8_digital fabrication

make ideas come true

"Any sufficiently advanced technology is indistinguishable from magic".

Arthur C. Clarke

The link between design and fabrication has always been crucial for architecture and industrial design. New manufacturing techniques, assembly processes, and materials, often prompt paradigm shifts in design. For instance, the introduction of structural steel fabrication to the design of structures enabled new formal ambitions; but required new expertise in detailing and pre-fabrication. This new approach, based on the design of component, progressively marginalized handcraft and made the designer essential within the building process.

Before the *digital revolution*, the designer managed the complexity of building projects by breaking down components into individual parts, and studying part to whole assembly strategies through scale models and drawings. The scale models and subsequent construction drawings were then transferred to suppliers and contractors to interpret and fabricate the assembly components. This process was limited to orthogonal structures, and lacked the capacity to respond to complex shapes, with few notable exceptions such as Jorn Utzon, Heinz Isler, Antoni Gaudí etc.. The digital revolution liberated this constraint by integrating design output directly with fabrication.

The first stage of *digital revolution* focused on controlling the project by generating holistic digital tridimensional models. The digital model was then interpreted by the computer to generate bi-dimensional plans, sections, elevations and details. Informed **digital fabrication**, and in particular **CNC**[23] processes, directly link 3D geometry to the final components bypassing the production of drawings. Digital fabrication or the automated production of components improves accuracy and makes complexity ordinary; since a complex operation will have the same level of machining difficulty as a simple operation.

Since building processes are directly interpreted from 3D geometry, designers produce traditional drawings to merely aid in the assembly of components. Drawings can also be omitted by printing assembly instructions directly on components, or more futuristically by providing robots or drones with coded instructions. The ambition to directly translate an idea into reality is already possible for small scale objects or components. In other words, it is possible to create a physical object from a 3D virtual model using **Rapid Prototyping** (RP). Rapid Prototyping is an additive fabrication technique in which material is deposited in layers to print a component. This technique will likely have a resounding impact on the future of manufacturing and construction.

8.1 Fabrication Techniques

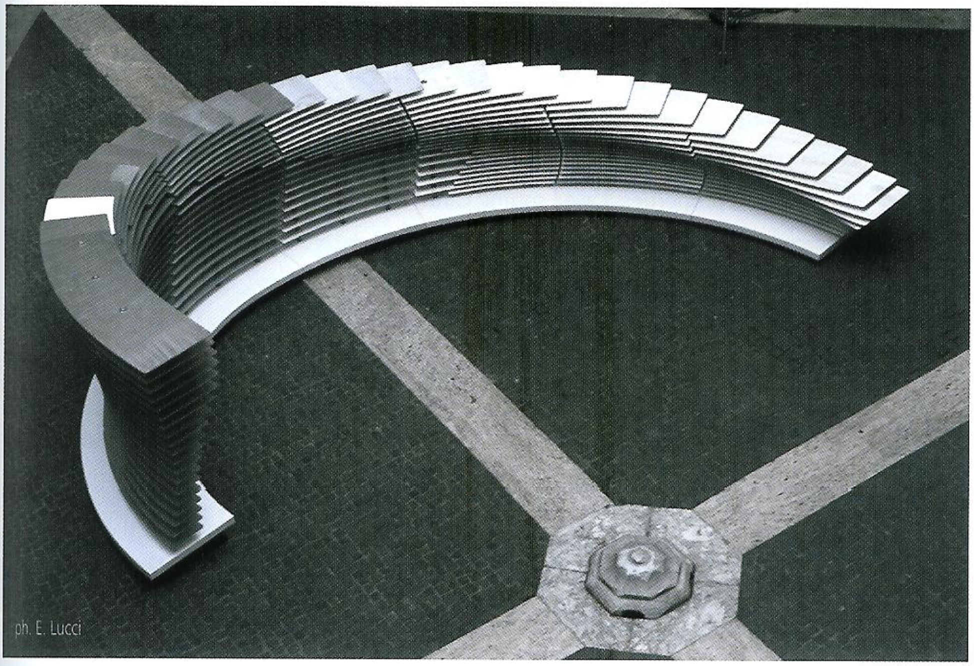
Fabrication techniques can be sorted according to processes and materials.

8.1.1 Bi-dimensional Cutting

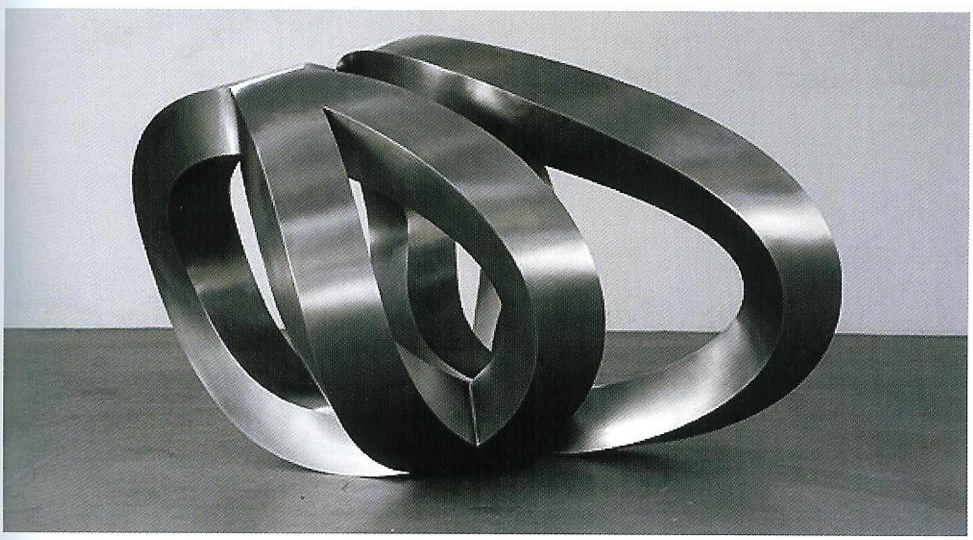
Bi-dimensional fabrications transform planar sheets of: aluminum, steel, plywood, acrylic etc. of varying thicknesses into components for tridimensional assemblies. **Planar sheets** can be used to form geometries using techniques such as: stacking, faceting etc.. Flat sheets can also be **bent** to form complex developable geometries, or geometries with null Gaussian Curvature.

NOTE 23

The acronym "Computer Numerical Control" identifies the use of computer in driving and controlling a machine movement. The machine can be a milling cutter, a lathe, a laser or waterjet cutter.



ABOVE. The NU:S installation (2012) designed by Arturo Tedeschi and Maurizio Degni was made by overlapping planar sheets of aluminum cut by a waterjet machine. BELOW. A sculpture by Carlo Borer (2011) created by bending and connecting shaped metallic plates. The sculpure's geometry is a set of zero Gaussian Curvature surfaces. Image courtesy of Galerie Frank Pages.



Cutting-based processes include:

- **CNC Laser[24] cutters**

  Laser cutters burn or melt material using a focused laser set to a specified power and cutting speed. The cutting speed and power are set based upon the materials dimensional and physical properties. Laser cutting cannot be used for every material; for example, aluminum sheets will reflect the laser.

- **CNC Plasma cutters**

  Plasma cutters cut material using a focused stream of super heated gas or plasma. Plasma cutting is widely used to cut steel and aluminum.

- **CNC Waterjet cutter**

  Waterjet cutters cut materials using a focused jet of water combined with an abrasive substance. The major advantage of the Waterjet is that it does not create *heat-affected zones* were the molecular structure is modified. The Waterjet can be used for a wide range of materials from steel to wood.

FIGURE 8.1

A waterjet machine in action while is cutting a 5 mm aluminum sheet. Image courtesy of Lamberti Design.

NOTE 24

The word LASER is an acronym that stands for "light amplification by stimulated emission of radiation".

8.1.2 Subtractive techniques

Subtractive techniques, such as CNC milling, create objects by removing material. Subtractive methods can achieve the same output of cutting machines with the added ability to specify the Z depth of a cut.

FIGURE 8.2
The Driftwood Pavilion was created using 3-Axis mill from large-scale wooden planks.

Solid blocks of materials from wood to polystyrene can be milled to carve described geometry. Not all geometry can be achieved using 3 axis milling; and in many cases objects must be decomposed into several parts to prevent undercutting.

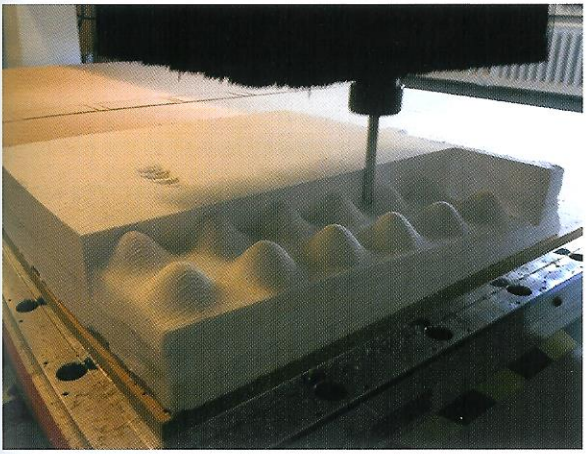


FIGURE 8.3
The Illinois School of Architecture, Rheotomic Farm; Mock-Up Milling, Gaelan Finney-Day, Przemek Swiatek, Brian Vesely.

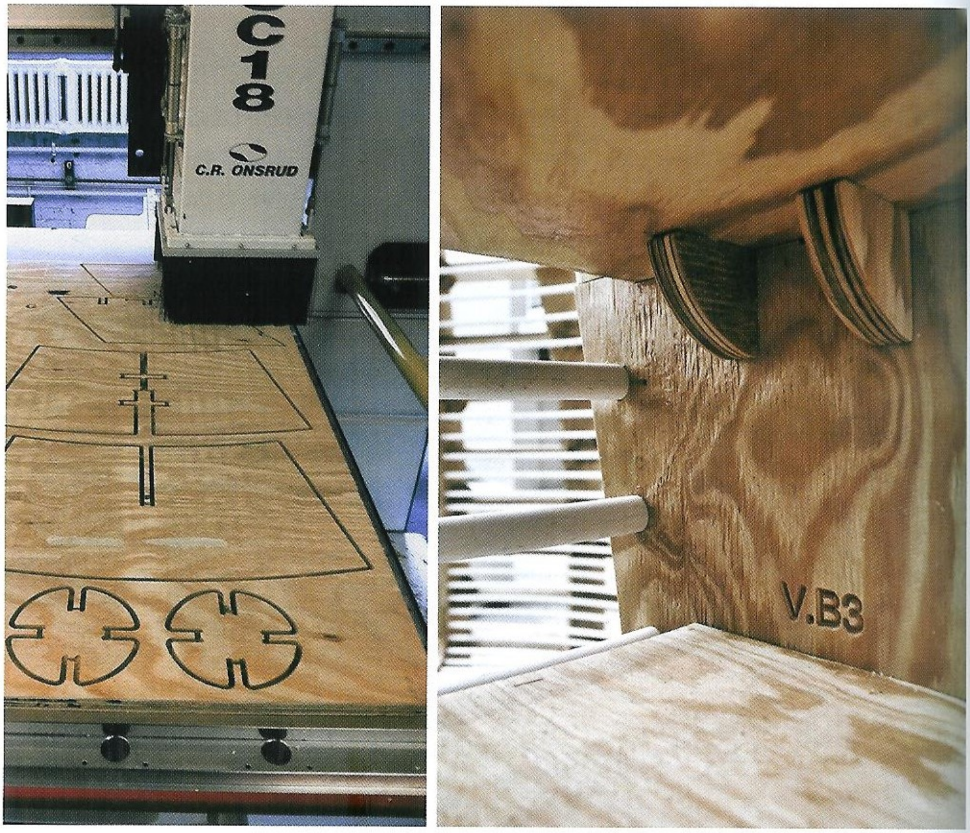


FIGURE 8.4
The Illinois School of Architecture, Kiva; Mock-Up Milling, Arch 576 Post Digital Strategies, Critic: Brian Vesely.

Subtractive techniques include:

- **CNC milling machines**

  Milling is a tooling process that uses a cutter head to remove material from a sheet or block of material. Mills vary in their size and depth capacity as well as the number of axis that the cutter head can be manipulated. The most commons machines are 2D, 2.5D, and 3D machines: 2D mills cut at a specified Z depth similar to cutting machines, 2.5D (two and a half) mills operate in 3 axes but only perform operations in two axes simultaneously, and 3D mills perform operations in all three axes simultaneously. More advanced 5 axis mills move in four or more axes to create custom parts with limited tooling restrictions. Milling machines are informed by digital geometry which is used to describe tooling paths.

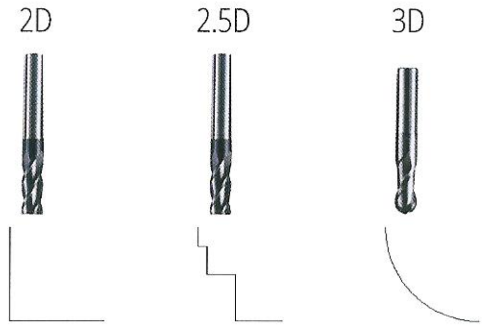


FIGURE 8.5
Aura, by Zaha Hadid Architects (design team F. Wirz and M. Lanza), exhibited at Villa Foscari "La Malcontenta" in Mira, Italy (2008). The sculpture was created relying on a 6 axis CNC machine using polyurethan foam as material to mill.
Image courtesy of Zaha Hadid Architects. Image copyright by Luke Hayes.

- **Hot-wire foam cutter**

  Hot-wire cutters use an electronically heated wire to cut polystyrene foam or similar materials. Several different types of hot-wire cutters exist from wires able to cut on a single plane to cutters able to cut on multiple planes. This method is used to quickly generate tridimensional shapes.

- **Robotic arms**

  Robotic arms can be used to facilitate other fabrication techniques, such as: holding a milling cutter head or heated wires, grasping and folding, forming etc.. Recent research in academia as well as avant-garde professional offices, have investigated design possibilities enabled by the high degree of flexibility provided by the robotic arm.

