles

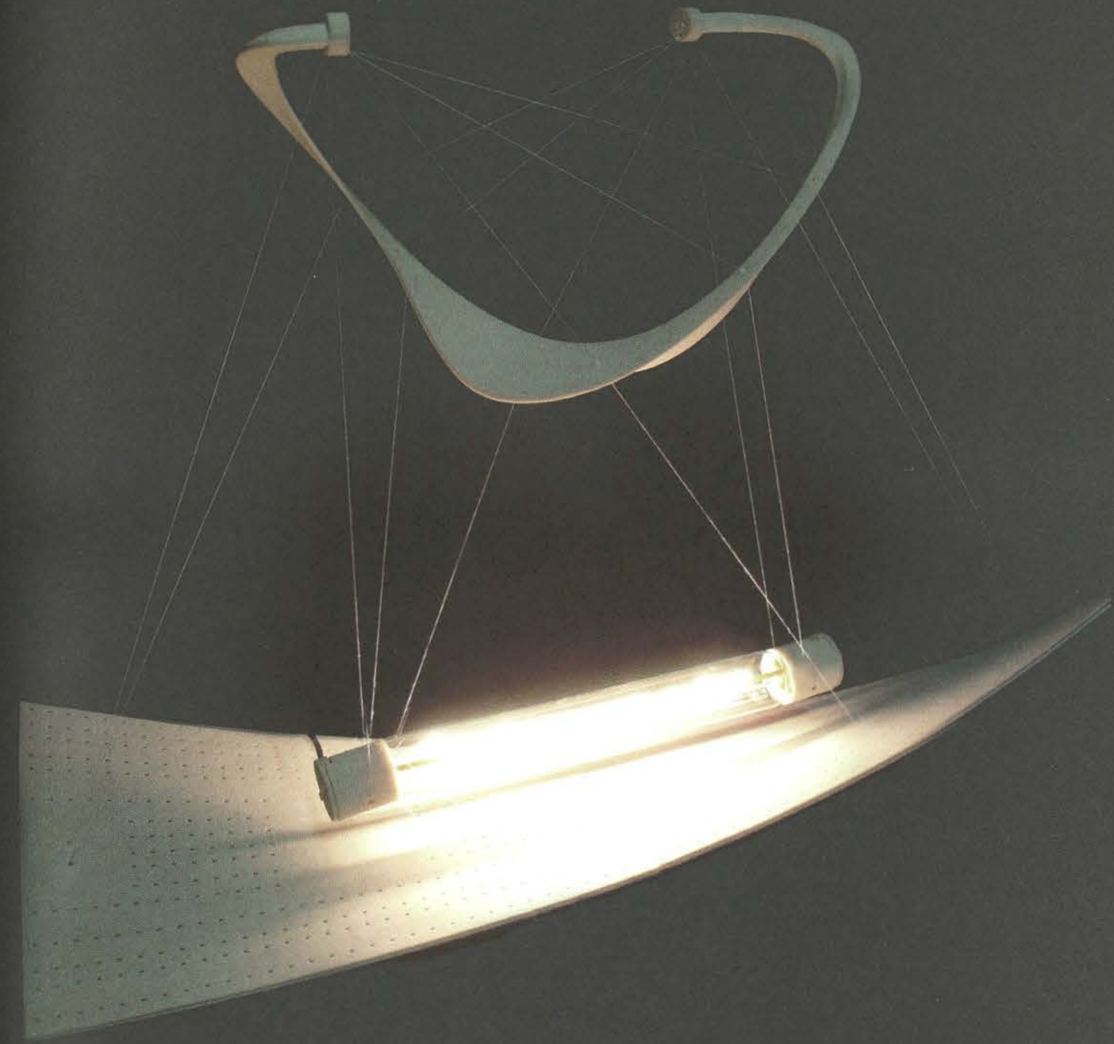


Rapid prototype model with light bulb in place

and an inner structure connecting the supports to the light bulb ends. Because of the slightly asymmetrical placement of the slightly asymmetrical placement of the supports, the whole field is twisting and as a result, this twist is passed to all the elements extracted from it. This meant that we were able to achieve a rather complex distribution of elements that balances itself in space.
What we try to achieve through our approach is design consistency rather than structural optimization strictly speaking.
This consistency is achieved by interrogating a single field for all design decisions. We chose not to discard the designer's intuition in favour of an automaton style algorithm but to embrace it at variable stages. Algorithms are still operational and necessary in many stages of the process and their development was an integral part of our approach but their parameters are exposed through interfaces for the designer to make the most of the information present in the field. What the stress field did is generate a space within which to carry the design that in contrast to most commercial software is neither homogeneous nor isotropic but finite. So instead of starting the design process in a tabula rasa of a Cartesian system one is thrown in a finite volume of variable density where at every point a different Cartesian system defined by the three principal stress directions is bound. What is "parametric" is not the object to be designed itself but the space in which objects are embedded and informed.

The upper element is extracted from streamlines of the minor stress direction connecting the two support regions. The element helps to shape the cables and its middle part acts in compression.





The cables are extracted from streamlines of the major stress direction. The design decision was to use steel wire rope as most of the plastics used in rapid prototyping are brittle and do not work well in tension. There is a single wire which weaves through all the elements (top arc, lamp caps, shade) rendering the need for manual balancing and micro-adjustments in wire lengths redundant. At the tips of the compression arc there are special elements with three holes each to help lock the wire in place. As suggested by the topology of the streamlines an outer loop supports the shade and an inner loop, the light itself.

The bottom shade is composed of three layers measuring roughly 1mm in thickness each. The bottom one is completely solid and the top one has a more or less regular perforation pattern. The middle layer however reflects the material density of the analyzed field in the form of a variable span grid, which becomes denser near the supports and sparser directly under the light. When the light is off one sees only the solid surface underneath and when the light is turned on, the perforation pattern of the top surface shines through the variable density grid revealing the varying material densities inside. The surface itself is roughly normal to the major principal stress direction.