# DIGITAL MAKING

## *Exploring Design with Computer Controlled Fabrication*

By Sameer Kashyap

Bachelor of Architecture (2001)
Sushant School of Art and Architecture

Submitted to the Department of Architecture
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Architecture Studies
Massachusetts Institute of Technology
June 2004

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## *Abstract*

This thesis examines the underlying issues innate to the design process of developing architectural solutions using the digital for "making" architecture, focusing on architectural production. It proposes an alternative method for fabricating architecture that supports a fast, inexpensive design process using a combination of digital modeling (explicit or with generative methods) and computer controlled fabrication machines. A series of explorations and studies are conducted to establish a procedure for the integration of representational techniques and fabrication processes into methods for digital making. The thesis also suggests how computer-controlled fabrication can be integrated into design exploration, by embedding activities of digital making into the design process.

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# Chapter 1

## *Introduction*

## *1.1 Background*

Physical output from Rapid Prototyping and CAD/CAM machines represents a significant new method for visualization and fabrication of architecture. The possibility to directly realize tangible three-dimensional objects from computer models challenges traditional means of representation. These developments in the means of representation and fabrication require parallel changes in the architectural design process.

Representation and fabrication have always been inherent to the architectural design process[i]. Manipulation of material by hand leads to the creation of unique objects. Tools have developed as extensions of the hands, for example the chisel, saw, hand drill etc. As tools developed they became mechanized, such as the electric drill, but were still largely operated by hand. Up until now such tools have been sufficient for the design needs of buildings that were an outgrowth of the industrial revolution.

The computer as a tool could be thought of as an extension of the mind, similar to the hand-tool relation. As observed by Bill Mitchell, "Just as the industrial revolution replaced human muscle power by energy consuming machines, the computer revolution is replacing human brain power by information processing machines."[ii]

To date, software for architecture and engineering has progressed from coarse drafting systems to highly sophisticated modeling and analysis tools. As we enter into the post-industrial-digital era, Computer Aided Design and Manufacturing (CAD/CAM) technologies make it possible to easily create and modify digital models and manipulate material through computer controlled movements to create physical three dimensional objects. This encourages repetition and variation that results in the making of distinct things. Furthermore, recent developments in the software industry allow designers to act as "creators of computational systems that can produce infinite possibilities and variations"[iii], extending the role of an architect to a "tool maker". The combination of these advances has profound implications on the architectural design process and production.

Today, both architectural practices and schools of architecture have started to incorporate cutting edge tools and equipment for computer controlled fabrication as an integral part of their facilities, challenging the potential of the digital for the "making" of architecture.

This thesis examines the underlying issues innate to the design process of developing architectural solutions using the digital for "making" architecture, with a focus on architectural production. It proposes an alternative method for fabricating architecture using a combination of digital modeling (both explicit and with generative methods) and rapid prototyping and CAD/CAM fabrication machines. The thesis also suggests how computer-controlled fabrication can be integrated into design exploration by embedding activities of digital making into the design process.

The procedures outlined here are derived from experiences in three related contexts: 1. My personal explorations in the field of Digital Fabrication; 2. Involvement as a researcher with the Digital Design Fabrication Group and the Design Fabrication Workshop at the Massachusetts Institute of Technology (MIT); 3. Through, one-to-one discussion and analysis of various written materials by academicians and students in related fields.

## *1.2 Methods*

### *1.2.1 Digital Modeling*

Digital models are used to represent different aspects of design. This study is guided by an intention of directly translating 3-D digital models into material realization, with a focus on architectural production. Various digital modeling platforms are used including, AutoCAD (AutoDesk) Catia (Dassault Systems) and Rhinoceros (NURBS modeling software).

### *1.2.2 Computer Controlled Fabrication*

Computer Controlled Fabrication enables us to translate three dimensional digital models into material realization. This is done by manipulating material with a machine that moves through computer controlled movements. These can be broken down into two broad groups: CAD/CAM fabrication machines (CNC machines) and Rapid Prototyping machines (RP machines). CNC machines use *2D fabrication* processes or *subtractive fabrication* processes of manipulating materials to create objects. RP machines use *additive fabrication* processes.

A *2D fabrication process* involves a two axis motion of cutting head relative to sheet material. For example, laser cutter, paper cutter etc. *Subtractive fabrication* involves the removal of a specified volume of material from solids using electro-, chemically- or mechanically – reductive processes. For example, milling machine lathes etc. Since both 2D and subtractive fabrication processes involve manipulation of material by subtractive methods, sometimes both are referred to as Subtractive fabrication. *Additive fabrication* involves the incremental forming by adding material in a layer by layer fashion, a process which can be understood as the inverse of milling. Examples of this technique are, the ZCorp 3D printer, a Thermojet printer, etc.

**Figure 1.1 ZCorp.. 3D printer**

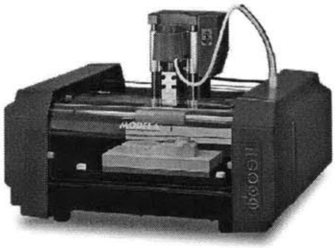

**Figure 1.2 Roland Milling Machine**

The following computer controlled fabrication machines[iv] were used for the review of fabrication techniques. However, most of the explorations discussed in this thesis were fabricated using the ZCorp. 3D printer and the Laser Cutter.

*Laser cutter*: uses 2D cutting processes for materials like wood paper, acetate, museum board

*Paper cutter*: uses 2D cutting processes for materials like paper

*Water-jet:* uses 2D cutting processes for materials like wood, foam, rubber, metal, glass, stone etc.

*Milling machine:* uses subtractive fabrication processes for materials like wood, foams, metals, plastics etc

*ZCorp. 3D printing machine:* uses additive fabrication processes with layers of starch powder.

*Stratasys 3D FDM printer:* uses additive fabrication processes with layers of plastic

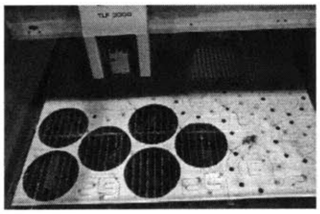

**Figure 1.3 Laser Cutter**

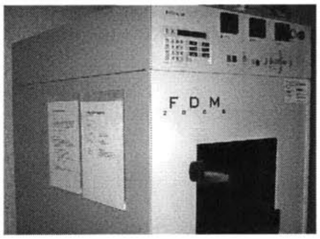

**Figure 1.4 StrataSys. FDM printer**

### *1.2.3 Generative Methods*

#### *End-user programming (Scripting)*[v]

End-user programming means the active participation of end-users in the software development process. In this perspective, tasks that are traditionally performed by developers are transferred to users.[vi].The experiments in section 2.2 of this thesis are written in RhinoScript and AutoLisp. These are End–user programming Languages for Rhinoceros and AutoCad respectively. RhinoScript is based on the Visual Basic Programming language and AutoLisp is based on LISP programming language.

Scripting languages enable one to encode new functionality within existing software, as opposed to creating new software. They allow the user to access the underlying structure of existing software and embed new functionality into it. Using scripted procedures in existing model oriented software environments (for example, *RhinoScript* in Rhino NURBS modeling software) the user can "generate" design representations for configurations with sets of intelligent, responsive components, thus giving tremendous expressive control to the designer in addition to unprecedented productivity gains.

Note[vii]: A script is a set of instructions written in computer code and executed within a specific software environment. This is done in a way which is very similar to conventional programming, with the same basic structures of variables, loops, conditionals, and functions.

#### *Parametric Modeling*[viii]

Parametric modeling is a computer aided design (CAD) system where the geometrical components of a 3D computer model are subject to variations, therefore allowing the designer more flexibility and control. Here the model is constructed in a systematic way, where the geometrical components are associated in sets of relations which are subject to parameterization.

A parametric model represents multiple instances of design. Depending on how the model is constructed, the components will have a specific behavior according to values of the parameters. Parametric models are used as tools for an interactive dialog between the designer and the computer.

Design representation by both methods – End-user programming and parametric modeling - involve generation of instances of geometrical components, hence referred to as generative methods.

### *1.2.4 Observations*

My work has been structured around my association with the Digital Design Fabrication group and a series of workshops that I have participated in at the Massachusetts Institute of Technology. "The Design Fabrication Group is a center for education and research in areas of rapid prototyping and CAD/CAM operations for architects and designers. The group's pedagogy is to engage faculty and students in research focused on the relationship between design computing and the physical output of information using rapid prototyping and CAD/CAM machines for design representation and reflection."[ix] I have also participated in a series of workshops at MIT that focus on related issues (Parametric and Generative tools for Design and Fabrication (Spring 2003), Digital Design Fabrication (Fall 2003) and Digital Design Fabrication Workshop (Spring 2004). I had the opportunity to participate in the first workshop as a student. This workshop was a collaborative course with Foster and Partners in London that explored a computationally-based, explorative approach to design. Parametric and generative design tools were combined with digital fabrication and rapid-prototyping techniques, in a cyclical process, to generate and evaluate alternative, innovative design solutions to a design problem. Over the past year I was also closely associated with the Digital Design Fabrication Workshops as a research assistant. These workshops focused on the relationship between design, various forms of computer modeling and the physical representation of information using rapid prototyping devices. Many ideas expressed in this document have evolved out of discussions and observations with my colleagues and students in these workshops.

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[i] Adapted from Kevin R. Klinger, *Making Digital Architecture*, in Digital Design Media 2002

[ii] William J. Mitchell, Malcolm McCullough, *Digital Design Media*, p 3

[iii] Cristiano Ceccato, Integration: Master [Planner | Programmer | Builder]

[iv] For more details on fabrication machines, refer to appendix

[v] For further information about End-User Programming, refer to Yanni Loukissas, *Rulebuilding; Exploring Design Worlds through End-User Programming*, SMArchS Thesis, MIT

[vi] Fabio Paternò, End-User Development, Empowering People to Flexibly Employ Advanced Information and Communication Technology

[vii] Yanni Loukissas, Rulebuilding; *Exploring Design Worlds through End-User Programming*, SMArchS Thesis, MIT

[viii] For further information, refer to Carlos Barrios, *On Parametric Modeling and Design* (unpublished paper, MIT)

[ix] *Digital Design Fabrication Group* website, Massachusetts Institute of Technology

# Chapter 2

## *Explorations with Computer Controlled Fabrication*

The CNC machines discussed in this thesis are originally developed for the aerospace industry and have been adopted for varying purposes in other fields such as mechanical engineering, manufacturing and industrial design[x]. Rapid Prototyping machines are used to fabricate three-dimensional models for visual inspection in these fields as well as in medicine[xi]. It is only recently that architects have started exploring the potential offered by such machines. Due to current size restrictions, computer controlled fabrication creates small monolithic and homogeneous objects that are better suited for fields like engineering and industrial design than for architects, who engage in the design of large objects that contain considerable technical complexity and consist of widely varying materials and components. Regardless of the limitations, these machines are working for architects in many ways.

Computer controlled fabrication machines allow accurate fabrication of designs at different scales. The possibility of manufacturing and assembling at smaller scales can not only make it easier for designers to evaluate their ideas with tangible physical representations, but engage in design for manufacturability and assembly of buildings as well.

This chapter consists of a series of explorations, conducted through experiments and observations, that investigate how computer controlled fabrication can be integrated into the architectural design process.

## 2.1 *Short Experiments in Digital Making*

The following experiments demonstrate how a combination of digital modeling with generative methods and computer controlled fabrication machines can produce physical surface models. This approach accommodates the generation of joints/connection systems that correspond to the possibilities and limitations of existing computer controlled fabrication machines. When means of production and definition of form are accounted for in the design approach, there could potentially be a closer link between formal design intentions and their physical realization.

### 2.1.1 *Approximating NURBS surfaces*[xii]

This section describes an alternative way of fabricating sketch physical representations of curved NURBS surfaces using a combination of digital modeling with End-user programming and 2D fabrication machines. By adopting this approach it is possible to produce in-expensive, quick sketch variations of digital representations of NURBS surfaces for evaluation early in the design process.