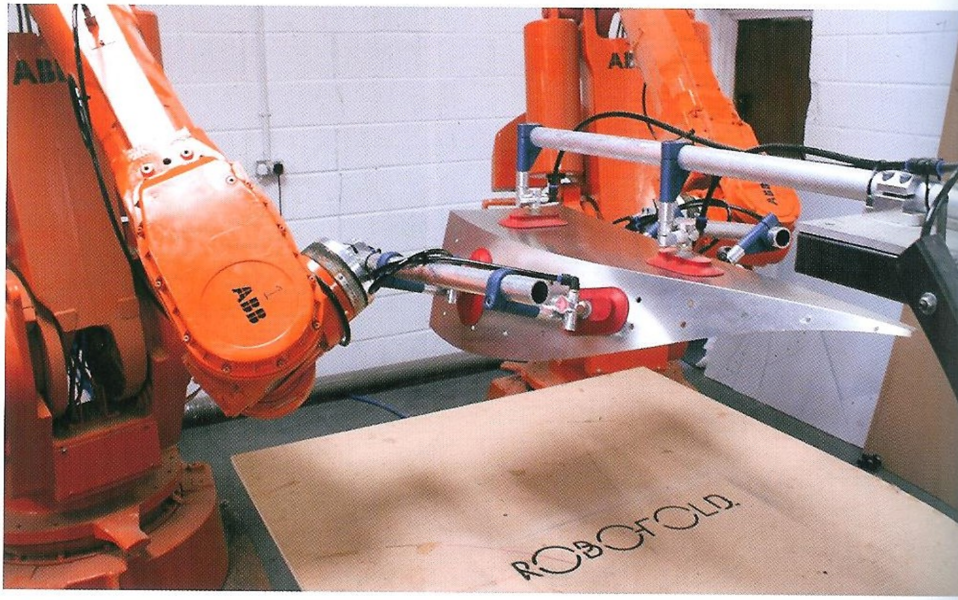


FIGURE 8.6
Objects made from formed sheet metal are usually produced with a stamping press or expensive moulds. The RoboFold technology (www.robofold.com) allows to form sheet metal by using robots. Image courtesy of RoboFold.

8.1.3 Additive techniques

Additive Manufacturing (AM) creates tridimensional objects by an accumulation of successive layers. Terms such as, **Rapid Prototyping** or **3D printing** are increasingly used to describe additive manufacturing. Additive manufacturing enables designers to fabricate objects that are impossible to make using subtractive techniques. Objects such as branching shapes, complex twisting, moving parts with intricate details can be realized, albeit at a small scale.

Additive manufacturing is defined by describing deposition paths. Deposition paths are created by slicing **a digital model, developed in Rhino or another modeling software, into layers with a defined slice thickness or resolution. The contours describe how material is deposited, layer by layer**.

The AM process involves three steps:

1. Creation of a digital 3D model. *A printable model is required to meet the criteria discussed in 8.2.*
2. Conversion of the digital model into a code based machine-readable format.
3. 3D printing the object.

The most commonly used 3D printing format is Standard Tessellation Language (STL), an interface developed by 3D Systems®. An STL conversion triangulates an initial tridimensional model and outputs the coordinates of each vertex according to the right-hand rule. The number of triangulation iterations can be equated to the smoothness of the final model, meaning the more triangles the smoother the model. The output can be described in ASCII and Binary. Binary is the more common language because of the smaller file dimension. The most common 3D printing techniques are: stereolithography (SLA), selective laser sintering (SLS) and fuse deposition modeling (FDM).

- **Stereolithgraphy (SLA)**
  SLA printing was developed in 1983 by Charles Hull. A SLA printer consists of four main elements: a vat containing a photosensitive liquid form resin, a mobile perforated-platform, a UV beam, and a computer that controls both the beam and the platform. The platform is initially positioned on the top of the vat, just below a thin layer of resin. As the UV beam strikes the resin, the resin selectively solidifies and a layer is formed; as defined by one layer of the *sliced* digital model. The platform is then lowered the distance of one layer to print the next slice, this process continues until all the sections are created. After the object is completed, it is rinsed with a liquid solvent and baked in a UV oven to cure the plastic. Resin that is not solidified remains in the initial liquid form. Un-solidified liquid is unable to support overlying parts; for this reason, it is often necessary to create support structures. SLA printers can produce very-high-resolution objects, but are slow and expensive.

- **Selective Laser Sintering (SLS)**
  SLS printing was developed in 1986 by Carl Deckard at The University of Texas Department of Mechanical Engineering. SLS printers (see figure 8.7) use a high-power laser to selectively fuse powdered particles of plastic, metals, ceramic, glass etc.. An SLS printer consists of four main elements: a laser, a powder cartridge, a roller, and a fabrication platform. A thin layer of powdered material is spread by a roller across the fabrication platform where the laser traces a bidimensional section of the object, sintering the material together. The platform is then lowered the distance of one layer thickness and subsequently the roller deposits new material from the powder cartridge to be sintered forming the next layer. This process continues until the part is completed. SLS does not require support structures since the sintered parts are surrounded and supported by the non-fused powder.

FIGURE 8.7
The Selective Laser Sintering (SLS) process is based on a high-power laser beam, a levelling roller, a powder cartridge and a fabrication platform

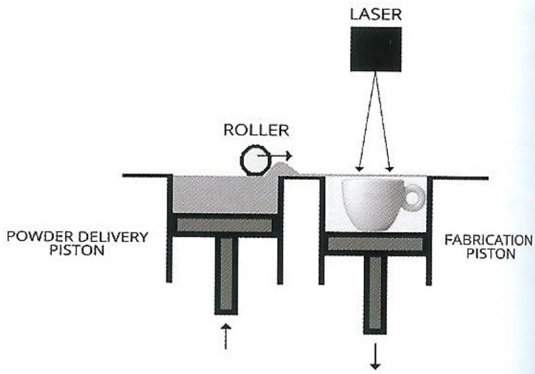


FIGURE 8.8
NU:S parametric shoes (2012) designed by Maurizio Degni, Alessio Spinelli and Arturo Tedeschi were made by a SLS process using nylon powder. Image courtesy of SOLIDO 3D.

- **Fuse deposition modeling (FDM).**
  FDM printing was developed in 1988 by Scott Crump. FDM printers form geometry by melting plastic filament and depositing thin layers additively on a platform. The FDM printers, similar to SLA printers, require support structures for overhanging parts. Some FDM printers can print multiple materials, in this way supports can be printed in a material that is easy to remove; such as water soluble filament. FDM printers use two types of plastic; ABS, or an organic version: PLA.

Other innovative techniques have been tested recently; such as the MX3D-Metal printer developed by Joris Laarman in collaboration with the software company Autodesk. MX3D-Metal printing utilizes a robotic arm to deposits molten metal onto an existing metal surface. Autodesk notes of this innovation: *"The arm is controlled by new software Autodesk created that can give the robot more fluid instructions for where the metal should go. Because of how quickly the metal hardens, the new object doesn't need an additional support structure"* (Autodesk).

Conceptually, additive techniques revolutionize the topic of **optimization**. Traditionally, optimization has been linked to simplifying fabrication techniques such as: cutting operations, complexity through similarity, describing developable surfaces or planar panels etc.. Optimization of additive techniques involves finding the optimal shape which meets a prescribed set of performance targets; such as minimally using material. Additionally, advanced form-finding strategies such as **topology optimization** (chapter 10), are becoming increasingly important in architecture and product design.

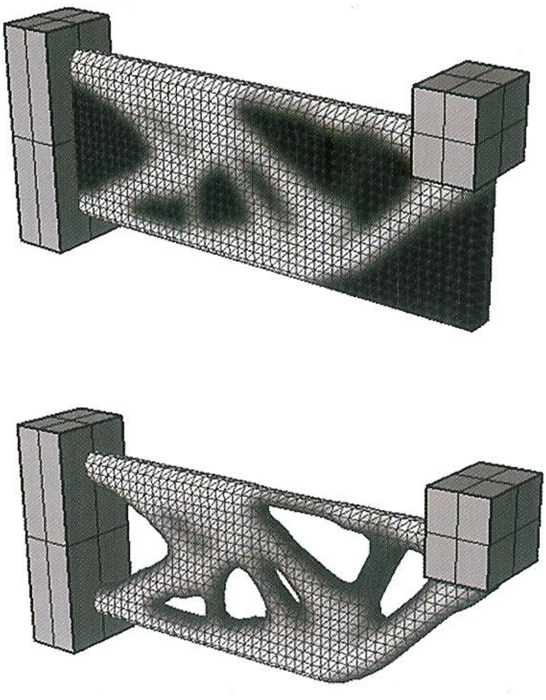


FIGURE 8.9
Topology optimization drives material distribution within the volume of the truss.

8.2 Modeling Printable Objects

Translating digital ideas to physical objects using 3D printing is currently viable for **small scale objects**. The definition of a *small scale object* is constantly changing; since advances in 3D printing technologies are enabling increasingly larger objects to be printed. Currently the single printing-session dimensional limits of high end commercial printers are 1000L x 1000W x 500H mm.

Producing digital models for 3D printing is not technically different from producing conventional 3D models. Similar to all forms of fabrication, when using additive fabrication consideration should be given to the constraints of the selected printing technology as well as real world characteristics. Moreover, the way geometry is defined to create a printable model is crucial.

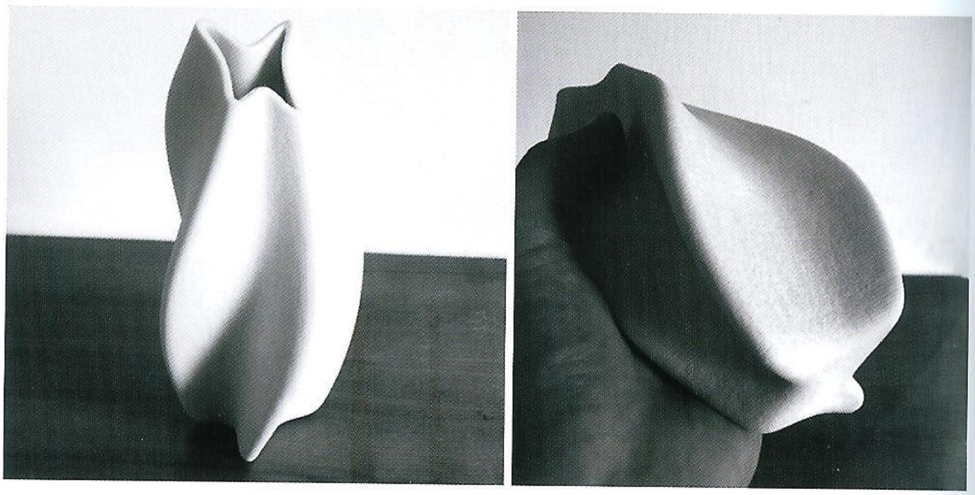


Figure 8.10
Pandora |AL, Arturo Tedeschi (2011), made by a SLS process using nylon powder.

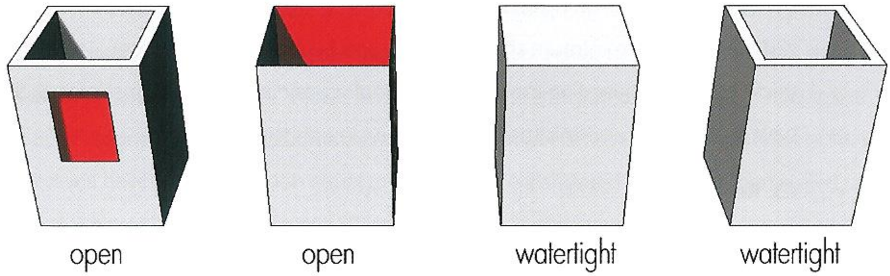
8.2.1 Main characteristics of a printable 3D model.

Printable 3D models differ from 3D models developed for visualization and rendering. Printable objects must consider: geometric digital modeling criteria, the specifics of the machine that will "read" and print the generated code, and the characteristics of the materials used for printing.

The geometric characteristics of a printable object are:

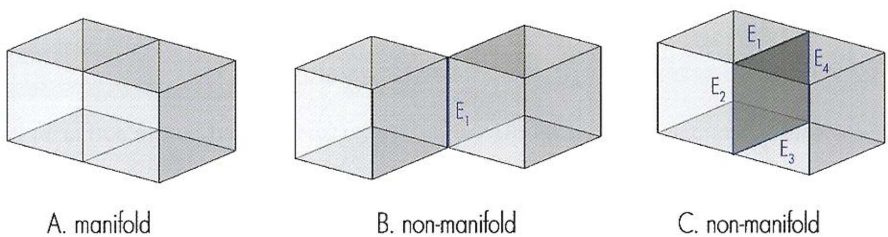
- **G1. Closed (watertight) geometries**

  Each surface or mesh has an *inside* face (colored in red in the image) and an *outside* face (colored in gray). A 3D object is *watertight* and printable if no inner faces are visible.



- **G.2. Manifold mesh**

  Only manifold models will be printed correctly. A geometry is called manifold if does not contain edges shared by more than two faces. Non-manifold geometries can be the result of inconsistent models (image B) or overlapped objects (image C), issues that are problematic when printing. Paragraph 6.6.3 explained how to remove overlapped faces from a mesh.



- **G3. Orientable mesh (correct normals)**

  The geometry must be an orientable mesh. In other words, the 3D model must be composed of face normals which follow the same directional logic.

- **G.4. No self-intersections**

  The geometry must not be composed of intersecting non-booleaned objects.

A printable object must also meet the following constraints:

- **C1. Maximum size (or build volume)**

  Objects cannot be larger than a maximum size of the ***build volume*** or ***tray size***. These values are measured in XYZ dimensions and are specific to each printer. Models that are larger than *build volume* can be divided into smaller parts which can be assembled into the larger component.

- **C2. Minimum wall-thickness**

  Is defined as the minimum thickness that can be printed by a printer. The minimum wall thickness varies based on the specific technology and material. For instance, SLS prints can have a minimum wall-thickness of 0.7mm using plastic materials.

- **C3. Resolution**

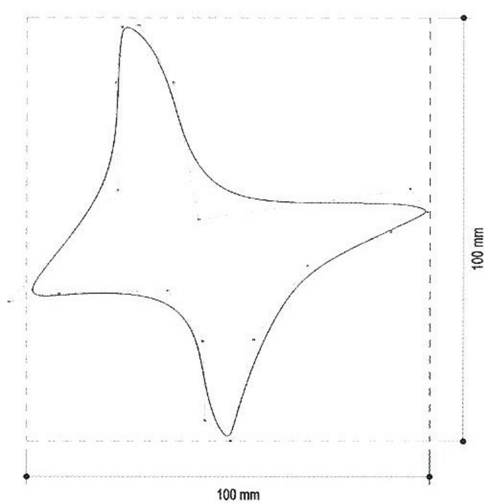
  The *horizontal (XY)* and *vertical (Z)* resolutions are based on: the specific technology, the material, and the overall quality of the desired print. The horizontal resolution is the smallest movement that the extruder or print head can make horizontally and is expressed in microns (100 micron = 0.1 mm). The vertical resolution is the thickness of a 3D printed layer. As follows, details smaller than the horizontal or vertical resolutions cannot be printed.

- **C4. Gravity**

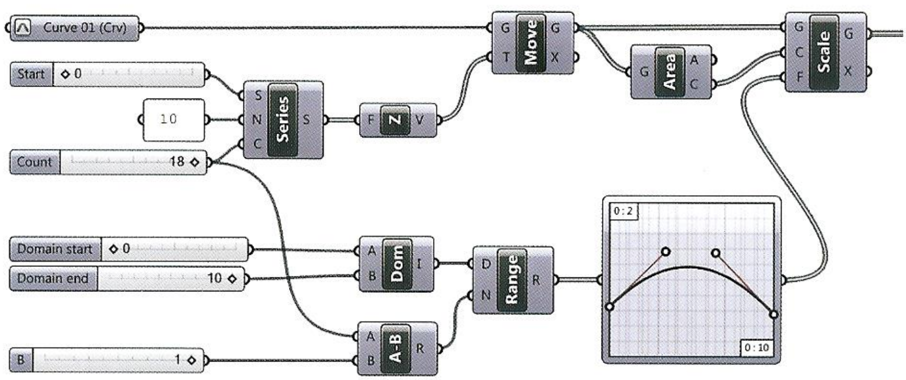
  The printed 3D model is a physical object that must obey natural laws when printing. Basic gravity-point tests and simulations can be performed using external software to check models for successful printability.

8.2.2 Example: parametric modeling of a vase

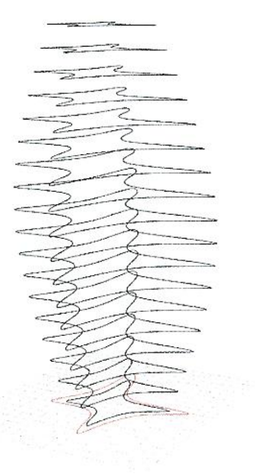
The following example is based on the Pandora|AL vase designed by the author in 2011, using a common desktop printer with a *build volume* of 200 x 200 x 200 mm; and will demonstrate a technique to create printable geometries.



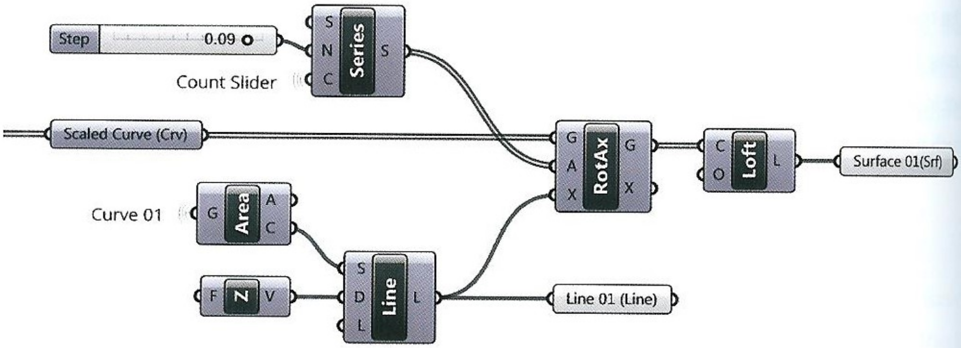
The first step in the algorithm is to define a closed NURBS curve within a 100 x 100 mm square. Next, the curve is translated vertically according to scalar multiplication. Scalar factors generated by the *Series* component are multiplied by the *Unit Z-Vector*, generating a set of translated curves with a step size of 10 mm. The {Z} *Build Volume* constraint is 200mm, as a result the C-input of *Series* component is set to 18. The resulting object will have a {Z} dimension equal to 180 mm. The translated curves are then scaled using the component *Scale* with: center of scaling (C-input) defined as the centroid of each translated curve using the *Area* component, and the scaling factor (F-input) defined using the *Graph Mapper* component set to *Bezier*. Since the {X} and {Y} *Build Volume* constraints are 200mm the Y domain is set between (0,2) such that the maximum scale factor (2) will yield geometry within the build volume.



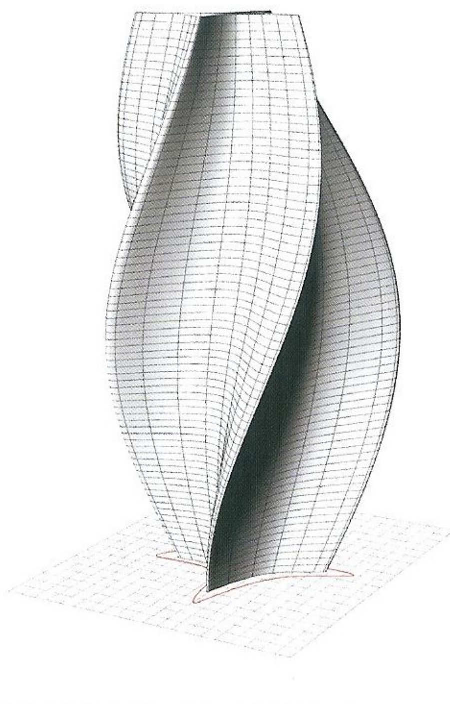
The following image displays the resulting geometry. The initial curve is colored in red.



The second step is to perform a rotation for each translated and scaled curve around a central axis using the component *Rotate Axis* (Transform > Euclidean). The angle of rotation in radians (A-input) for each curve is defined using the *Series* component. Lastly, the rotated curves are lofted using the *loft* component defining an untrimmed surface.



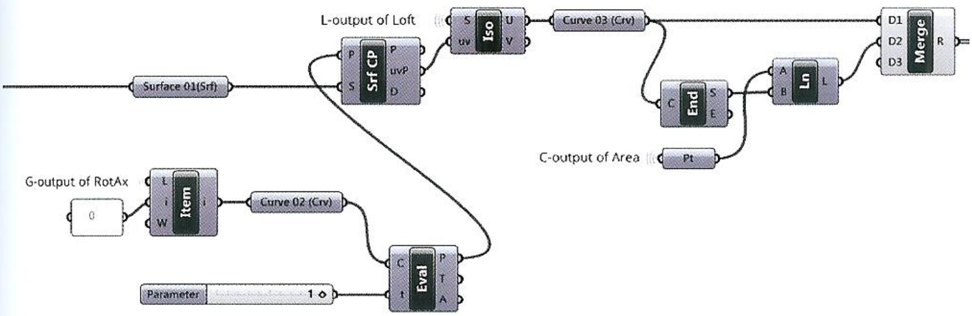
The untrimmed surface is not a printable object since it contains no thickness and is not *watertight.*

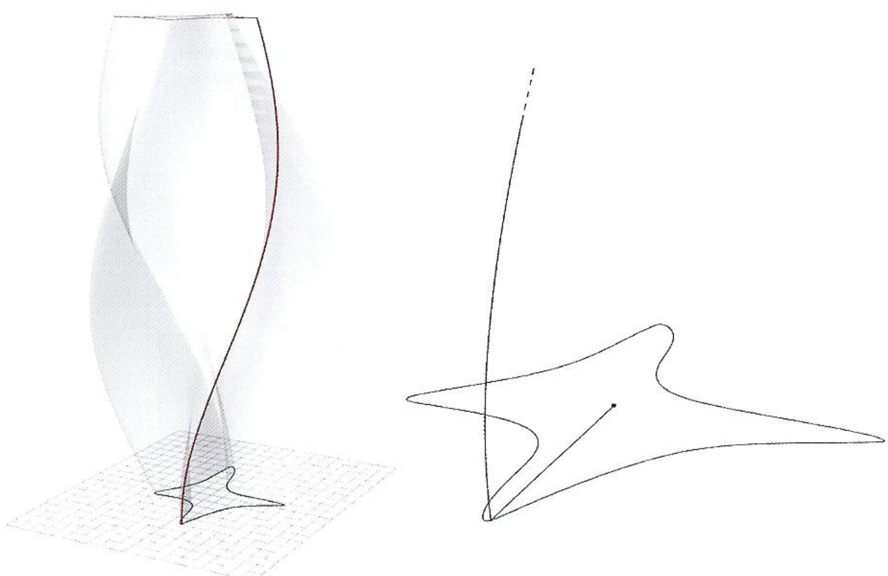


Since the desired output is a vase, a lower cap can be created by the component *Boundary Surfaces.* If the cap and the loft surfaces are joined, then assigned a wall thickness using the component *Mesh*

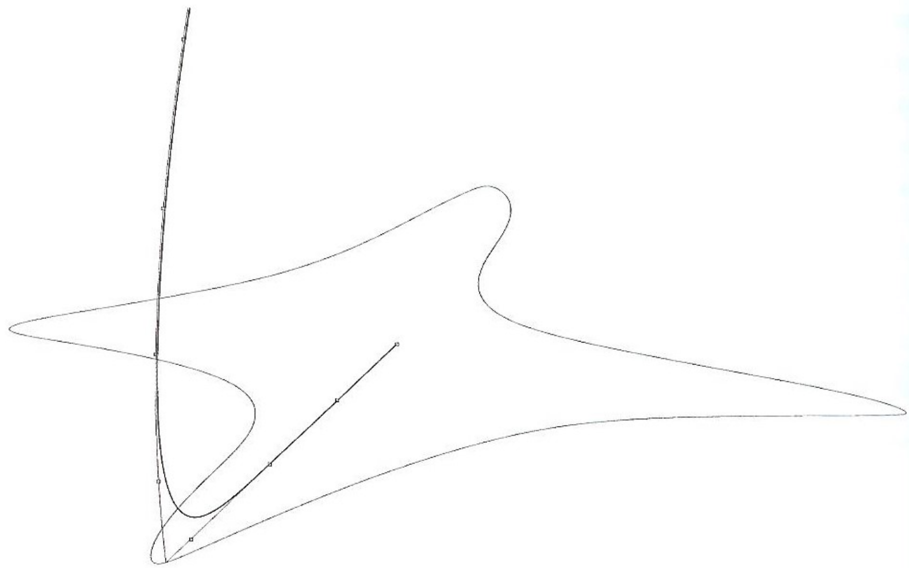
Thicken (Weaverbird > Transform) a printable object will result with sharp edges.

To create a smooth edge an alternative strategy is used. A vertical isocurve is extracted from the lofted geometry at a point defined on curve (0) using the component *Evaluate Curve* with t=1. The extracted isocurve is joined with a curve defined from the centroid of curve (0) and the start point of the isocurve.

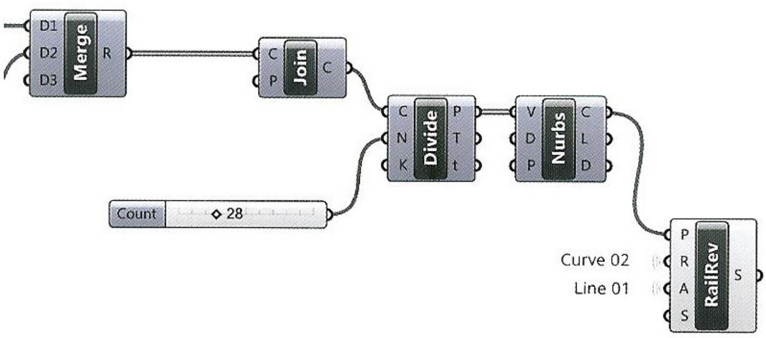




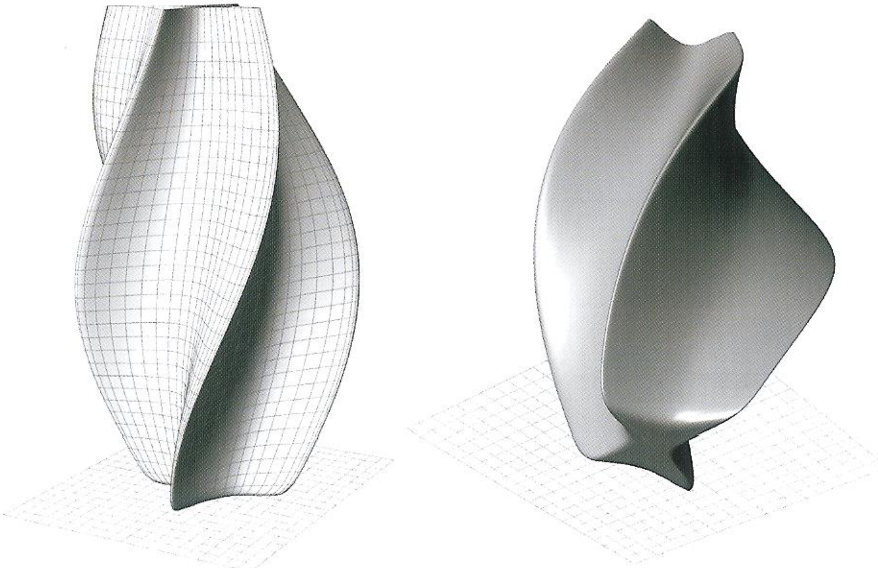
The defined curve is then divided using the component *Divide Curve.* Outputting, in this case 28 points, which are used to generate a smooth, freeform (non-planar) curve using the component *Nurbs Curve*.