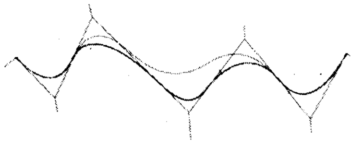


**Figure 2.1: The shape of a NURBS curve can be changed by interactively manipulating the control points, weights and knots**

#### *What are NURBS Surfaces*[xiii]

Non–Uniform Rational B-Splines are a particular type of mathematical spline curves that can be manipulated through a control polygon. The concepts of splines are based on wooden ship curves that are used to draw continuous curves before computers. The control points of the control polygon have associated weights. The equation of the curve can be of different orders (Figure 2.1). Drafting splines were used to draw complex curves in the cross section of ship hulls and airplane fuselages. Those splines were flexible strips made of plastic, wood or metal that were bent to achieve the desired smooth curve and fixed in place with weights. Mathematicians borrowed the term in a direct analogy to describe families of complex curves. NURBS curves are shaped primarily by changing the location of control points, which do not have to lie on the curve itself, except at end points. Each control point has an associated weight, which determines the extent of influence on the curve[xiv] (Figure 2.2).

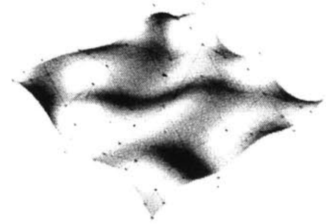


**Figure 2.2: Control lattice for a NURBS surface**

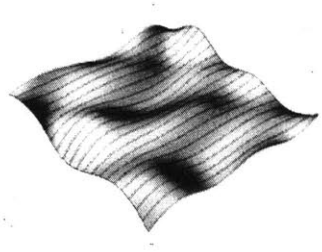


**Figure 2.3: Isoparametric contours in the "U" direction of a NURBS surface**

Not only is it easy to control the shape and interactively manipulate the control points, weights and knots, but one of the biggest advantages of using NURBS is the possibility of constructing these mathematically defined surfaces using computer controlled fabrication. Various additive Rapid prototyping techniques could be adopted to get quick physical representations of NURBS surfaces. However some of the limiting factors of using such methods are that it is not possible to increase the scale of the physical representation and such techniques are very expensive, especially when they are to be integrated at the initial design stages where many alternatives have to be tested.

## *Experiment 1:*

Rapid Automated Production of approximated NURBS Surfaces

*Geometry* - *NURBS surfaces*
*Material* - *Chip Board*
*Fabrication Machine* - *Laser Cutter*
*Generative Method* - *Rhino Scripting*

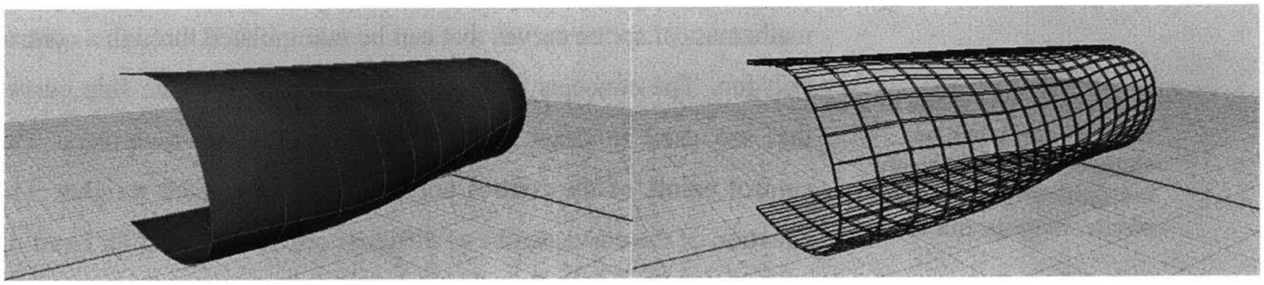


**Figure 2.4: Screenshots of NURBS surface representation showing isoparms and NURBS surface representation showing rib members along isoparms**

## *Task*

To produce physical sketch surface models for curved NURBS surfaces using 2D Fabrication Machines for evaluation during initial stages of the design process.

## *Methodology*

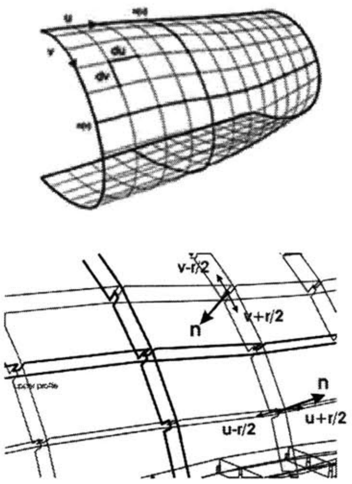
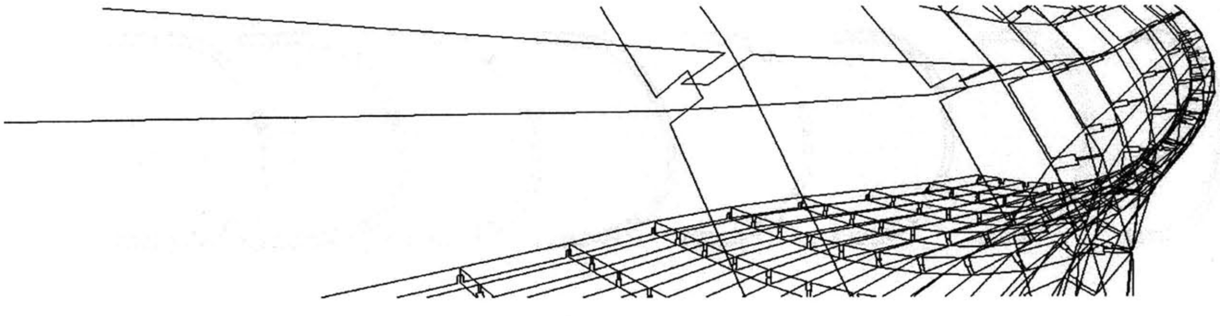


**Figure 2.5: Sketch diagram showing the proposed interlocking groove systems**

Understanding how the software creates and visualizes NURBS objects provides a clue for creating tangible physical representations of approximated NURBS surfaces. NURBS objects are defined within a "local" parametric space, situated in the three-dimensional Cartesian geometric space within which the objects are represented. This parametric space is one dimensional for NURBS curves, even though the curves exist in a 3D geometrical space. The one dimensionality of curves is defined at a topological level by a single parameter commonly referred to as *T*. Surfaces have two dimensions in parametric space, often referred to as *U* and *V* in order to distinguish them from the X, Y and Z of the Cartesian three dimensional geometric space. Isoparametric curves ("isoparms") are used to aid in digitally visualizing NURBS surfaces through contouring in the *U* and *V* directions (Figure 2.3). These curves have a constant *U* or *V* parameter in the parametric NURBS math, and are used to visualize digital models of NURBS surfaces to create decomposable rib components for physical models. The intent is to create a supporting framework of rib components that could be

**Figure 2.6: Interlocking grooves generated by scripting procedures**



manufactured by using the Laser cutter assembled together along the "isoparms" (Figure 2.4).

A self-assemble, interlocking connection system at the intersections of the *UV* "functional tests that were conducted to test the feasibility of the system. (Figure 2.5 shows)

The *UV* intersection points along the isoparametric curve were accessed node by node and line by line to trace the profile of a rib. This profile was then offset to accommodate the desired depth of the rib and grooves were plotted at every intersection. This procedure was followed for each rib member. Each isoparm was unique, thus every rib component was unique. However, the underlying procedure for creating each rib was the same.

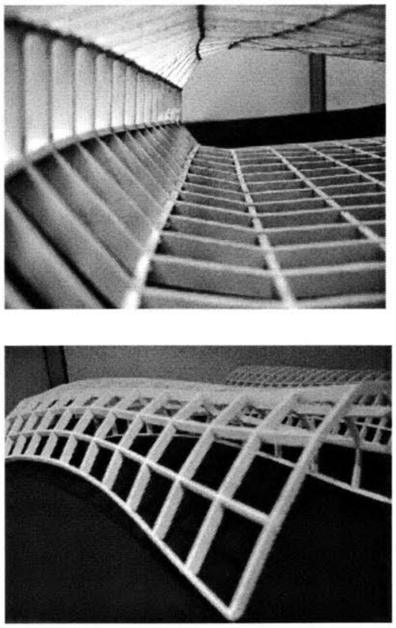
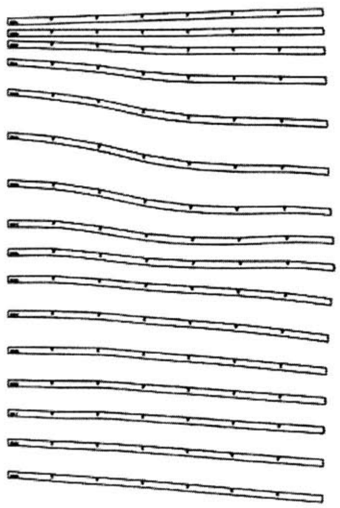
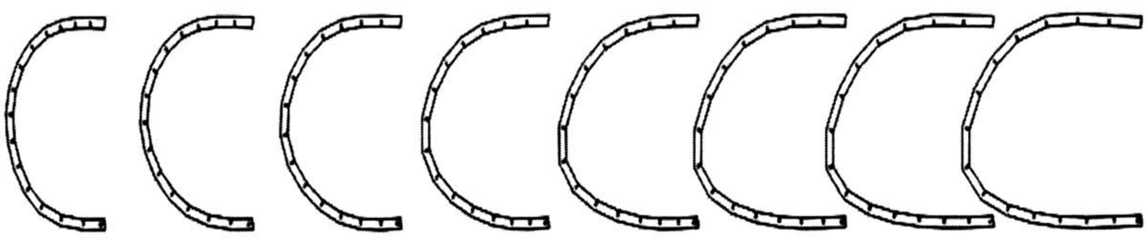


**Figure 2.7: Physical model of the NURBS surface**

The next task was to translate this procedure of creating the rib components into a generative method. This was done by parametrically defining a layout for the ribs with explicit variables and extracting this information from the underlying geometry of the NURBS surface. RhinoScripting was adopted for this purpose. Thickness of members, depth of ribs, tolerances, thickness of chip board, and the number of isoparms in both *U* and *V* directions were parametrically defined as variables in the script, which were assigned by the user while running the script. These variables can be altered by the user by re- running the script. In other words the script was like a set of pre-recorded instructions which can be played again and again, allowing the user to change certain variables or conditions that

**Figure 2.8: Cut sheet layout of ribs**





were identified and pre-defined when initially creating the script.

It is noted that not only is it very time consuming to perform the above tasks manually, but it is also difficult to understand and access the geometry in a wire frame model. The use of scripted procedures both speeds up the process by automatically creating the rib components and avoids human errors.

Once the script has been written it can be modified, improved or simply re-used for other projects as well.

*Preparation of assembling instructions and assembly process*

End-user programming is used not only to automate the process of "rib" creation, but also to lay them out in a format that can be interpreted by the Laser Cutter. The script labels the pieces both in the design model and in the cut sheet layouts (Figure 2.8), thus automating the laborious task of preparing assembling instructions. These "ribs" are then rearranged on a sheet, which has the same dimensions as the bed of the Laser cutter. The output size of the fabrication machine is again a limiting factor for the scale of the physical representation, which cannot be increased beyond the size of the biggest component fitting onto the Laser cutter bed.