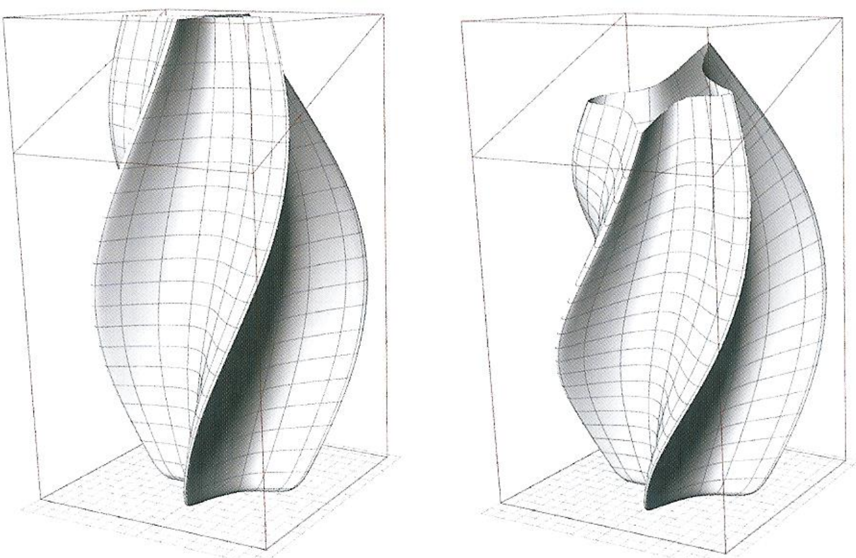
The *Nurbs Curve* is then revolved using the component *Rail Revolution* (Surface > Freeform) along rail curve (R-input) defined by *Curve 02* and a revolution axis defined by *Line 01*.



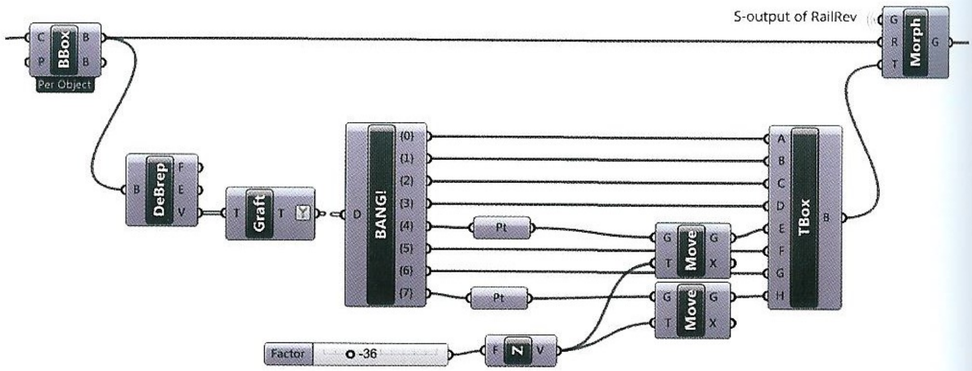
The output of the rail revolution, displayed in the following image, is a NURBS surface with smooth edges.



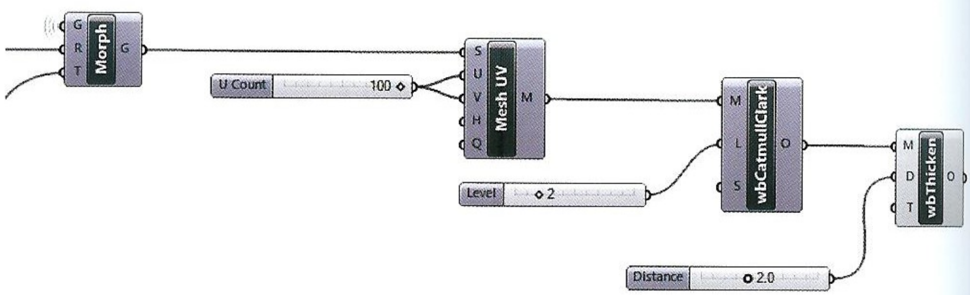
The Resulting NURBS surface is then morphed using the component *Box Morph*.

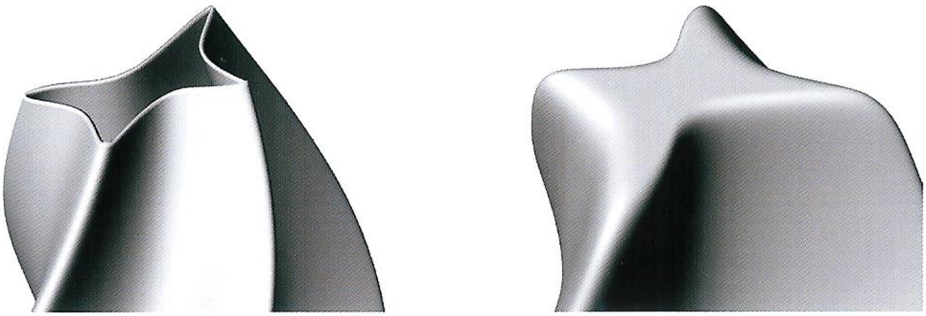


The *Box Morph* component requires a reference box input (R) and a target box input (T) to perform a morphing operation. The R-input is satisfied as the bounding box of the NURBS surface using the component *Bounding* Box (Surface > Primitive). The target box is a deformation of the bounding box, achieved by extracting and subsequently translating vertices. The manipulated vertices are then rebuilt into a target box using the component *Twisted Box* (Transform > Morph).



The resulting twisted output is then converted into a mesh using the component *Mesh Surface* and is subsequently smoothed using the *Wb Catmull Clark* subdivision method. The resulting smoothed geometry is then assigned a wall thickness of 2.0 mm using the component *Mesh Thicken* (Weaverbird > Transform), defining a *watertight* printable object.





ABOVE. The final mesh is smoothed by the Catmull-Clark component and the watertightness is achievd through a proper thickness.
BELOW. Different vertical sections show the absence of intersections and the perfect watertightness.

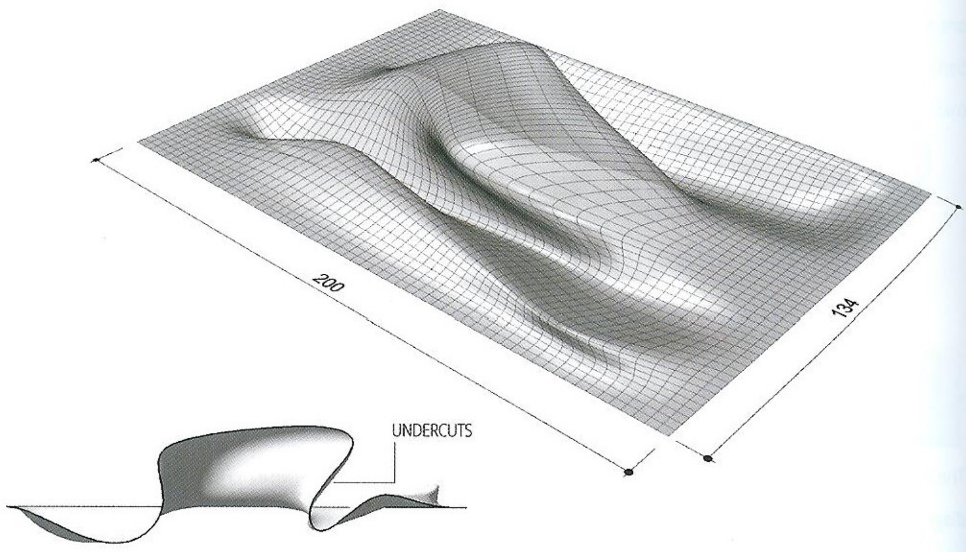
The final mesh can be baked into Rhino, checked through the command *check* which is a tool for diagnosing potential geometry errors. If no errors occur, the mesh can be exported and converted into a STL file (File > Save As or Export > STL) to be transferred to a 3D printer or other software.

8.3 Modeling objects for cutting based operations

Medium-scale objects, or objects that are currently outside of the means of additive processes, can be fabricated using cutting based operations. Medium scale fabrications can be assembled from parts relying on techniques such as sectioning and waffling.

8.3.1 Example: sectioning and waffling

Sectioning or contouring a model in one direction is a common technique used to build complex shapes by defining planar developable surfaces. For instance, a freeform surface can be sliced into a set of parallel and planar sections based on an interval equal to the thickness of the material to be milled. Upon gluing the sections together in sequence, the original surface can be approximated. The surface could also be milled from a single block of material; however undercuts require the use of a 3D milling machines.



Sectioning creates continuity parallel to the cut section and limited continuity in the direction normal to section-planes. A common fabrication technique is to leave a space between each section to create the illusion of continuity in the normal direction.

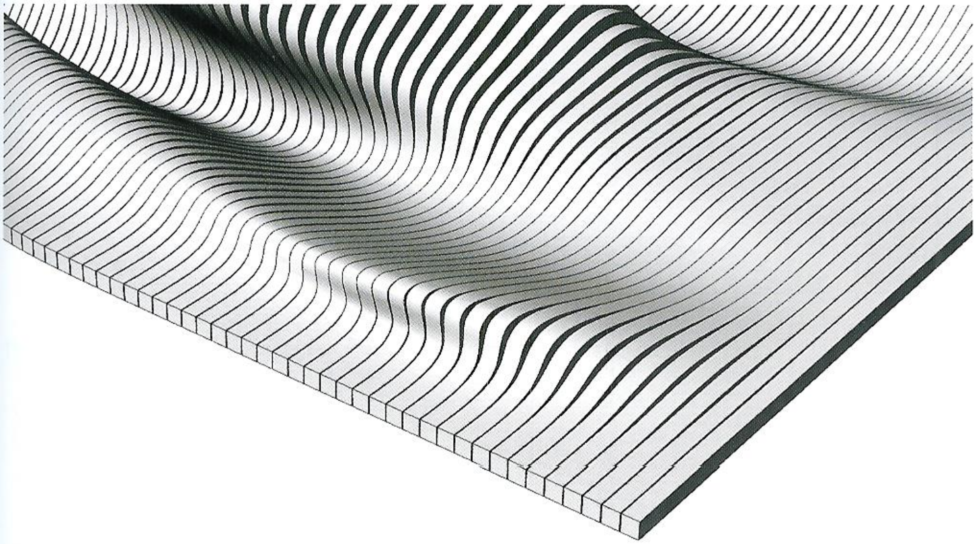
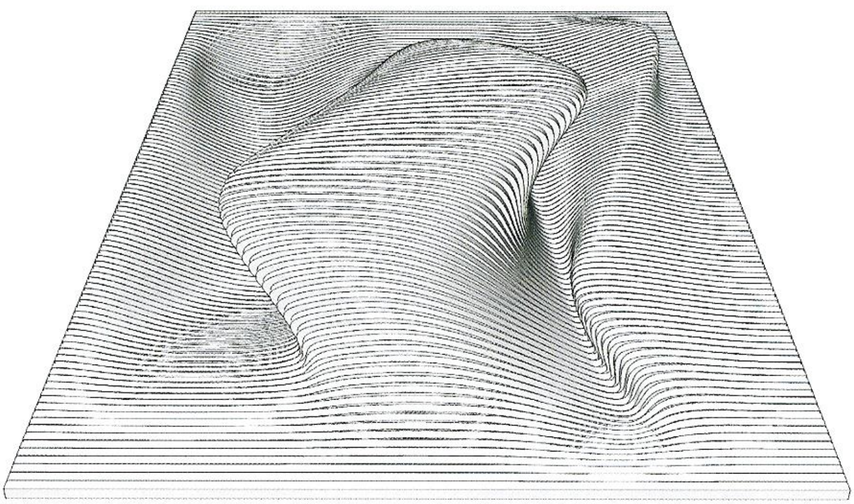
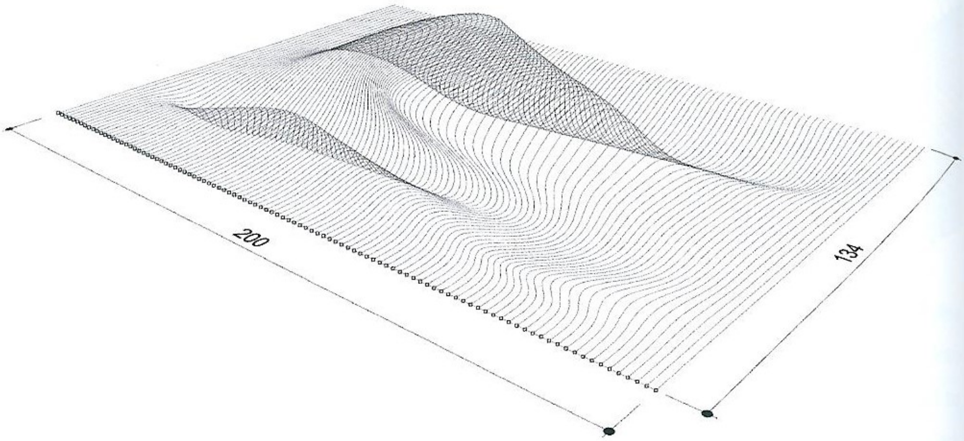


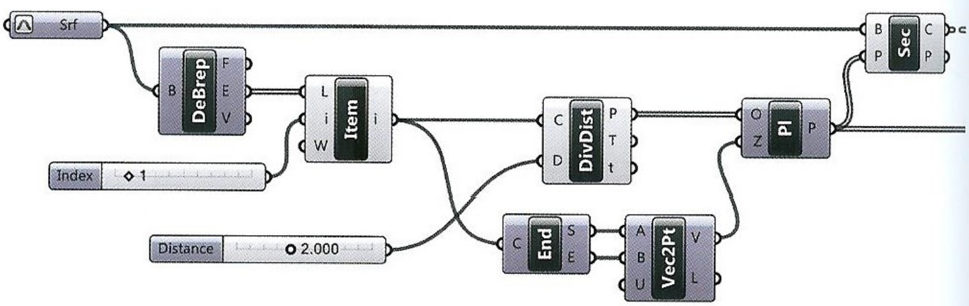
FIGURE 8.11
With *sectioning* is impossible to get continuity in the direction normal to section-planes.



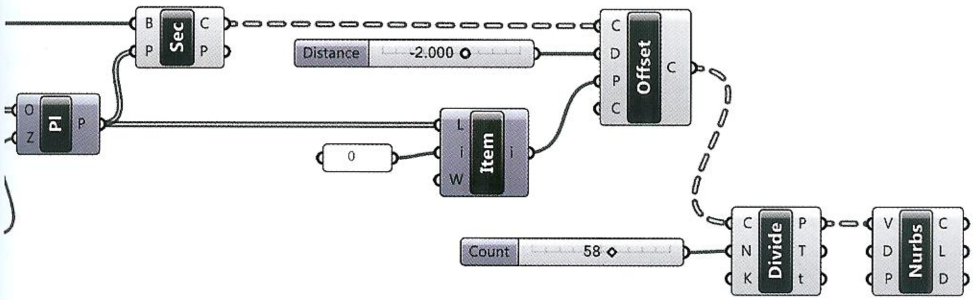
To define an unidirectional sectioning algorithm, a surface created in Grasshopper or set from Rhino is required. The subsequent steps are to define: a slicing direction, a series of planes, and finally intersect the planes with the model; defining the sections. In this instance, the surface's boundary forms a rectangle and one edge can be used to define the origin points for sectioning planes.



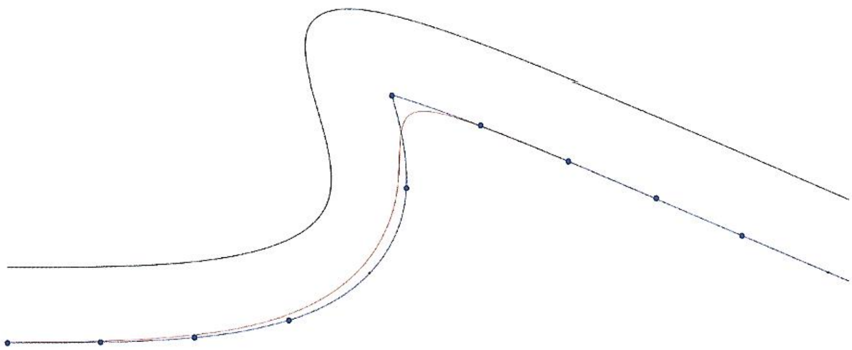
The component *Divide Distance* divides a curve with a preset distance equal to the thickness of the material to mill. At each division point a plane is defined using the component *Plane Normal* (Vector > Plane). Each plane is then intersected with the initial Brep using the component *Sec* (Intersect > Mathematical) to calculated the section curves.



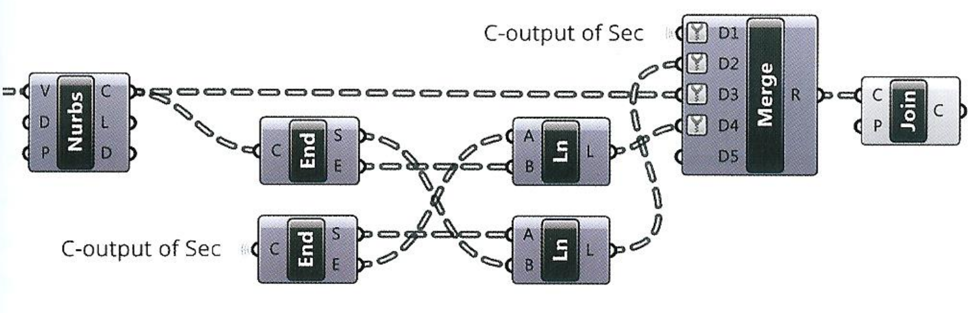
Next, each curve is offset with respect to the defined plane, using the component *Offset* (Curve > Util). Offsetting may yield discontinuities which can be eliminated by dividing the curve into N-parts and rebuilding the curves using the *Nurbs* component.

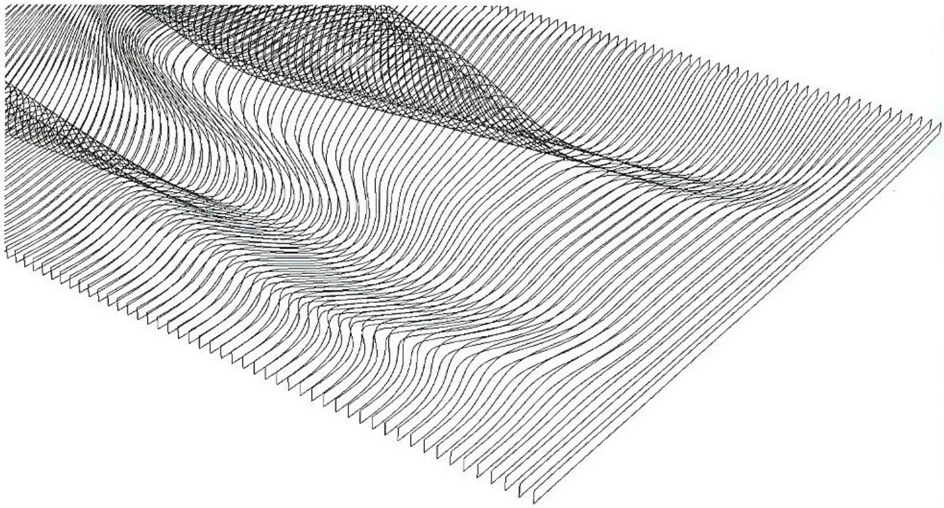


The blue curve is the original curve and the red curve is the rebuilt curve.

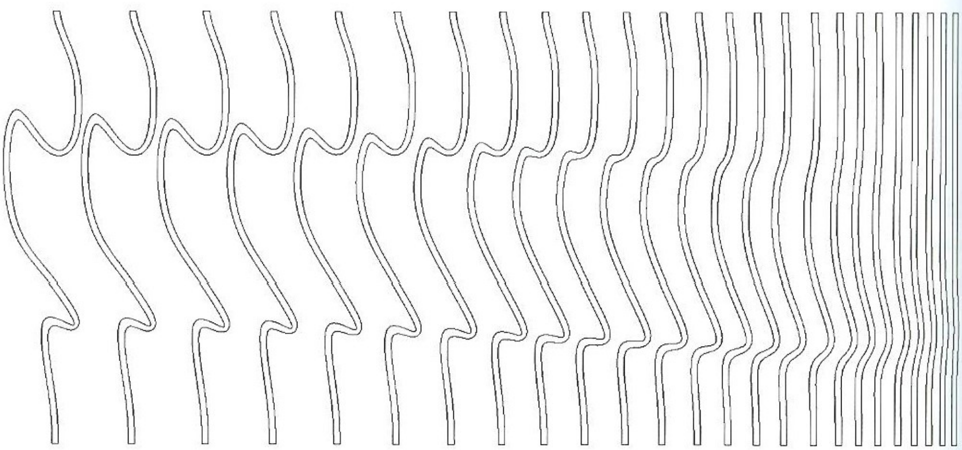


Lastly, each section curve is joined with its smooth offset by defining two segments that connect the curves' end points. The four curves are merged into a single branch using the *Merge* component set to *simplify* mode. The merged branches are joined using the component *Join*, returning a list of *closed planar curves*. These curves can then be oriented to a plane for milling (see 4.2.3).



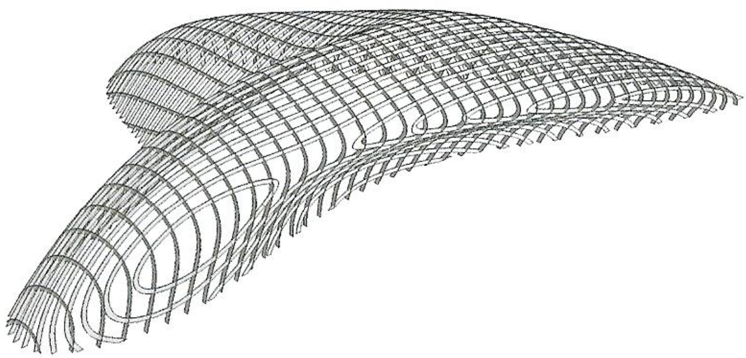


ABOVE. The image shows the output of *Join Curves*, i.e. a set of closed planar curves. BELOW. These curves can be easily oriented on the XY plane relying on the Orient component (4.2.3).



Once the curves are oriented, such that that all parts of every curve are coincident with the XY plane, they can be transferred to a cutting or milling machine. Most CNC machines cannot read NURBS curves. As a result the NURBS curves must be converted into **arcs and segments**. The conversion is based on two main strategies: the first strategy is to divide the curves into a large number of points and then define a polyline through the resulting points, the second strategy is to use Rhino's *Convert* command to convert curves into arcs or polylines with set tolerances. After conversion, the resulting geometries are *nested* in order to minimize the material waste either manually, by a third party software, or by a plug-in.

Another technique to build freeform objects by planar sections is based on a bi-directional strategy usually referred to as ***waffling***. Waffling performs the section contouring procedure in two orthogonal directions. There are several Grasshopper plug-ins available to automate the process.



The following image shows different waffling alternatives, which are based on the initial shape and the direction of sectioning, to achieve a desired output.

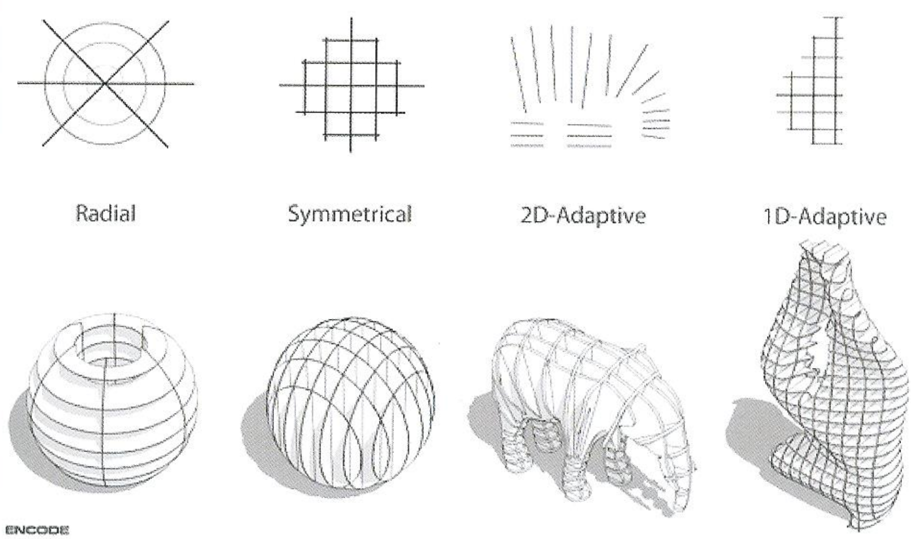
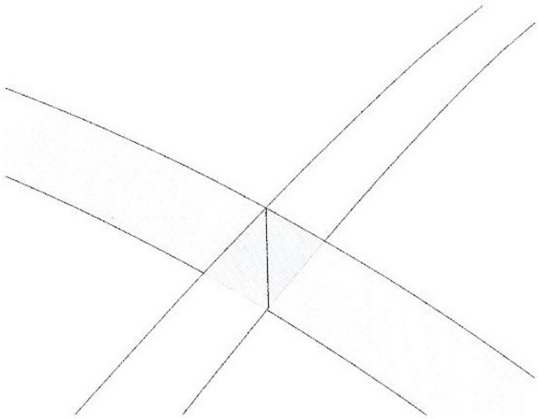


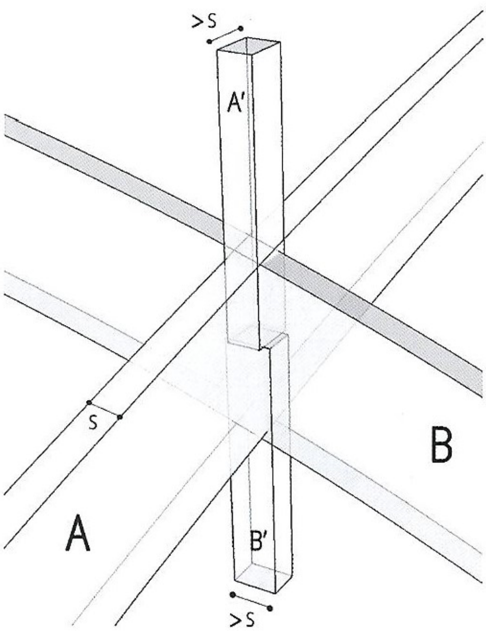
FIGURE 8.12
Different kinds of waffling. Image courtesy of Hassan Ragab.

Waffling requires intersections on which to perform a standard set of operations:

- Every possible intersection between every *rib* (or planar surface) is calculated and a list of intersection-segments are returned.

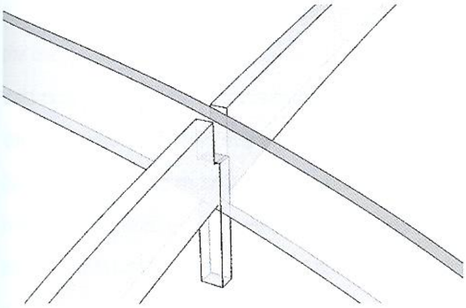


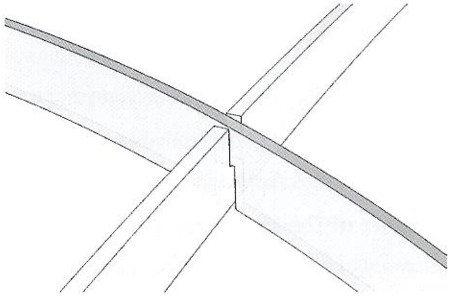
- At each intersection-segment two domain boxes (A' and B') are created. The boxes are subsequently subtracted using the *Solid Difference operation*: A-A' and B-B'.

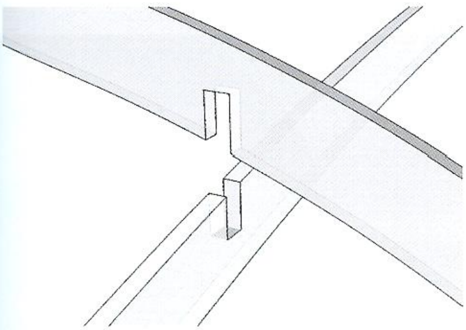


3

A complete waffling exercise can be found using the QR code above.







A solid difference allows to create node-intesec-tions between ribs.

FIGURE 8.13
Parametric Soft Wall by Studio Kami, Rome (2012). Image courtesy of Studio Kami (www.studiokami.it).

8.4 NU:S Installation

"The collective approach is not utopian and is indeed possible. The NU:S project clearly demonstrates that this methodology is both creative and attainable, and is an example of one of the directions artists in Italy are taking. "NU:S Fashion clothes Architecture", is an art installation exhibited first at Bramante Cloister, and later at The Museum of Contemporary Art of Rome. The project came from a cross-fertilization within different artistic fields and fascination for technology, computational design, and the Renaissance philosophies.

FIGURE 8.11
The NU:S installation. Photo by G. Catani and L. Sorrentino.