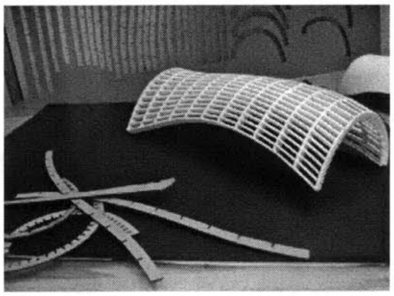


**Figure 2.9: Model showing rib components and assembled surface**

Once the layout was complete and the ribs were cut, they were assembled to fabricate the approximated NURBS surface. The tolerance value for the ribs was changed after a few initial tests. Defining the tolerance within the program was found most useful at this stage because as the parameter for the tolerance value was changed in the script, the connection details in the ribs would be updated automatically to accommodate the new tolerance values. Another important observation during the assembly process was the orientation of the ribs with respect to the labeling. Labeling helped identify and orient a piece, but it was still necessary to constantly refer to the digital model while re-assembling the physical sketch surface model (Figures 2.8, 2.9).

### *Results*

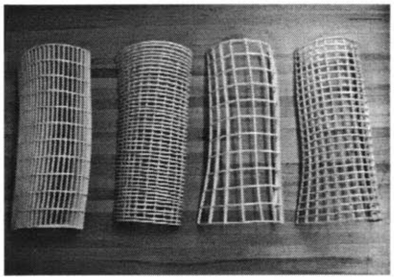


**Figure 2.10: Variations**

Variations: As mentioned earlier the ribs were programmed to follow the *UV* lines of the NURBS surface model. The density of the *UV* lines were changed by "re-building" the surface in the software. Thus by changing the density of the *UV* lines in the digital surface model, the density of the ribs was controlled programmatically (Figure 2.10).

Figure 2.11 shows a variation of the script, where the surface was "re-built" such that the distance between 2 consecutive contours in a chosen direction (lets say, *U* direction) was the same as the thickness of the material being used (in this case the chip board). Thus, there was no need for members in the other direction (in this case, the V direction). The script would now slice up the digital model into thin, horizontal layers. Eventually the entire model was fabricated by gluing together these ribs layer by layer. By adopting this methodology the digital solid model was turned into ribs that could be assembled together in a way that was very similar to the deposition printer, but in this case the layers were made out of the chip board and not the starch powder used by the deposition printer. This method is analogous to the software of the deposition printer that produces a very long sequence of instructions for the depositing pellets of the material, and then the fabrication machine executes these instructions one by one.

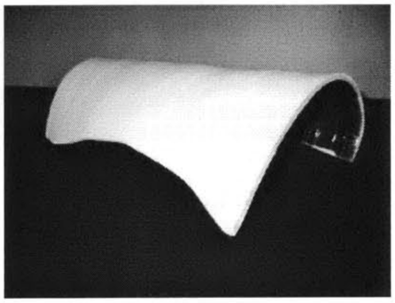


**Figure 2.11: NURBS surface generated by contouring**

### *Post-Script*

- Here the NURBS surfaces are approximated by following the isoparametric curves that define the NURBS surface, leading to "true" tectonic expression of the 3D surface. However, it would be very difficult to produce larger scale, actual building components, as they pose a challenge of fabricating doubly curved structural members and require precise positioning in the construction assembly. In the case of the above exploration, it was possible to bend and twist the chip board to follow the *U* and *V* isoparametric curves and to produce quick physical sketch models; but it would not be possible to do this with buildings at real scale, for example with materials like steel.

- For the same reason as mentioned above, it is possible to make sketch models for partially curved NURBS surfaces, where the isoparametric lines bend within the limits of the bending stiffness offered by the chip board or alternative material that is used, and hence cannot be applied for highly sculpted surfaces or complex topologies.

- A good understanding of surface properties, underlying algorithms mathematics of surfaces and knowledge of how the software creates the surfaces is very important. Such information is necessary to have access and control over the CAD model.

### *2.1.2 Approximating surfaces by Meshing/Triangulation*

This section describes an alternative way of rapid prototyping and manufacturing physical representations of surfaces using meshing/ triangulation as a production strategy to approximate them. By prototyping surfaces this way, physical models at various scales, including full scale building components, can be produced.

#### *Digital Representation of Surfaces – Tessellation, Triangulation and Surface Patches.*[xv]

Surface modeling systems represent curved surfaces internally by storing parameter values that are required to define them. These parameters are used in conjunction with appropriate mathematical formulae to generate accurate digital representations of surfaces as required.

An alternative approach is to approximate curved surfaces by small planer facets – just as a curved line can be approximated by small, straight segments. These facets are often triangular, since triangles are always planer, but facets of other shapes can be used as well. This technique proves to be adequate for many practical purposes and it simplifies computational tasks that a surface modeling system must perform. It is widely used in contexts where precise representation of surfaces is not critical.

Where a surface is approximated by a mesh of triangles, linear interpolation between the vertices of any triangle produces points that rest on the plane defined by its three points. If the surface is approximated by a mesh of quadrilaterals, however, the vertices of a given quadrilateral do not necessarily lie on the same plane. In this case, linear interpolation between them will produce a bilinear curved surface. Quadrilateral bilinear patches provide an alternative to triangular plane facets for representation of curved surfaces.

This experiment looks at how the technique of approximating surfaces by bilinear surface patches/ triangulation, primarily used by surface modeling systems for efficient visualization of surfaces, can be harnessed to produce physical sketch models of surfaces.

### *Precedent Examples*

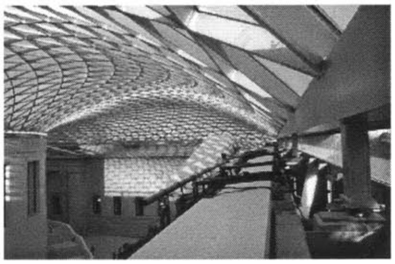


**Figure 2.12: Great Court, British Museum, London**

Tessellation of surfaces has been attempted by many architecture firms in recent years. Triangulation is the most commonly applied form of planner tessellation. The British Museum[xvi] (London) designed by Foster and Partners (engineers Buro Happold in collaboration with Chris Williams), is one of the most prominent examples of surface approximation by tessellation. It has a triangular framework consisting of 4,878 hollow rods and 1,566 connecter nodes, different from one other and fabricated with computer controlled fabrication. The final surface was then filled with 3312 glass panels. Another example of triangular tessellation is the glass roof of the DG Bank (Berlin, Germany) designed by Frank O Gehry and Associates (engineers for the glass roof Schlaich Bergeman and Partners). Here a triangulated space frame is constructed of solid stainless steel with star shaped node junctions, each milled using a 5 axis milling machine. The frame is infilled with about 1500 different glass panels. Other examples include the courtyard roofing for the Museum für Hamburgische Geschichte by von Gerkan, Marg und Partners[xvii] (engineers for the glass roof Schlaich Bergeman and Partners).

## *Experiment 2:*

Approximating Surfaces by meshing / triangulation

*Geometry* - *Coons patch*
*Material* - *Chip Board, High Density Foam*
*Fabrication Machine* - *Laser Cutter, Milling Machine*
*Generative Method* - *Auto Lisp/ AutoCAD*
*Production Strategy* - *Surface approximation*
*by triangulation and assembly*

### *Task*

The ambition of this exploration was to directly realize the meshing pattern used to represent surfaces in the computer model with the physical, so that representations at various scales, including full size building components, can be manufactured.

### *Methodology*

The idea of curved surface patches may be extended in various ways to provide curved surface representations. An obvious generalization of the bilinear patch, for example, is a patch bounded by four arbitrary curves. This type of patch, provides more precise control over slopes and is know as a coons patch[xviii]. This experiment harnesses the surface approximation technique of a coons patch for creating physical representations from wire frame models.

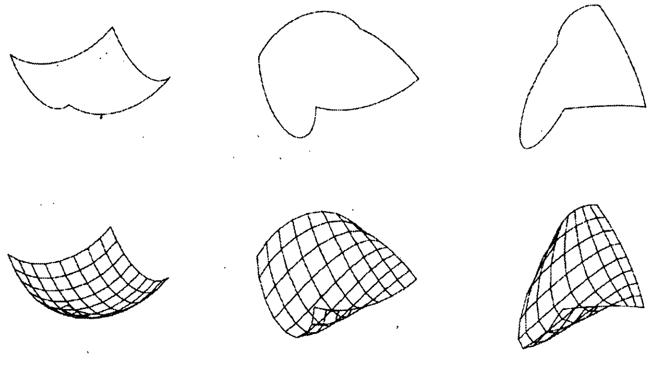
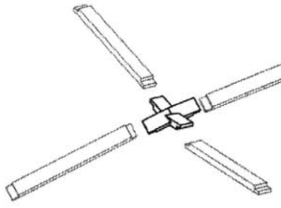
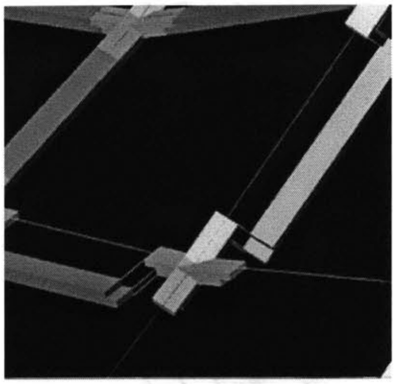

(a) (b) (c)

**Figure 2.13: Coons Patches;**

**(a) Edges of equal 2nd-order curves, vertices regular**
**(b) Edges of arbitrary 2nd-order curves, vertices regular**
**(c) Edges of arbitrary 2nd-order curves, vertices arbitrary**





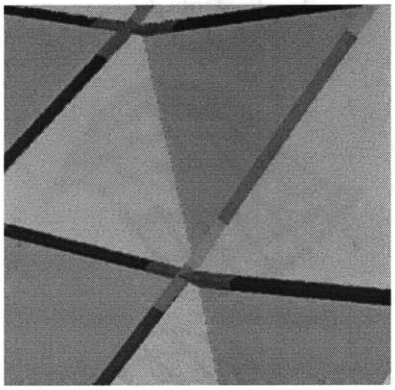


**Figure 2.14: Proposed node-bar system for the approximated Coons patch surface**

**Figure 2.15: Screenshots showing generating of members using scripting procedures**

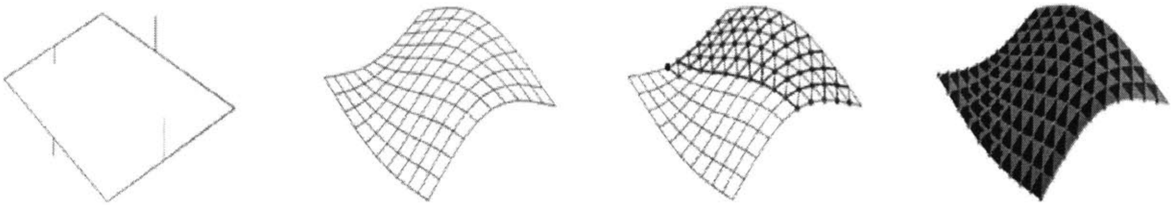
Figure 2.13 shows how the underlying algorithm of the surface modeling system, based on four bounded arcs defined by the user, generates a meshed surface. Each mesh module is a bilinear curved surface.

The node conditions of the meshed surface are analyzed first in this study. All node conditions are unique and have 4 component mesh members on different planes that intersect at the node. Interpolating the nodes with lines results in double curve members that cannot be fabricated using 2D fabrication machines. Therefore, each mesh member and associated nodes must be manufactured individually. Figure 2.14 shows a bar-joint junction detail (very similar to a tongue and groove joint) that is finalized for this exploration.

Each member and node junction in the surface patch is accessed line by line, point by point to create a 3D solid model and 2D profiles that are interpreted and manufactured by the fabrication machines. This is a very time consuming and laborious task.

It is also observed that each bar-joint junction detail requires the same underlying procedure for creating the geometry of the bars and joints, this could be defined by a point location of a node junction and four direction vectors in 3D Cartesian space, representing the directions of the mesh members intersecting at that node junction, thus giving the opportunity to script or program the 'bar-joint junction detail'.

This procedure is systematically defined and programmed into a script that creates a coons surface, using an existing procedure from



the CAD software, and extracts the information that is required, creating the 'bar-joint junction detail'. User input of various variables, like tolerances, thickness of material and number of mesh modules in X or Y or both directions, is required to instantiate the script. Running the script creates digital models for all joints and bars needed to fabricate the surface.