The work had no preconceived result or over-arching direction, only interaction. It was a herculean experiment, where the goal was the study of the interplay between creative forces, not the result. This is fundamentally different from any other event because what was created was imagined and made within *and for the project. The NU:S installation, designed by Arturo Tedeschi and Maurizio Degni, was inspired by the ascessional flow of the cloister as well as its symbolic strength, these contaminating the mathematical intrinsic logic of Renaissance architecture, reinterpreting it through the new parametric paradigm. The sculpture was also inspired by tailoring expertise since the introduction of digital techniques and fabrication processes in architecture allowed a concept of personalization only similar to haute couture. [...] The interesting aspect about this project is that new media led to artistic innovation, the very same phenomenon that characterized the Renaissance. In the 15th century artists applied perspective to drawing, whereas today computational design is employed to support innovation.*

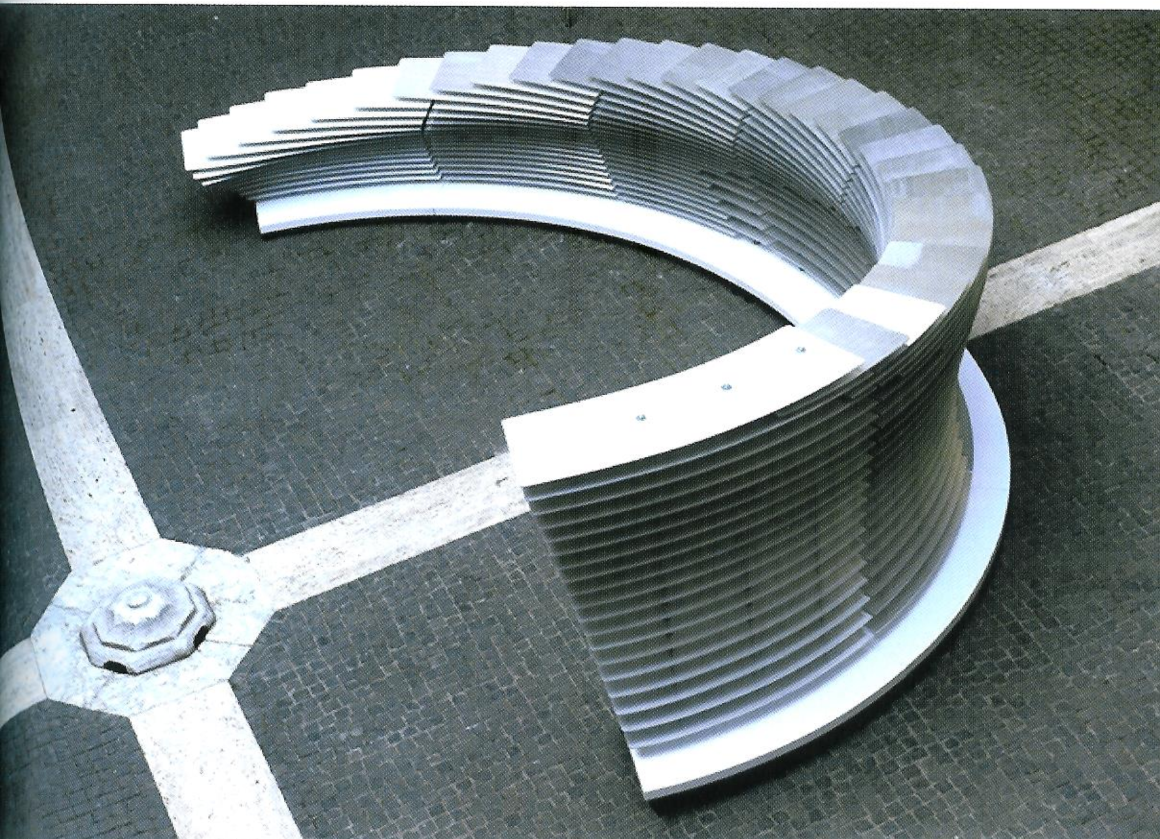


FIGURE 8.12
The NU:S installation. Photo by E. Lucci.

There are different levels of possibilities in the new digital instruments and technical planning methods, and NU:S tried to explore these. Sometimes there was a one directional process, sometimes bi-directional, sometimes even multi-directional. The revolutionary factor in the work was how each *designer maintained his own identity, even while adopting software and hardware foreign to their specific field".*

Antonella Buono

Antonella Buono graduated as a Fashion Designer and Product Responsible. Afterward, she focused on costume design and during the last eleven years she has worked in the advertising and movie industry as a stylist and a costume designer. Beyond her work as a stylist, she teaches Fashion Design at UARC for the Philadelphia University as well as courses in Rome. She is interested in cross-fertilization within different artistic fields, which she examines as an independent researcher. www.glamnicism.com

FIGURE 8.13

NU:S parametric shoes (2012) designed by Maurizio Degni, Alessio Spinelli and Arturo Tedeschi (sinterized nylon powder). The particular aesthetic of parametric structures - predominantly found in architectural design - has been expressed in this project through the creation of a "wearable object". Photo by G. Catani and L. Sorrentino.

8.5 Large-scale objects

Large-scale fabrications, or objects that in their articulation require technical, structural and functional issues to be considered, such as pavilions, canopies, shells, houses, and buildings; require additional techniques. The fabrication of large-scale objects usually involves the assembly of individually fabricated parts to transfer loads. Two important trajectories for fabricating large scale objects are currently being researched in academia and in the architecture profession. The first approach aims to reduce complexity and differentiation of components while the second aims to simplify the building process.

1. Computational approach.
   The main challenge of building a freeform facade has traditionally been to approximate a surface using **planar** panels of the same dimensions. This strategy is used to reduce manufacturing costs and optimize the reuse of molds. This process of surface discretization was often achieved through the triangulation of a surface. This technique has several disadvantages including: the weight of the support-structure, the complexity of each structural node etc. Nowadays cutting-edge computational techniques have been developed in order to achieve **planar quad panels** (PQ Meshes) from an arbitrary freeform surface and, under certain conditions, to get **planar hexagonal panels** (P-Hex Meshes). P-Hex Meshes simplifies the fabrication of the underlying structure as each node of an hexagon connect just three rods.

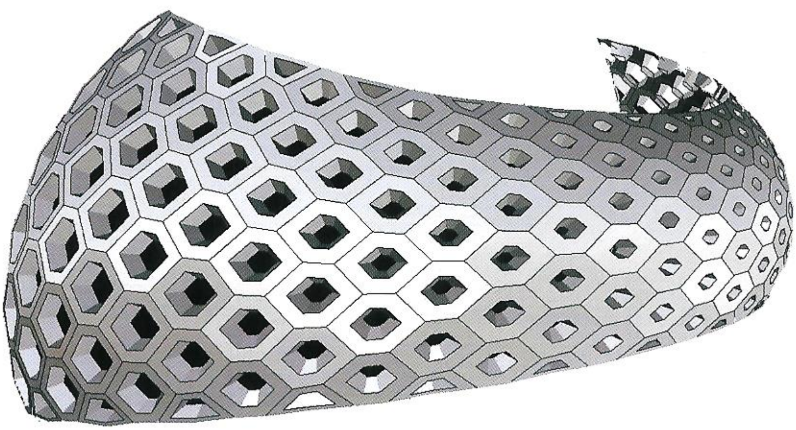


FIGURE 8.14

A freeform surface approximated through a set of planar hexagonal panels.

Developable strategies also play an important role in the construction of freeform objects. Several algorithms have been developed in order to find developable surfaces or sets of surfaces to approximate a freeform geometry. Since every developable surface is a ruled surface, a set of straight lines can always be found. These lines can become the axis of linear beams, ultimately simplifying the support structure.

2. Innovative fabrication.

   Whereas *computational approaches* operate within the traditional fabrication environment, *innovative fabrications* focus on developing new fabrication strategies. For instance, pioneer companies like D-Shape, guided by the italian engineer and inventor Enrico Dini, are successfully testing additive techniques to print large-scale objects. The D-Shape procedure compels designers to rethink the conception and optimization of structures.

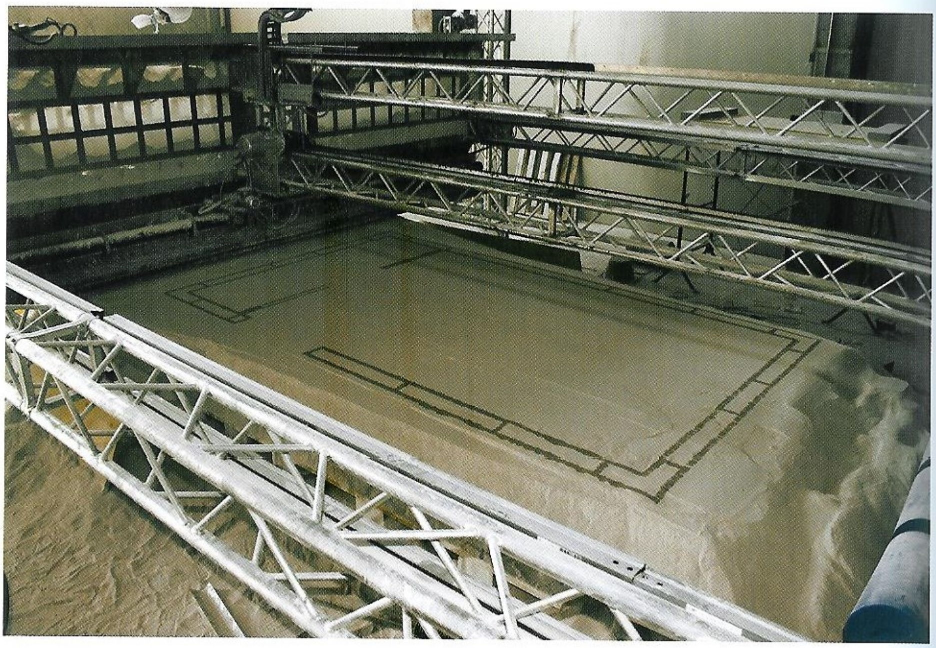


FIGURE 8.15
The 6m x 6m D-Shape printer, built by the italian engineer Enrico Dini. This is the first large-scale 3D printer. Image courtesy of D-Shape (www.d-shape.com).

Over the material, Past the Digital: Back to Cities

Stefano Andreani
Lecturer in Architectural Technology & Research Associate
Harvard University - Graduate School of Design

The history of architecture features a combination of different technological timelines. As Mario Carpo points out in his *The Alphabet and the Algorithm* book,[1] we can identify three technical ages – the age of hand-making, the age of mechanical-making, and the age of digital-making.

This distinction is of particular relevance if we think of the intrinsic dichotomy of architectural design: on the one hand, the built environment is based on the production of material objects, which in turn depend on the evolution of manufacturing technologies; whereas on the other hand, architectural design translates into abstract operations that are very much influenced by cultural environments and medium of representation. The world of hand-making that preceded the machine-made environment was characterized by unique pieces, mainly conceived and produced through a process of imitation rather than replication. The first break, the transition – as Carpo defines it – "from *artisanal variability* to *mechanical identicality*", occurred with the industrial revolution. But the second break in this sequence, the passage from mechanically-made identical copies to digitally-generated differential variations, is happening now. Hand-making creates variations, as does digital making; but the capacity to design and mass-produce serial variations (or *differentiality*) is specific to the present digital environment. Unlimited variability, however, may result in a loss of relevance and ultimately in a loss of meaning.

Back to the nineties, the digital revolution began to narrow down the gap between design and fabrication. Computers, in fact, not only could easily deliver tools for the ideation and manipulation of complex mathematical forms; these new tools could also be directly applied to the conception, representation, and production of objects.

Back then Bernard Cache stated that "*mathematics has effectively become an object of manufacture,*"[2] and Greg Lynn remarked that computer-aided design had "*allowed architects to explore calculus-*

1. Mario Carpo, *The Alphabet and the Algorithm* (Cambridge, MA: MIT Press, 2011).
2. Bernard Cache, "Objectile: The Pursuit of Philosophy by Other Means," in Stephen Perrella, ed., *Hypersurface Architecture II*, special issue (AD Profile 141), *Architectural Design* 69, nos. 9–10, 1999.

based forms for the first time."[3] The concept of *multiple variations* then emerged to define this new idea of the digitally-made object, what Deleuze would refer to as *objectile* – a function that contains an infinite number of objects[4].

> *The objectile is not an object but an algorithm – a parametric function which may determine an infinite variety of objects, all different (one for each set of parameters) yet all similar (as the underlying function is the same for all). Instead of focusing on one instance from a virtual series of many, the new technological paradigm is increasingly dealing with variations that can all be designed and fabricated sequentially: mathematical continuity in this case is set in a manufacturing series, not in a diachronic sequence, and used to mass produce the infinite variants of the same objectile – at the same unit cost as identical copies.*[5]

This technological shift defines the basic principles of a *nonstandard series* – i.e., a set in which each item has some features in common with all others. It thus follows the notion of *mass-customization,* which was born as a marketing strategy well before the rise of CAD-CAM technologies.[6] The term first appeared in 1987, with Stanley M. Davis' *Future Perfect* book, supplying both a name and a conceptual framework for processes initially from the clothing industry and recognizing that mass customization simply extended the capabilities latent in CAD/CAM processes.[7] In 1993, B. Joseph Pine II expanded on Davis' ideas articulating the production systems into three main categories: craft production, mass production, and mass customization – which combined elements of the first two.[8]
However, in the realm of architecture, the increasing power of today's computational tools might lead to discrepancies, rather than proximities, between the digital and physical worlds. As John Frazer argues when referring to the evolution of computational design, "*We went to all this effort in order to solve real social, environmental and technical problems where we believed a computer could significantly assist. But now that there is a massive computer power and software cheaply available, most scripting has become nothing more than an onanistic self indulgence in a cozy graphic environment. Endless repetition and variation on elaborate geometrical schema with no apparent social, environmental*

3. Greg Lynn, *Animate Form* (New York, NY: Princeton Architectural Press, 1999).
4. Gilles Deleuze, *Le pli: Leibniz et le baroque* (Paris: Editions de minuit, 1988).
5. Mario Carpo, *The Alphabet and the Algorithm*.
6. Stanley M. Davis, *Future Perfect* (Reading, MA: Addison-Wesley, 1987).
7. Dan Willis Todd and Woodward, "Diminishing Difficulty: Mass Customization and the Digital Production of Architecture," in *Fabricating architecture: Selected readings in digital design and manufacturing* (New York: Princeton Architectural Press, 2010).
8. B. Joseph Pine II, *Mass Customization: The New Frontier in Business Competition* (Boston, MA: Harvard Business School Press, 1993).

and technical purpose whatsoever."[9] A true paradigmatic shift in architectural design and fabrication may lie instead on the role of, and push for, *innovation* – in the sense of "*an activity that generates vitality*" as proposed by Mark Burry.[10] A conceptual approach to innovation that highlights the role of the environment in affecting an idea, supporting its development, and eventually its implementation and dissemination.

Innovation is what actually drives the research activities pursued by the Design Robotics Group (DRG) at the Graduate School of Design of Harvard University. The research unit, led by Professor Martin Bechthold, promotes the understanding, development and deployment of innovative technologies in the use of design as an agent of change in the quest for a better future. DRG looks at the role of material processes and systems in the built environment, with a special interest in robotic and computer-numerically controlled (CNC) fabrication processes. Combining issues of design computation, materials and assembly processes, the projects result in speculative prototypes as well as applied research geared towards industry integration. DRG work in material systems is best characterized as process-oriented, strategic and focused on performance.

An example of the implementation of the design-oriented research pursued by the Harvard DRG is the 'Ceramics 2.0' Workshop Cluster at the 2012 SmartGeometry, where ceramic material systems were explored through a combination of computational design methods and a six-axis robotic manipulator equipped with a wire-cutting tool. Run by Prof. Martin Bechthold, Jose Luis Garcia del Castillo, Aurgho Jyoti, Nathan King and the author, the workshop built upon the 'Flowing Matter' project developed at Harvard GSD.[11] Going back and forth between manual and robotic clay manipulation, workshop participants developed design intuitions that expanded beyond what would have been feasible when limited to either physical or computational methods. Exploring a material system in this open-ended manner generated a host of powerful ideas and much discussion. The workshop demonstrated that design robotics has matured to a point that brainstorming and sketching are now possible in newly hybridized modes that combine robotics with exploratory hands-on experiments.[12]

This line of research on ceramic building systems eventually resulted in the articulation of the

9. John Frazer, in M. Burry (ed.), *Scripting Cultures: Architectural design and programming* (Chichester: John Wiley&Sons, 2011).

10. Mark Burry, "The Innovation Imperative: Architectures of Vitality," *AD The Innovation Imperative: Architectures of Vitality* 221 (2013): 8-17.

11. Stefano Andreani, et al., "Flowing Matter: Robotic fabrication of complex ceramic systems," in *Proceedings of ISARC 2012: The 29th International Symposium on Automation and Robotics in Construction* (Eindhoven, 2012).

12. Martin Bechthold, "Design Robotics: New Strategies for Material System Research," in Brady Peters et al., eds. *Inside Smartgeometry: Expanding the Architectural Possibilities of Computational Design* (London: John Wiley & Sons, 2013): 254–265.

'[R]evolving Brick' project.[13] Developed at Harvard GSD by Prof. Martin Bechthold and the author, the on-going study introduces the concept of *strategic customization* in the industrial fabrication context.

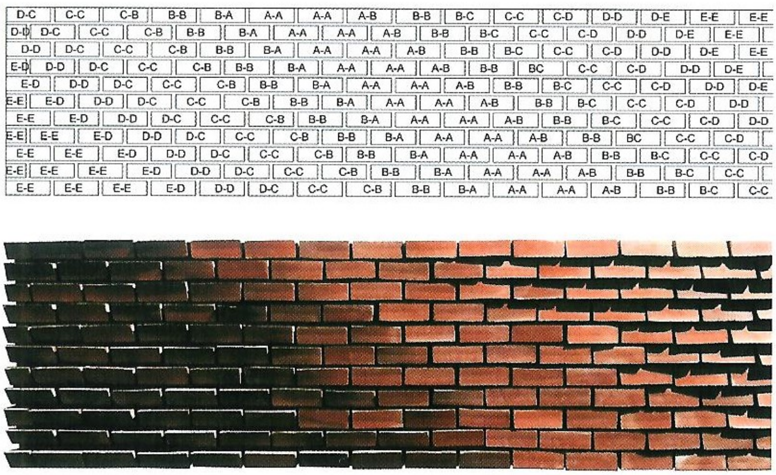


FIGURE 1
© Stefano Andreani.

The project in fact integrates robotic technology on the production side, so that the age-old rectangular form of the brick can be successfully overcome, while maintaining the efficiency of tried and true mass-production methods. The resulting mass-customization of brick forms opens up a new design space in brick construction. In order to combine ornamental effects with sustainable design in architectural ceramic systems, this work also developed strategies to improve the energy efficiency of brick envelopes. In particular, by combining material proprieties and geometric parameters, the research shows that it is possible to optimize the material configuration to generate solar-selective thermal mass systems that include self-shading. Exploiting the advantages of the geometric complexity available through the proposed shaping process, the new material system merges aesthetics and environmental performance by creating design pattern articulations that respond to variable climatic and diurnal cycles. The resulting integrated workflow would eventually let both architects and manufacturers re-think the way brick building systems can be used, and let designers re-create novel and unexpected relationships with this traditional material.

13. Stefano Andreani and Martin Bechthold, "[R]evolving Brick: Geometry and Performance Innovation in Ceramic Building Systems through Design Robotics," in Fabio Gramazio et al., eds. *Fabricate: Negotiating Design and Making* (Zurich: Gta Publishers, 2014).

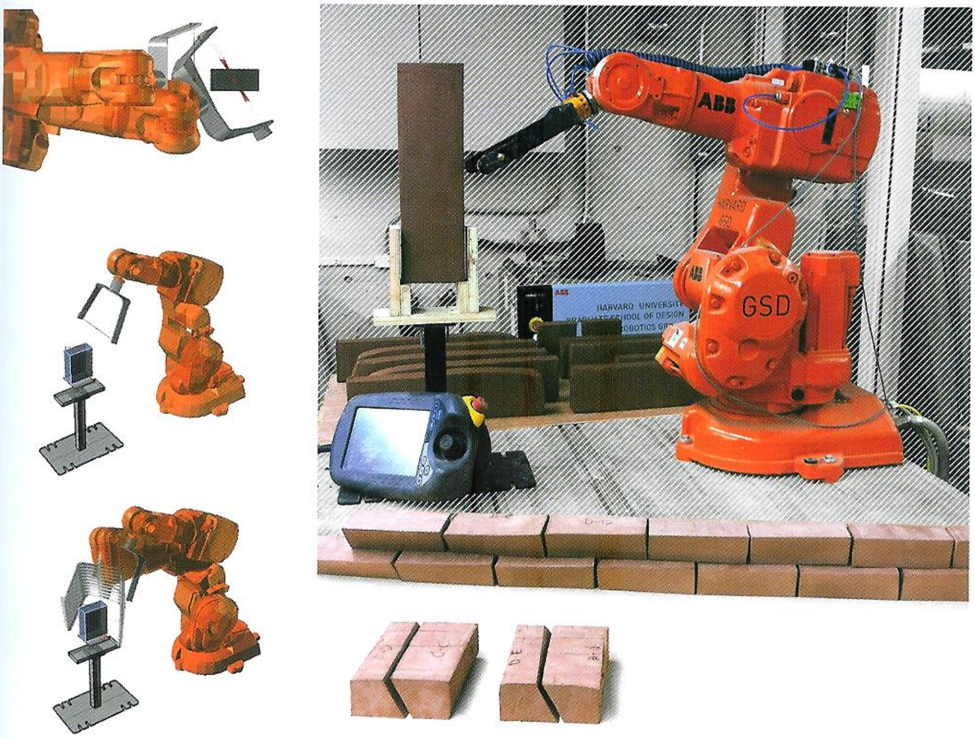


FIGURE 2
© Stefano Andreani.

Concepts such as complex geometry optimization, material structural efficiency, and advanced fabrication methods find unique expression in the design and fabrication of the 'Floating Ceramic Shell' – a structural ceramic and concrete shell system being developed as a collaboration between the Harvard Graduate School of Design and the Institute for Structural Design at TU Graz, Austria. Sponsored by the Valencia Trade Fair Association and by ASCER, the mock-up of the ceramic shell system was exhibited at the 2014 Cevisama in Valencia, Spain as the centerpiece of this year's international show. Floating overhead like a giant pair of wings, the installation consisted of a ceramic deck measuring about 7.8 by 4.5 meters in a plan view, suspended from the centre columns of the fair building. This shell has a double-curvature surface, which is composed of just a single type of ceramic piece – whereas double-curvature surfaces usually need several types of pieces. In order to achieve this simplification, the ceramic units overlap each other, thus accommodating the differences in measurements of the doubly-curved surface.[14]

14. "Trans/Hitos 2014," *Domus*, February 20th, 2014, http://www.domusweb.it/en/news/2014/02/20/trans_hitos_2014.html

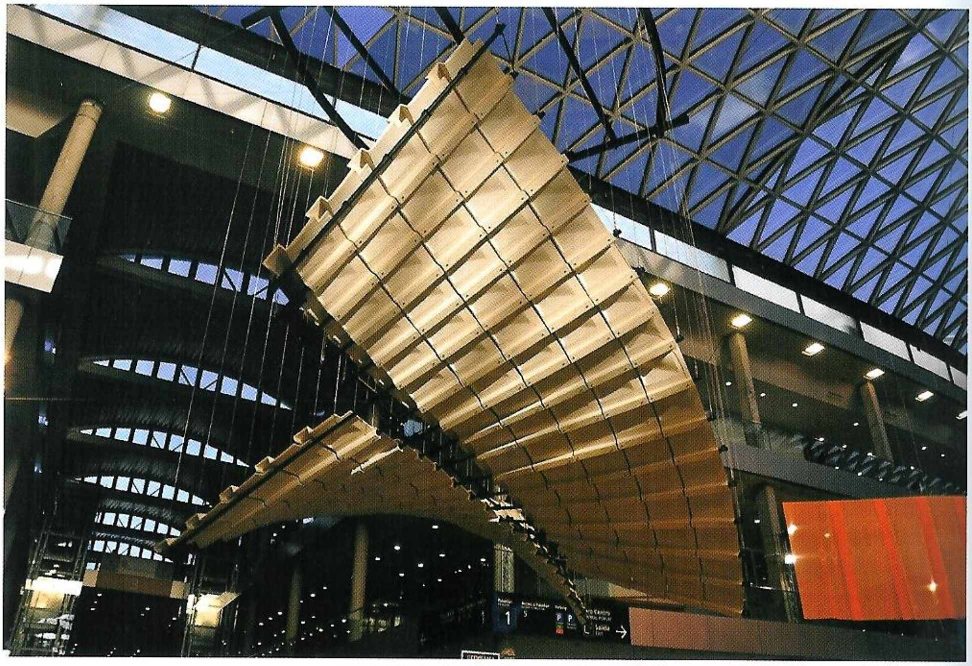


FIGURE 3
© Andreas Trummer.

The large ceramic stoneware elements are designed to enclose channels that form a perpendicular network of connecting ultra-high strength fiber concrete ribs. Ribs and tiles form a composite structural surface. Structural tests will be eventually performed on various-scale prototypes before the actual erection of the ceramic/concrete shell.

Material system research pursued at Harvard GSD thus embraces a variety of materials and techniques. A further investigation is the 'Robotic Casting' workshop at the 2012 Robotics in Architecture in Vienna, run by Prof. Martin Bechthold, Nathan King and the author. The workshop explored novel approaches to serially customized casting processes enabled through the strategic deployment of 6-axis robotic manipulators. Traditional casting techniques currently limit designers to repetitive use of identical elements in order to distribute the cost of the molds. Serialized customization, mass-customization or related techniques that produce highly variable, individualized design expressions are rarely possible, yet increasingly demanded in pursuit of contemporary architectural forms. Robotic casting is a new casting method developed by the Design Robotics Group that uses strategically designed molds that are oriented robotically and, when filled with variable material volumes, produce families of varied yet similar shapes. Studies performed during the workshop proposed modular assemblies driven by acoustic, lighting, views, or assembly techniques of interlocking and staggering. Robotic code was created with a DRG Grasshopper component that outputs angle rotations and volume measurements for each piece. Following the digital design process, the workshop team produced, in 14 hours, a doubly-curved, perforated wall consisting of 40 individual elements.

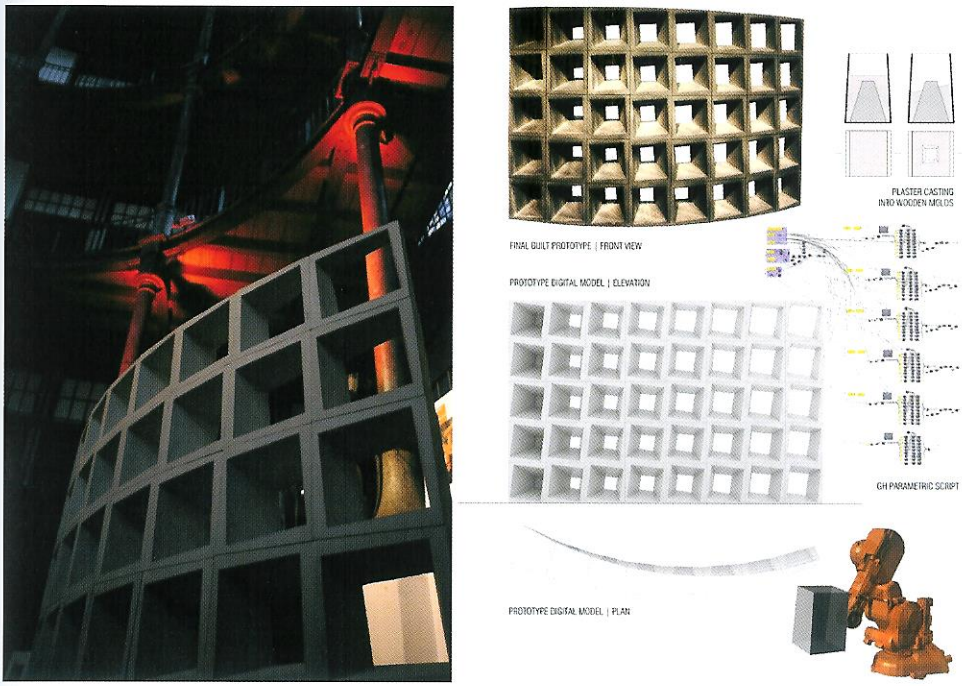


FIGURE 4
© Stefano Andreani.