The frame of the meshed surface can be fabricated by assembling bars and the joints. However, the doubly curved surfaces, bounded by the four bars that constitute a module of the mesh, have to be covered with panels. Doubly curved panels cannot be fabricated by 2D fabrication devices. Therefore, these four sided modules are divided by lines that runs across the diagonal of the mesh module, sub-dividing the quadrilateral mesh module into two triangles. Now these triangular panels can be fabricated using the laser cutter (Figure 2.16).

The code is then re-programmed to triangulate all the panels, label them and lay them out flat on a sheet so that they could be interpreted and manufactured using the laser cutter (Figure 2.17).

Another challenging task is to physically assemble these components exactly like the digital model. Precise 3D locations for all nodes are required to do this. An interface to an excel spreadsheet is programmed for this. Running the script automatically creates a new excel spreadsheet, containing x, y, z coordinates for each node, with respect to the origin located at the bottom left corner of the surface (Figure 2.18).

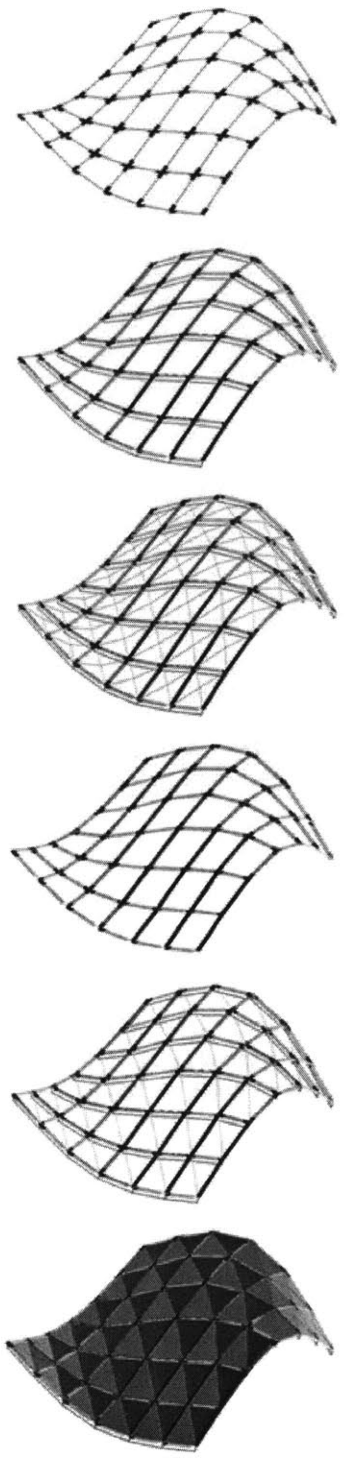


**Figure 2.16: Screenshots showing the generation of system components through scripting**

### *Results*

The following images show physical models of surface patches. Variations of this surface can be fabricated by altering the parameters of tessellation, where the surface tabulations in X or Y or both directions are changed (similar to the previous experiment).

Note: The node detail could be fine tuned and optimized as the design develops. Since the joint is generated parametrically, its definition could be re-programmed in script and appropriate changes would be updated at all node junctions.

### *Post Script*

- This is an effective way to make sketch models, however the user does not have control over the surface except for changing the spacing or density of the meshing. Here the meshing is created by the underlying algorithm of the surface modeling software. Similarly, other multi-sided tessellation patterns are also possible and are provided by many software packages, where the user can choose the tessellation pattern of their choice. However, as stated above, the user does not have much control over the algorithms besides changing the tessellation parameters and exploring various scenarios.

- Custom subdivision patterns, like those proposed by Frank Gehry's office (Dennis Sheldon), could be programmed whereby desired patterning is programmed instead of harnessing the underlying algorithm of the surface modeling software.

- Another strategy is to design the algorithm to generate the surface. For example, the British Museum roof, where the surface is analytically and mathematically defined, has a quadrilateral mesh of

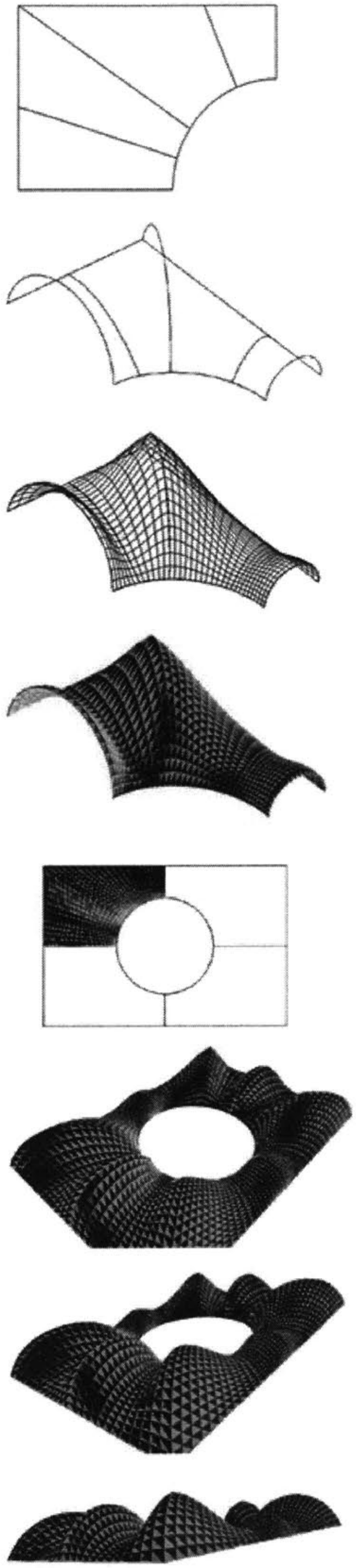


**Figure 2.19: Screenshots showing the mapping of a script to a wire frame**

the surface that is triangulated by selectively interpolating intersecting nodes in an aesthetically interesting way[xix].

- Other ways of triangulating, like projecting a two-dimensional triangular pattern on a surface using surface modeling systems, could also be adopted.

Regardless of the way triangulations or any other patterning is achieved, the above strategy is useful for making physical sketch models using Digital modeling with generative methods and fabrication machines.

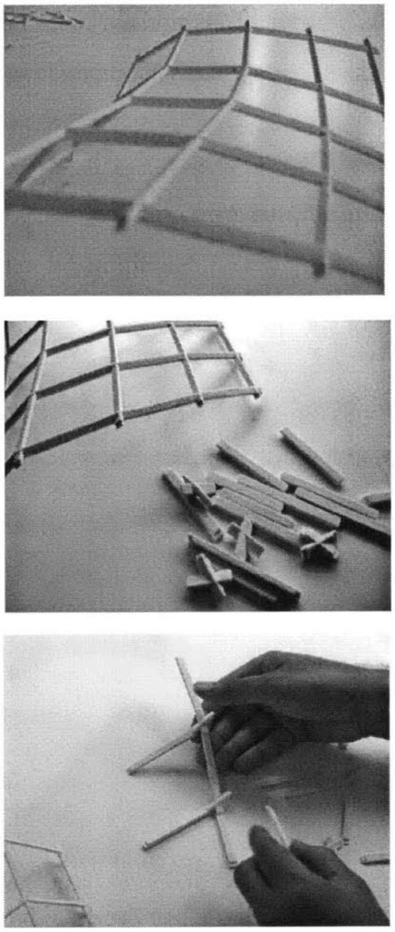


**Figure 2.20: Images showing physical models and assembly process**

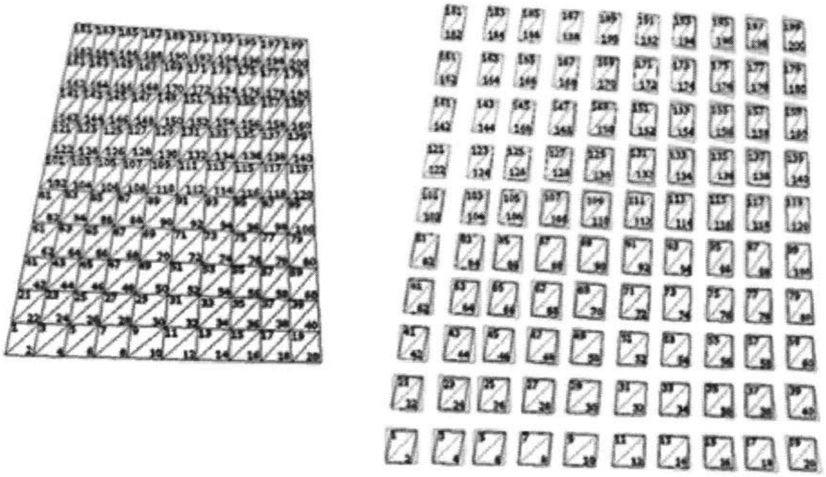


**Figure 2.17: Screenshot of cut sheet layout generated by scripting**

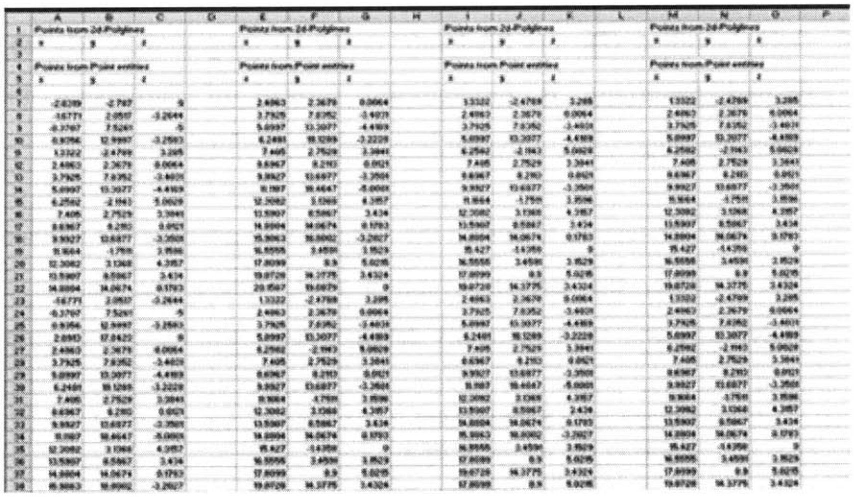


**Figure 2.18: Excel spreadsheet of clouds of point generated by scripting**

## 2.1.3 Approximation of translational surfaces

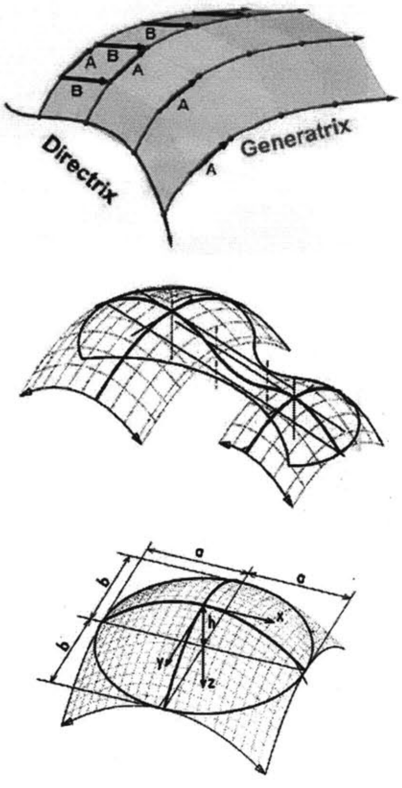


**Figure 2.21: Construction of a translation surface**

This exploration looks at how Digital modeling with 2D fabrication machines and end user programming are used to make sketch physical models with faceted approximation of translational surfaces. Programming is used to define the geometry and the CNC tool paths, so that approximated surfaces can be physically modeled at various scales.