The projects described above, particularly the ones developed in workshop contexts as collective experience, can be seen as manifestations of a fundamental objective at Harvard GSD: design and manufacturing can really permeate each other, blurring the boundaries between the digital and physical worlds. The widespread movement of fab-labs, the increasing use of 3d printing techniques, and the creation of ecosystems or hubs of innovation in cities reinforce the idea that the employment of digital-fabrication technologies is rapidly becoming ubiquitous. Digital design, the use of big data, and nanotechnology can play a valuable role in creating new manufacturing methods, processes and systems, and not just products. Looking at economies as *product space*, Harvard economist Ricardo Hausmann argues that "*developments around information technology, 3-D printing, and networks will* *allow for a redesign of manufacturing. The world will be massively investing in it."*[15]

FIGURE 5
© Stefano Andreani.

In this context, the Responsive Environments and Artifacts Lab (REAL) at the Harvard Graduate School of Design, led by Professor Allen Sayegh, looks at how new technologies can impact the built environments in which we live, work, and play. Pursuing the design of digital, virtual and physical worlds as an indivisible whole, REAL investigates the all-pervasive nature of digital information and interaction at scales ranging from our bodies to the larger urban contexts we occupy and the infrastructures that support them. Through multi-disciplinary projects in the U.S., Europe and China, REAL is developing novel theoretical frameworks for tackling pressing problems of contemporary cities, from the redefinition of local manufacturing activities for bringing factories back to cities, through the development of new digital and physical tools for improving health and wellbeing of urban environments, to the deployment of advanced technologies in high-rise, high-density cities

15. Antonio Regalado, "You Must Make the New Machines," in The Next Wave of Manufacturing, *MIT Technology Review*, 2013.

that mediate that scale of the body with the scale of the tall building.

The future dynamics of contemporary cities will likely encompass a seamless integration of smart objects, interactive environments, and digitally-augmented fabrication machines with the everyday life of citizens. As designers, it is then our responsibility to develop ecological models of implementation for ensuring the creation of high-quality environments in our cities.

Stefano Andreani

Harvard University, Boston, 03.25.2014

Stefano Andreani is a licensed architectural engineer and educator interested in the strategic implementation of advanced technologies in architecture for innovative design solutions. As Research Associate at the Graduate School of Design of Harvard University, he pursues research on performative material systems within the Design Robotics Group (DRG) and on the future of learning and healthcare practices and environments within the Responsive Environments and Artifacts Lab (REAL). Andreani received a Master in Design Technology degree from Harvard GSD and a Master in Architectural Engineering from the University of Perugia, where he was Assistant Professor of Architectural Technology. His professional work mainly focuses on high-rise design, as Project Designer at RBA Studio and as Design Technology Consultant for the South China University of Technology.

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

(Digital) Form-finding

Alberto Pugnale
Lecturer in Architectural design at the University of Melbourne

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

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

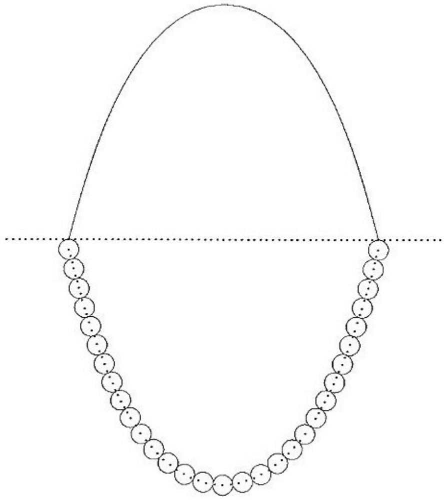


FIGURE 1
A catenary arch and its inverted shape.

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

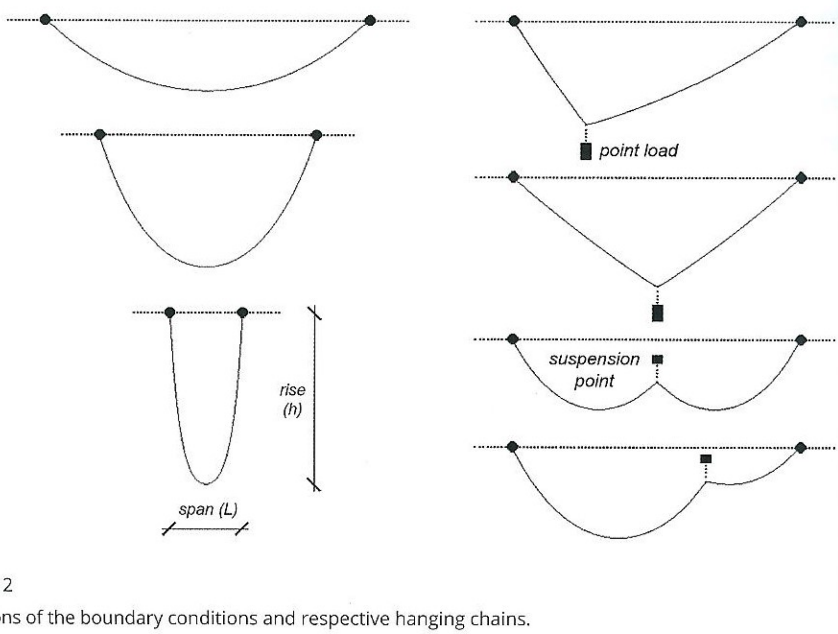


FIGURE 2
Variations of the boundary conditions and respective hanging chains.

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

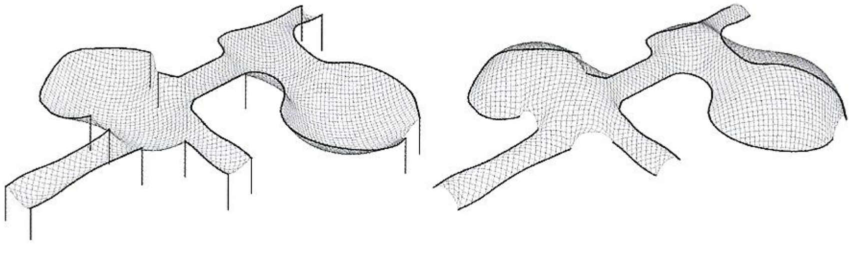


FIGURE 3

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

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

The third method of making hanging models was developed by Heinz Isler in 1955, and it was specific for the form-finding of RC shells which are a continuous type of structures. Such a characteristic was simulated through suspension of wet pieces of fabric or membrane - the derived forms were then frozen and finally inverted[8]. Very different results can be obtained by varying the type of fabric used, i.e. the properties of the model material play an important role in the process.

Amongst the shells Isler designed throughout his career, the ones of the Deitingen service station, built in 1968 on the Bern-Zurich motorway, and the roof of the open-air theatre in Grötzingen, dated 1977 and with a thickness of only 11cm, are the most representative of the structural lightness this form-finding technique can lead to.

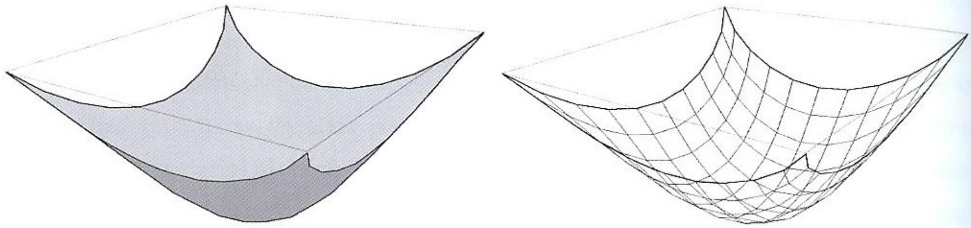


FIGURE 4

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

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

8. See: Isler H., *New Shapes for Shells – Twenty Years After*, in "Bulletin of the International Association for Shell Structures", no.71/72, 1980, pp. 9-26. See also: Isler H., *New Shapes for Shells*, in "Bullettin of the IASS, no.8, 1961; and: Isler H., *Concrete Shells Derived from Experimental Shapes*, in "Structural Engineering International, Vol.3, 1994, pp. 142-147.

9. See: Otto F., Rasch B., "Finding Form: Towards an Architecture of the Minimal", Axel Menges, 1996, pp. 58-59.

10. Several examples of minimal surfaces can be found in: Gray A., Abbena E., Salamon S., "Modern Differential Geometry of Curves and Surfaces with Mathematica", 3rd ed., Boca Raton: CRC, 2006 (1993).

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

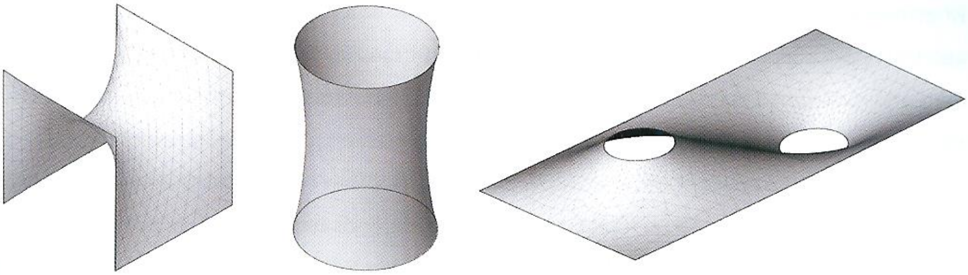


FIGURE 5
Generation of soap films from one (left), two (middle) and several closed frames (right).

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

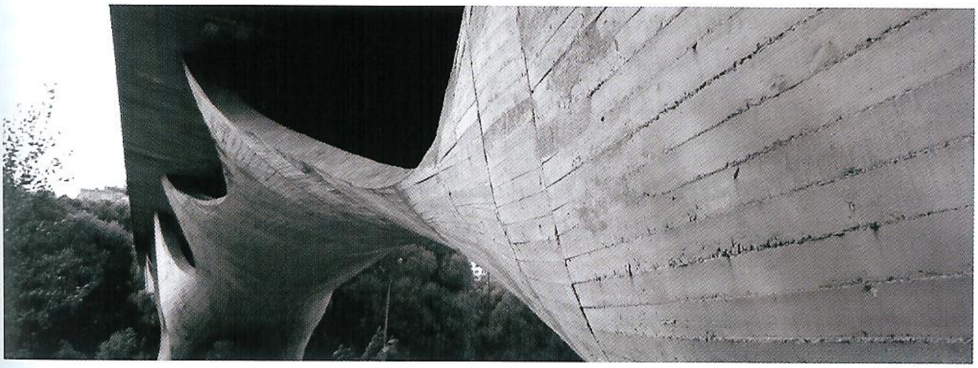


FIGURE 6
Bridge over the Basento River, Potenza (Italy).

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

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

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

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

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

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

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

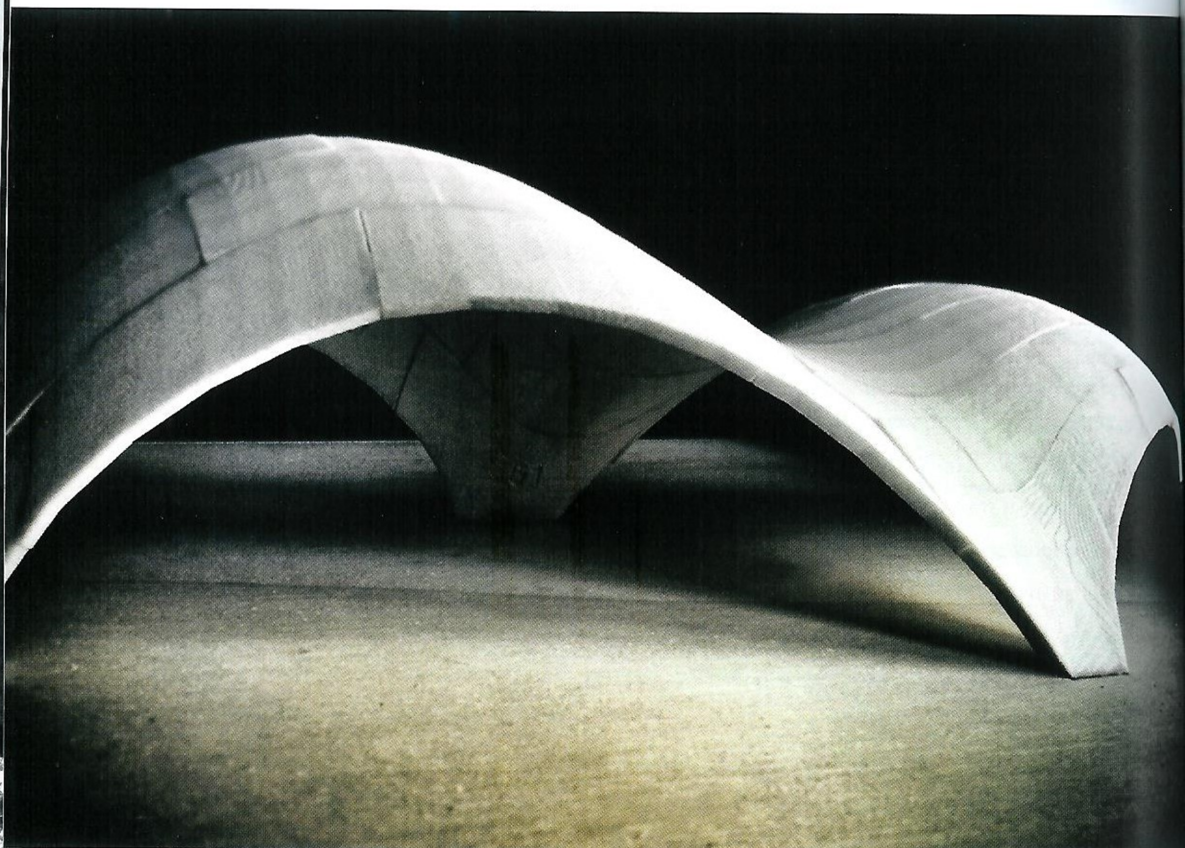
The last fundamental aspect of optimization is that it is not just limited to resolving questions of a static nature, which instead is an intrinsic characteristic of form-finding based on physical models. Techniques like GAs can be used in all those cases in which an architectural performance can be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

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

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

http://albertopugnale.wordpress.com/

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



Only-compression vault obtained through digital form-finding techniques. The scale model is made of 3D printed "bricks" that work in pure compression. The project was developed by Alessia De Luca under the supervision of the author.