### *What are Translational Surfaces*[xx]

Several projects discussed in the previous section show that free double curved surfaces can indeed be constructed with triangles, but unfortunately cannot achieve the cost effectiveness of construction made with rectangular glazing. Translational surfaces correspond to a vast variety of shapes that are made with identical, plane rectangular glazing. Such surfaces are designed with a geometrically smart technique that could allow construction of shapes by using plane quadrangular tiles.

If, for example, a curved line (approximated by small, straight segments) floats across another curved line (also approximated by small, straight segments) positioned perpendicularly to it, the resulting geometry can be covered with identical planar quadrilateral tiles to form an elliptical curvature layout (Figure 2.21). The first curved line is the generatrix and the second curved line is the directrix. Thus, a variety of surfaces can be formed with straight edges and can be constructed, which means that they could be individually supported. However, the directrix and generatrix do not have to necessarily consist of geometrically simple curves, but can be defined as random spatial curves, and thus present a vast variety of shapes.

### *Precedent Examples*

Many architectural firms have engaged in designing complex and provocative forms using faceted approximation of translational surfaces. For example, in some of their recent projects Foster and Partners have created complex geometries based on parameterized concatenated torus patches that blend into one another[xxi]. Frank O'Gehry and Associates have also developed similar approaches by overlaying pre-constrained parametrically defined surfaces on existing double curved surfaces that result in flat quadrilateral panel solutions to approximate curved surfaces.

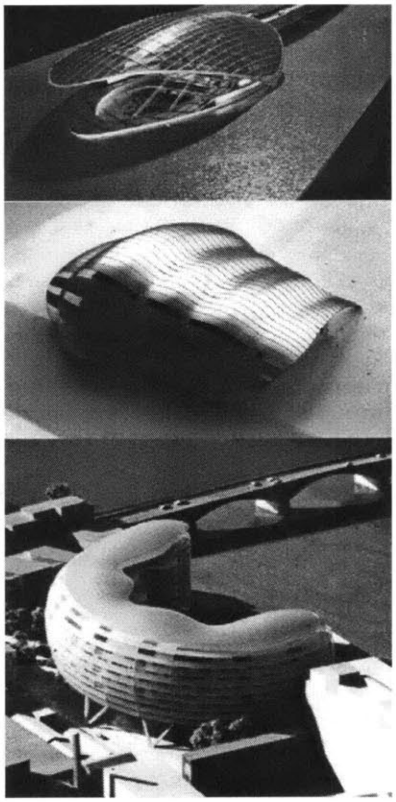


**Figure 2.22: Various projects constructed from translational surfaces, Architects Foster and Partners, London**

*Note:* The information of the various intersection nodes for such kinds of surfaces is often stored as a cloud of points in excel spreadsheets, for precise control of the geometry and for effectively communicating the geometry to various collaborators, engineers, fabricators, contractors etc. This idea of "making" physical models based on information of clouds of point in an excel spreadsheet, is also integrated, by programming an interface between Microsoft excel and the CAD software (in this case AutoCAD). Therefore, a kit of parts can be produced, based on the information provided in the excel spreadsheet, that could be assembled to fabricate the surface.

### *Experiment 3*

Rapid Manufacturing of Faceted Translational Surfaces

*Geometry* - *Translational Surfaces*
*Material* - *Chip Board*
*Fabrication Machine* - *Laser Cutter*
*Generative Method* - *Auto Lisp/ Auto CAD*
*Production Strategy* - *Surface approximation by Faceting and manufacturing by self assembly*

### *Task*

This exploration began with the idea to create physical scale representations of translational surfaces, analogous to the actual way building components are manufactured and assembled at full scale.

### *Methodology*

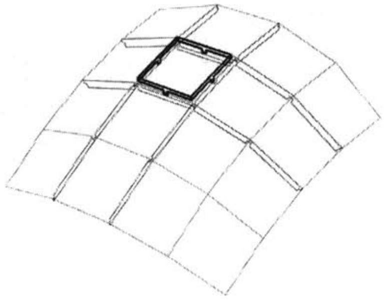


Figure 2.23: Proposed construction system with frames and plug-in panels

The geometry for faceted approximation of translational surfaces provides a clue for the digital making of these surfaces. The directrix and the generatrix are essential components required to define a translational surface and consist of curves approximated by straight lines that give a natural flat panel solution without any twists. Since these are always on the same plane, they can be substituted with the main frame members that can be laser cut. Also, since the directrix and generatrix are always perpendicular to one another, a straightforward self-assembly system can be adopted for the intersection conditions (Figure 2.23).

The challenge was to find how to make these wire-frame representations of translational surfaces into tangible physical models with a quick, inexpensive design process using generative programming and fabrication machines.

To generate the surface, an End-user program is written which requires an input of 2 arcs (representing the directrix and generatrix) and the number of facets that are desired along each arc. The translational surface geometry is defined from first principles by sweeping the generatrix along the directrix. The End-User Program generates flat quadrilateral tiles and nodal information for translational surfaces.

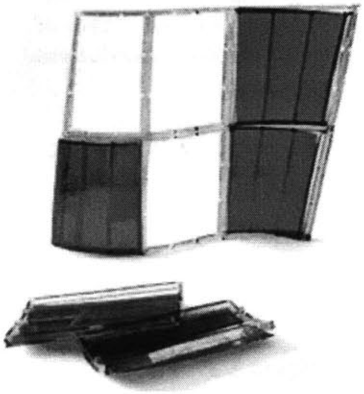


Figure 2.26: Physical model for construction system build using laser cutter

Once the geometry is created, a construction system is proposed with a main structural frame, an intermediate connecting frame and detachable panels. Figure 2.23 shows initial tests where the proposed system has 3 essential components: a main frame that support the structure of the surface, pre-fabricated plug-in panels and a sub-frame that connects the main frame to the plug in panels. These components are decomposed into a kit of parts that can be interpreted by the Laser cutter. This system is very similar to the cone exploration which has been discussed in section 2.2, however unlike the cone experiment where the panels are curved (and are slices of the original surface), the panels here are flat and approximate the translational surface.

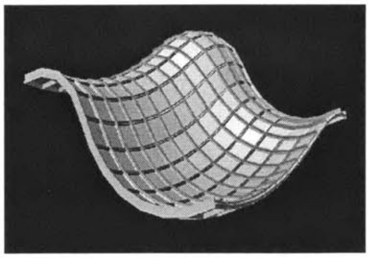


**Figure 2.25: Screenshot of translational surface script**

Having established a system of components, the next step was to identify the procedure for creating system components and batch-process it to generate all the components from the wire frame model of the translational surface. After carefully identifying and systematically laying out the various steps required for this procedure, the script is re-programmed to automate the generation of all the required system components (Figures 2.24, 2.25).

*Preparing assembling instructions and assembly process*

The script is re-programmed once again to label and layout the components in a format that is interpreted by the Laser Cutter.

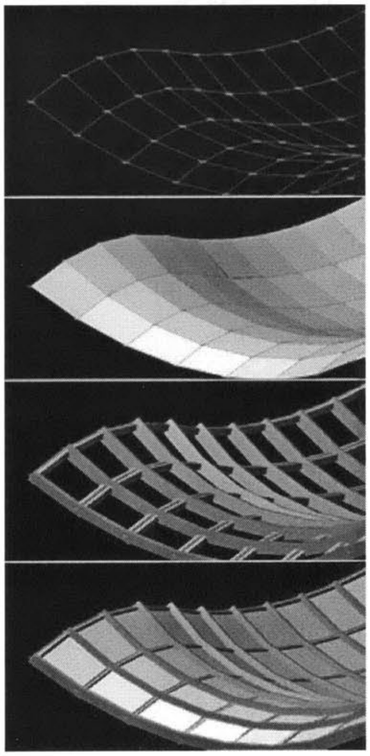


**Figure 2.24: Screenshots showing various stages of generation of translational surfaces**

Another important feature of this code is its interface with Microsoft Excel. Not only are the x, y, z coordinates of all intersection nodes saved as an excel sheet as explained in the previous section (often referred to as a point of clouds), but the code could directly understand and interpret the data from a Microsoft Excel spreadsheet. This two way interaction between the CAD software and Microsoft Excel makes it possible to import data from other software into the CAD software and get an output in the form of profiles a laser cutter can cut.

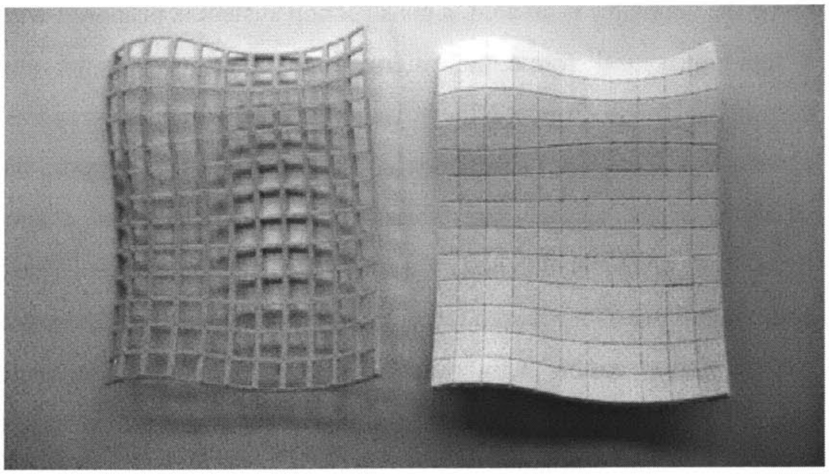


**Figure 2.27: Plaster models of translational surfaces generated by scripting**

### *Results*

Figure 2.27, shows images of the sketch models of faceted approximations for translational surfaces. It is noted that a similar system could be adopted for producing building components at full scale, with the main frame as the structural backbone and factory made plug-in panels that can be assembled on site.

### *Post script*

- This exploration demonstrates how direct computer programming of architectural geometry and CNC tool paths can enable "making" of a digital form and related treatment of material. In this exploration programming is also used to create the geometry. By creating the geometry programmatically, using the powerful engine of the underlying CAD software, the user has more control and access to the geometry.

- This exploration also demonstrates a digital based convergence of representation and production, where Fabrication machines are used to represent actual manufacturing methods and techniques.

## *2.2 Experiment – Integrated Design and Manufacturing Process*

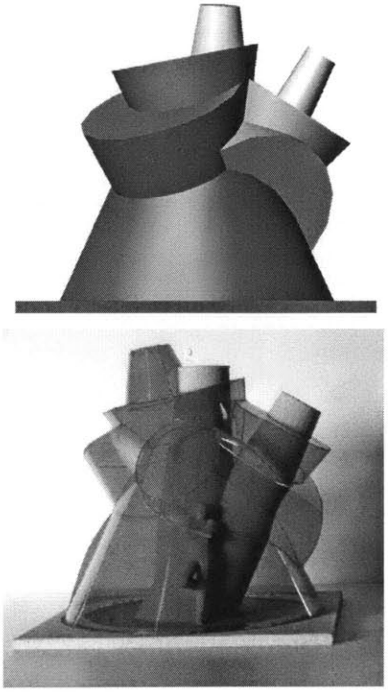


**Figure 2.28: Digital and physical models of abstract cone composition**

### *2.2.1 Task*

To test an alternative method for fabricating architecture using a combination of digital modeling and computer controlled fabrication machines, which involves an integrated design and manufacturing process, through the study of a single design case.

### *2.2.2 Methodology*

The methodology is divided into 3 phases. A design phase is first, where an abstract space is designed using an existing digital modeling platform. The design derivation phase is next, where the abstract space is resolved, such that it can constructed out of components. Finally, the third phase elaborates the design development procedure, such that the components are manufactured using CAD/CAM fabrication machines.

Each phase is associated with its own way of representing the design. These are: the design layout, the construction layout and the cut sheet layout. A design layout is a digital representation of the design with surface information; a construction layout is a digital representation of the design with manufacturable components; and a cut sheet layout is a digital representation of the design with the manufacturable components laid flat on a sheet, which is understood by the laser cutter (CAD/CAM fabrication machine being used).

#### *1. Design*

A set of CAD objects (tapered cones) and CAD operators (Boolean operations) were exploited to create an abstract composition (a set of intersecting tapered cones in this case). Cones were used in this

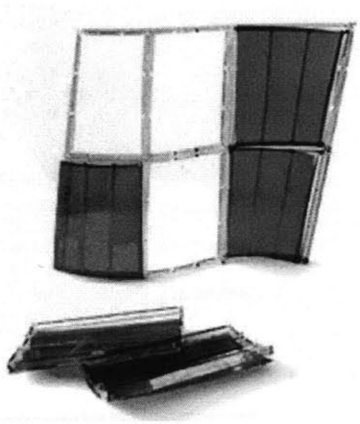


**Figure 2.29: Initial tests with system components for a small patch of a developable surface**

design exploration because their geometry consists of developable surfaces. These surfaces have curvature in one direction only, which allows the use of paper in their physical representation.

## 2. *Derivation Process*

The derivation process is defined as a process by which the design layout for a given geometrical composition is resolved into a construction layout. This process has many key issues relating to the integration of digital modeling with the output required by computer controlled fabrication machines, which revolve around being able to decompose a design scheme into component parts that could be manufactured and assembled. Described below are the various steps taken in the derivation process of the cone exploration.

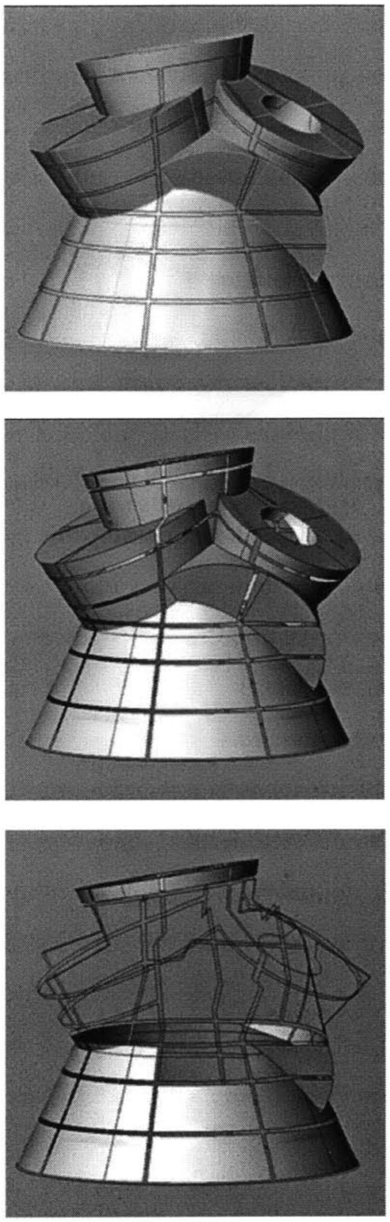
### *Establishing a system of components*

The first task in the derivation process is to define the various components required to manufacture a developable surface. A construction system is designed such that there are two essential components; the basic supporting framework and detachable panels that can be plugged onto the supporting framework. An intermediate sub-frame is introduced as a connecting element between the main supporting framework and the prefabricated panels, such that the panels could be plugged on to the supporting framework via the sub-frame. This construction system is similar to the panel system that was adopted for the Stata center at the Massachusetts Institute of Technology, designed by Frank Gehry and Associates.

### *Resolution of the construction system for the geometrical composition.*

The next task is to map the construction system onto the design layout of the cone composition. The cone composition has many complex intersecting conditions. It is difficult to fabricate and manufacture a supporting structure along these intersections using the proposed construction system, which relies on the use of 2D cutting devices for manufacturing components. The form is decomposed such that all intersecting conditions are a part of the panels and the supporting framework is intentionally located in such a fashion that the intersecting cone conditions are avoided. The following steps describe how developable surfaces of the cone composition are sliced into smaller surfaces: 1) Owing to the radial nature of the composition, a cookie cutter method for slicing the design scheme into 8 vertical sections through the center of the base cone is adopted; 2) The next step is to create horizontal sections which are proportional to the vertical sections; 3) A cookie cutting methodology for horizontal sections does not give acceptable results as they are very close to the intersection cone conditions and cut the cone base (in this case the ceiling) in an aesthetically unacceptable way; 4) Various options are tested to establish a set of rules for the location of the supporting framework in the cone composition, for example, a supporting frame at a particular offset distance from the base of every cone; supporting frame lines were intentionally generated to pass through intersection points of other supporting frames and the vertical frame to form a continues ring. (Refer to figure 2.30)

The process of sub-dividing the original surface into small surfaces requires constant input from the designers and cannot be automated.



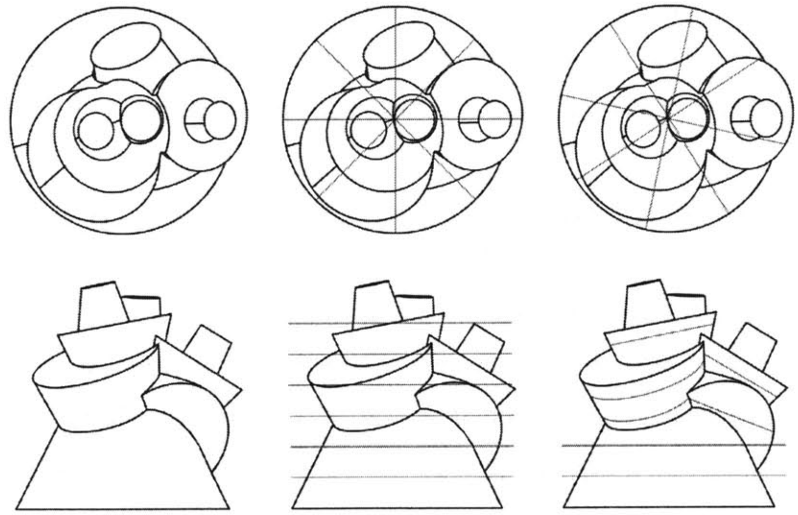


**Figure 2.30: Strategies adopted for slicing the overall composition into smaller surface patches**

After the basic division of the various smaller surfaces is finalized in the cone composition, a supporting structural framework is designed. This is done by offsetting the surface profiles. Today CAD software makes it possible to offset surfaces and extract surface information accurately, making it easier to manufacture and fabricate curved surfaces. A combination of CAD objects and operators (Boolean operations) are used to generate all the system components for the cone composition.

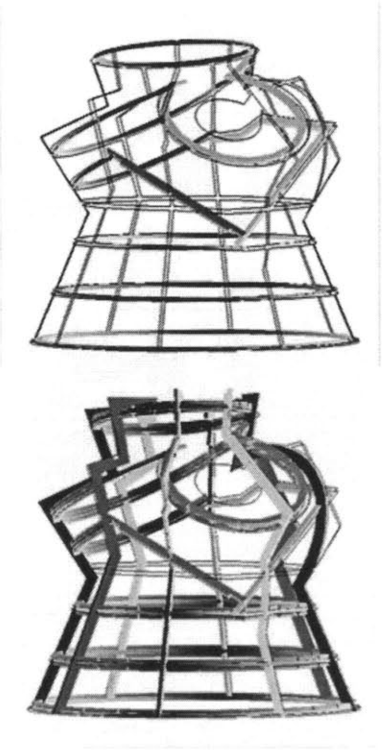


**Figure 2.31: Digital derivation of system components based on the wire frame model**

The use of physical models early in the design process was found to be particularly useful. Each generation of CAD model led to the next physical model, which led to further changes in the CAD model, until an acceptable dividing strategy was achieved. Here 3D CAD modeling and corresponding physical models helped the development of the design. This method was particularly useful for optimizing and fine tuning the design, such as in resolving joint details, Figure 2.32 describes a condition where supporting frames at different 3d planes meet. Initially a 3D milled joint (analogous to 5–axis milling at real scale) was proposed. Later the supporting framework was modified by sliding/displacing components, such that there was minimal effect on the overall appearance, and the expensive milling process was avoided. It can be argued that such a change would at some point be proposed by the engineers and the fabricators, but if this level of detail and understanding of the manufacturing process was handled by the designers at an earlier stage, it could reduce a lot of the back and forth movement and streamlining of the over all design and manufacturing process.

**Figure 2.32: Optimization of joints**

Having established a supporting framework, the next task is to make the panels that plug-into the supporting framework via the sub-frame. The sub-frames are derived from the supporting frame by a series of Boolean operations. There are about 72 different panels and each panel has to be sliced from the surface model. Each panel frame is derived from the end condition of the sub-frame and the corresponding edge condition of the sliced surface model.

## *3. CAD/CAM fabrication Machines*

The description of the components derived from the surface information is altered for interpretation by the Laser Cutter. For this purpose a construction layout consisting of 2D profiles is created by extracting from the 3D components of the construction model. Each system component is bar-coded and marked with the nodes of intersection with the adjacent layers of structure. There are 279 different system components for this design case.

### *Assembly Process*

The assembly process for the cone composition evolved with each new physical model. Many aspects, like the size and shape of individual components, sequence of assembly and unforeseen problems were encountered when simulating the assembly process. It was also observed that it was not possible to assemble components in a random way; a particular sequence of assembly was required.

Another important observation during the assembly process was the issue of tolerance. Due to errors in exacting the digital and physical components, tolerances developed and sometimes made it impossible to proceed with the assembly. Simulating the assembly process helped in the assignment of appropriate tolerances at appropriate locations.

The time and effort put in during early stages of design development proved to be very beneficial as the design evolved. No errors were encountered while assembling the system components for the final model. It is delighting to see that all component parts and unrolled surfaces manufactured by the rapid prototyping and CAD/CAM fabrication machines, assembled very accurately to fabricate the original form. All the pieces fit together exactly as the 3D digital

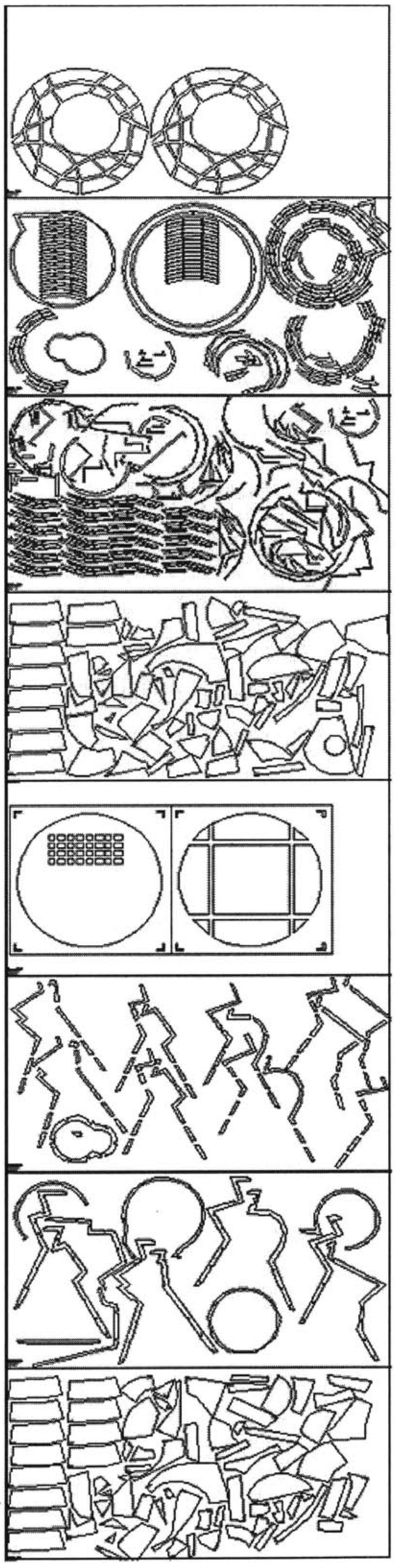


**Figure 2.33: Cut sheet layouts**

model. These components could therefore be manufactured and assembled at larger scales using NC devices (like the water jet cutter or the plasma cutter etc.).

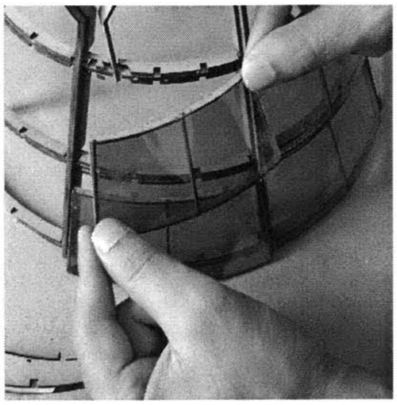


**Figure 2.34: Design for manufacturability**

### *2.2.3 Results*

The above example demonstrates how a combination of digital modeling with computer-controlled fabrication can be used for simulating CAD/CAM design and manufacturing processes in studios.

### *2.2.4 Post Script*

- Design for Manufacturability and Design for Assembly are very time consuming and elaborate processes. In this design exercise, the final form was frozen and the above methodology was adopted for manufacturing and assembling the cone composition. It is not possible to changes variables (like scale, tolerance values etc.) of the design without reconstructing the components from scratch. If the geometry is modeled parametrically instead of explicitly from the beginning, it could have both long term and short term benefits. Given these features, relationships like general/specific, conception/ fabrication data or large scale / local scale all become possible entryways into the process of design, at any given stage.

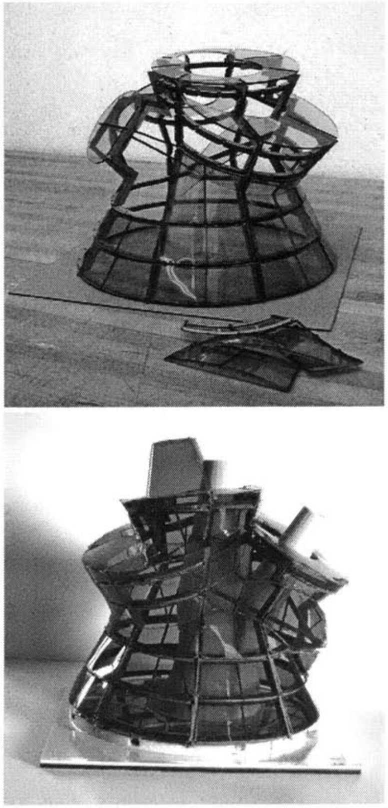


**Figure 2.36: Integrated design and manufacturing process**

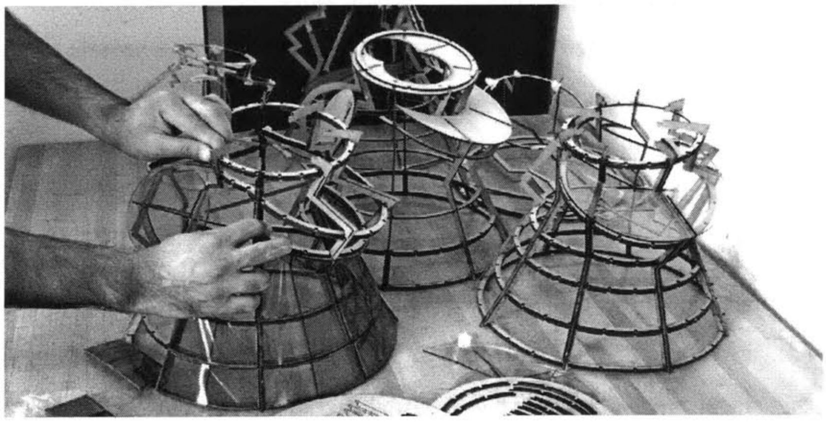


**Figure 2.35: Embedding computer controlled fabrication into the iterative design process**

- For this particular design case the computer controlled fabrication machine uses the same tool path as the CAD software. It is necessary to know the limitations and possibilities of machines while designing the components. Therefore, the aim is to select the machines needed to produce a component or vice versa. Integrated CAD/CAM products and software packages used by other design related fields like aerospace, automobile, industrial and furniture design, offer a wide set of design and manufacturing tools which share the same user interfaces and associative database. Such environments for integrated design and manufacturing for architects would help eliminate errors that might occur while transferring information.

- The use of different materials such as chip board and Plexiglas for the system components suggests different assembly processes (chip board is a little flexible, Plexiglas is brittle) and tolerances (e.g. plexi needs much more tolerance than chip board). Handling and experimenting with the actual materials which would be used to manufacture and fabricate forms at real scale could be very useful at earlier stages of design.

- Making the panels is a very time consuming and repetitive task. Computer controlled fabrication opens up the possibility for manufacturing components that are the same as well as components that are different, for example creating all the different panels in the above composition. However, generating the different components is a very time consuming task. To fully exploit the potential of computer controlled fabrication, the process of creating various components needs to be automated. A good example of such automation is the pre-fabricated panel layout for the Stata center at MIT (Architect Frank o' Gehry and Associates) by Zahner's shop. In this case fabrication of panel components is automated. Zahner's automated panel layout program (ZAPLA) uses scripted procedures

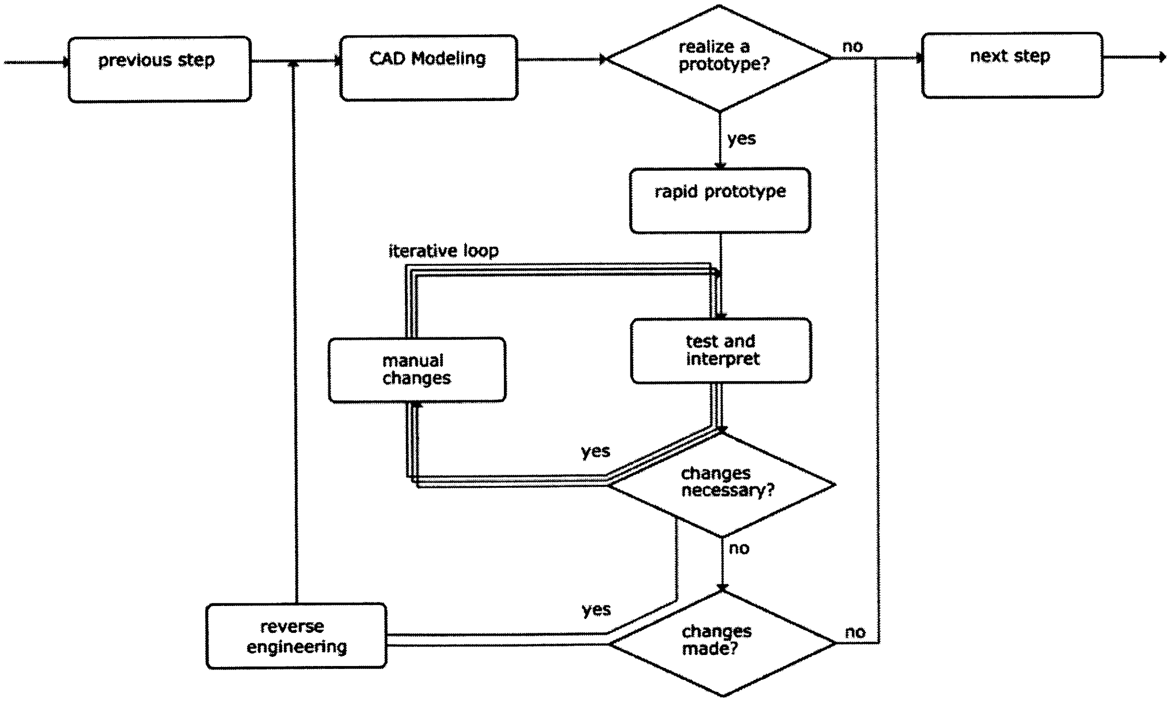
**Figure 2.37: Stata Center, MIT**

to generate panel component geometry from the surface model and face sheet boundary information[xxii].

### *Integrated Design and Manufacturing Process*

This case design exploration demonstrates the advantages of integrating digital modeling and computer controlled fabrication machines into a verification chain. The use of these technologies supports parallel adjustments of work processes. An immediate availability of prototypes represents a modern tool that can increase learning and improve the decision-making process considerably. The integration of these technologies into a verification chain results in a summing of individual advantages. Tests can be performed more quickly. Information is also fed back earlier and more accurately than using traditional development procedures.

**Figure 2.38: Iterative design process**



The accuracy and efficiency of computer-controlled fabrication in architecture offers numerous advantages as a design supporting tool. The main advantages are:

- To make prototypes for design evaluation
- Prototyping for functional tests
- Prototyping for manufacturing
- Prototyping for testing assembly sequence

## 2.3 Digital Design Fabrication Workshops

### 2.3.1 Context

The Digital Design Fabrication workshops were two consecutive workshops at the Massachusetts Institute of Technology that focused on integrating fabrication tools into the architectural design process through the use of design computing with rapid prototyping machines and knowledge of CAD/CAM operations. Larry Sass and Carlos Barrios were the instructors for these workshops. Jennifer Seely and I were the research assistants. My role as a research assistant included a pedagogical aspect that involved me in the entire process of student learning, from the foundational background of ideas related to the workshop to hands-on exercises. Through interactive discussions and review sessions, as well as instructions and assistance in using digital tools, I was offered the opportunity to engage students on a number of levels. During the course of both workshops, a strong community of learning and research developed among all participants — students, research assistants and instructors.

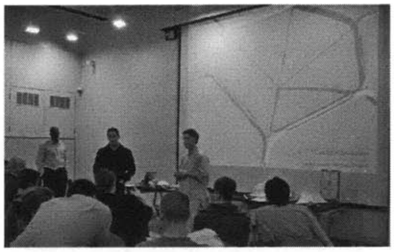


**Figure 2.39:** ***Digital Design Fabrication Workshop*** **at MIT (Spring 2004)**

The first workshop (Fall 2003) laid the foundation for CAD/CAM theory, methods and processes in architecture through a series of lectures, and tutorial sessions introduced students to various computational platforms for digital representation (AutoCAD, Rhinoceros, CATIA) and informed students about various fabrication processes with the opportunity to work directly with six different fabrication machines (two-dimensional fabrication processes with the laser cutter, paper cutter and water jet; subtractive fabrication processes with three-axis milling machine, and additive fabrication processes with three-dimensional deposition printer and FDM).

To encourage students to apply what they had learned in lectures and tutorial sessions, a series of ten short exercises were assigned through the course of the semester.

The second workshop in the following semester (Spring 2004) applied the theories and methods learned in the first workshop to larger scale projects, focusing on process and application to solve real world fabrication problems. The purpose was to serve as an intermediate step towards the use of fabrication tools in studio. This workshop also introduced students to the concepts of parametric design and gave extensive training in CATIA, which is a computational platform for digital representation with a parametric modeling environment. Such platforms are used by the aerospace and automobile industries to engage in integrated design-manufacturing processes.

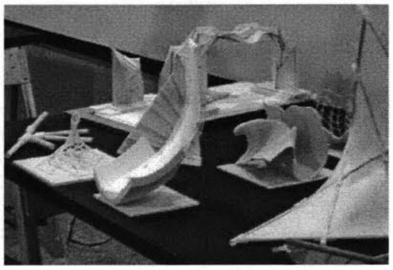


**Figure 2.40: Student models *Digital Design Fabrication Workshop* at MIT (Spring 2004)**

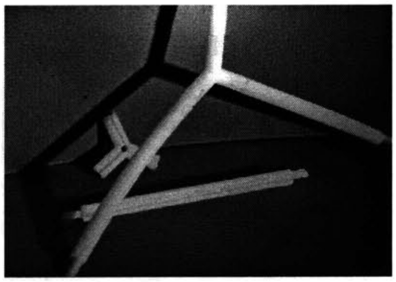
The students were given the opportunity to specialize independently or in pairs by exploring an integrated design and manufacturing process through the use of computer-controlled fabrication machines and digital representation platforms of their choice.

During this workshop I was able to directly observe and analyze the work of ten students who had chosen different methods and machines in various contexts and to learn from the approaches they adopted. Based on the class discussions and interviews conducted individually with the students, I better understood how the digital could be harnessed for 'making' architecture and the relationship between design computing, rapid prototyping and CAD/CAM machines.

The following section briefly highlights some of the experiences of the students through the course of the workshop.

## 2.3.2 Discussion

As observed by Larry Sass, "working with a new machine is like working with new software. You have to learn how to use the software first, only then can you fully potentials by considering the particularities of the fabrication machine. Working with the machines not only exposed their inherent exploit its potentials". It is interesting to observe how the students in the workshop began to craft their design ideas using fabrication machines. They soon acquired an eye and mind coordination of thinking through the design process and exploring limitations, but also gave students the confidence of using the machines in an exploratory way.



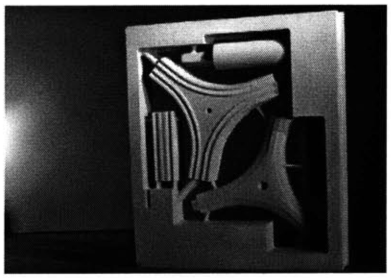


**Figure 2.41: Student models of joined details fabricated with StrataSys. FDM machine [above image] and Roland milling machine [lower image]**

*Workshop student*

> *"The milling machine works like a sculptor carving stone, except that the machine is both the hand and the too once you work with the machine you know what is possible to make and what is not, you start thinking like the machine."*

Another issue that immediately became clear as students started 'making' architecture with the fabrication machines was the need to work with different scales. Students explored designs at various scales, including full scale building components. Fabrication machines were used for making prototypes for; 1. design evaluation, 2. design of manufacturability, 3. design of assembly, and 4. for functional testing. An immediate availability of prototypes improved both the learning and decision making process. The use of fabrication machines supported parallel adjustments of work.

*Workshop student*

> *"I cannot understand anything on the computer; there are so many lines. The geometry is so complicated - it is very confusing, I need*

> *to 3D print the model so that I can understand what is happening only then can I explain it to others."*

With a strong foundation in the theories, methods and processes of CAD/CAM, the students started to relate these to studio design activities and processes. They harnessed the potential of 'making' architecture with computer controlled fabrication machines to simulate full scale CAD/CAM design and construction processes in studio.

> *Workshop student*
>
> *"Assembling the model is a challenging task in itself; matching the digital parts and machine cut parts is very difficult. I never realized this when I made the assembly models on the computer screen; it changes the way you think. "*

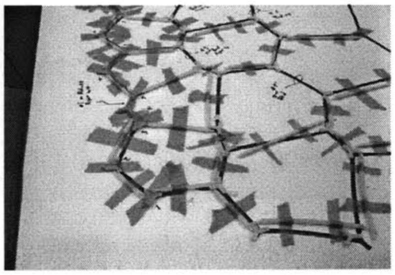


**Figure 2.42: Assembly process**

Having a solid understanding of different kinds of geometry and digital modeling methods (both explicit and generative), the students generated digital representations of assemblies and manufacture them using computer controlled fabrication machines. As opposed to creating models for rendering/visualizations, for the first time students created solid models in digital representation platforms for the purpose of 'making'. It was interesting to observe how the students soon realized that assembling these system components exactly like the digital model was equally challenging.

*Learning through experience*

> *Workshop student*
>
> *"Tolerance is an issue associated to all the machines and can most accurately be accounted for through experience."*
>
> *Workshop student*

> *"Working with machines helps us estimate the time that would be required for full scale CAD/CAM processes. One has to plan everything ahead of time."*

It is observed that parametric modeling is particularly useful for modeling complex building forms; however, their successful application requires careful articulation and a clear strategy of tectonic resolution such that sufficient clear interdependencies can be achieved. In other words, a well-defined strategy is essential for the effective application of parametric modeling. The user has to know exactly what he wants to do before starting the parametric model, making the "design process appear the enemy of intuition."[xxiii]

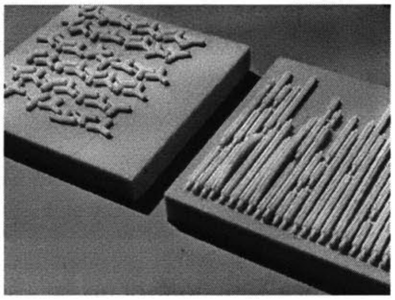


**Figure 2.43: Physical models of various system components modeled parametrically and fabricated using StrataSys. FDM machine**

*Workshop student*

> *"It is difficult to manipulate digitally generated objects. Even the simplest operations such as putting two objects together in some specific way can get very complicated because one has to explicitly instruct the machine in what to do. This presents two problems: firstly, one is forced into "designing" in a linear way; since it is often impossible to go back and change object properties. Secondly, one has to know a lot of design of details before actually "designing"- i.e. before constructing the details digitally."*

*Workshop student*

> *"It is very difficult to make a parametric model, you have to know exactly what you want, but once you know what you want it is a very useful tool. There were 64 different joints in our design; once I made a power copy for 2 joints I could generate all 64 joints"*

End-user programming was used by some workshop students for creating three dimensional geometry and CNC tool paths. By adopting this approach, the geometry and the tool paths were first described programmatically, and based on this description, three-dimensional geometry was created. Descriptive geometry is not a new concept in computation. In fact, before commercial software was available for creating and manipulating three dimensional forms, programmers created three dimensional forms by programming the description of the form. It is observed that programming and related concepts can give a better understanding of three-dimensional forms; however it is very difficult to directly start programming the description of the geometry. A mixed approach of working with hand and abstractly by a computer algorithm is found helpful. It is observed that the students who chose to adopt this methodology first made hand models and then translated their procedure into computer code.

> *Workshop student*
>
> *"Clearly when the complexity of an assembly's design grows, the difficulties encountered during the physical assembly grow. This fact is equally true for full-scale load bearing construction assembly as for its scaled rapid-prototyped counterpart. With this in mind, the management of the 'bits', the methodology of organization and tracking of all the parts within the assembly, may be the most difficult and tedious task. It may be here where a well-thought out script would offer the greatest benefit to realizing the promise of prototyping actually being 'rapid'. "*

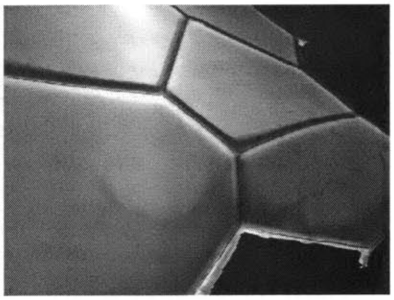


**Figure 2.44: Student model fabricated using StartaSys. FDA machines and latex sheets to approximate non-planar surfaces**

Several students attempted to make designs using materials like fabric, latex, plastic sheets, etc. The translation of a digital project into the physical realm heavily relied upon the considerations of the specific materials properties, laws of physics and effects of time. Parameters of materials properties, physical forces and fabrication processes were embedded into the digital modeling software such that a rapid feedback during the design development stages was achieved. One of the biggest limitations of exploring designs with fabrication machines was that the materials and processes (in particular additive fabrication processes) were not translated into reality. Conversely, the behavior of real materials were not easily computed.

> *Workshop Student*
>
> *"I cannot make any changes once I 3D-print the design. If I want to make any changes I have to 3D-print the design again; I'd rather sculpt the form I want with clay or foam board which I can manipulate for a more rapid feedback during initial design stages."*

Representations in architecture are required for both visualization and design development. Architectural models are also important for their contribution in re-representation, which facilitates analytical and creative thinking during the design process. This is traditionally done by altering or modifying models once they are created. Models produced by Rapid Prototyping using additive fabrication techniques aid three-dimensional visualization, not the design process. Unlike cardboard models that are assembled from parts and are assembled or disassembled into different parts by tearing or gluing, models produced by such techniques are fixed in form and fragile in material. Furthermore, it must be noted that sometimes models are to be made for geometrical or structural optimization. It is not possible to make such models using materials like starch powder.

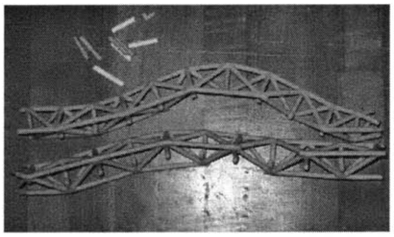


**Figure 2.45: Student model that broke during assembly**

> *Workshop student*
>
> *"The models that were created with these tools succeeded at providing visual explanations, but were too fragile and weak to simulate any supportive structural considerations. To create a physical model that structurally performs similar to a full size model is difficult and very often unfeasible. Perhaps it could be interesting to actually analyze the material strength of the models produced by each machine so that relationship could also be factored into the scale."*

### *Working with Computer Controlled Fabrication Machines*

*Workshop student*

> *"Sometimes knowledge of how something is produced via available manufacturing methodologies limits the imagination and prevents innovation."*

*Workshop student*

> *"The knowledge of how a rapid prototyping device works can paint one into a mental corner. A student understands how something is to be made via the FDM printer or Z-Corp, and then post-rationalizes a production process that allows the full scale realizations to have the same properties of geometry, assembly and homogeneity as the Z-Corp produced."*

*Workshop student*

> *"At the smaller scale, one is able to study assembly in terms of the form it creates, the relationship between parts, and the aligning of geometries from the digital to real. This method has faults with a small scale though, in that it only works for a 'model' where the function of the design may be depicted by the assembly method allowable at the scale of study (i.e. stacking if there are no mechanical fasteners due to a small scale)."*

*Workshop student*

> *" I have to sometime wait for 16-20 hours to get a 3D print of a simple variation in the design, and many time it does not print right, so I have to send the print twice or sometimes even three times; 3D printing is very time consuming."*

My association with the class further revealed the opportunities and limitations of computer-controlled fabrication and its application in architecture. These exploratory workshops allowed me to observe the multiplicity of methodologies the students adopted and helped me develop a broad overview of ways to integrate computer-controlled fabrication into the architectural design process.

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[x] Calicott, N., *Computer-Aided Manufacture in Architecture, the Pursuit of Novelty*, Architectural Press, Oxford, 2001

[xi] Thomas Modeen, *CADCAMing: The Use of Rapid Prototyping for the Conceptualization and Fabrication of Architecture*, eCAADe21 Digital Design

[xii] This experiment has been done in collaboration with Stylianos Dritsas as a part of *Parametric and Generative Tools for Design Development and Fabrication Workshop* at MIT, Spring 2003

[xiii] For further information on NURBS surfaces, refer to William J. Mitchell, Malcolm McCullough, *Digital Design Media*, p 195

[xiv] For further details, refer to Branko Kolarevic, *Architecture in the Digital Age, Design and Manufacturing*, p 15

[xv] William J. Mitchell, Malcolm McCullough, *Digital Design Media*, p 191

[xvi] Chris J. K. Williams, *The Analytic and Numerical Definition of the Geometry of the British Museum Great Court Roof*

[xvii] Sophia and Stefan Behling, *Glass; Structure and Technonoly in Architecture*, p 70

[xviii] William J. Mitchell, Malcolm McCullough, *Digital Design Media*, p 193

[xix] Chris J. K. Williams, *The Analytical and Numerical Definition of the Geometry of the British Museum Great Court Roof*

[xx] Sophia and Stefan Behling, *Glass; Structure and Technology in Architecture*, p 72

[xxi] Hugh Whitehead, *Laws of Form, in Architecture in the Digital Age, Design and Manufacturing*, p 83

[xxii] For further information, refer to Dennis R. Shelden, *Digital Surface Representation and the Constructability of Gehry's Architecture*

[xxiii] Mark Burry, *Between Intuition and Process: Parametric Design and Rapid Prototyping*, in *Architecture in the Digital Age, Design and Manufacturing*, Branko Kolarevic

# Chapter 3

## *Digital Making of Architecture*

The use of CAD/CAM is a relatively recent phenomenon in the field of Architecture. Today both architectural practices and schools of architecture have started to incorporate cutting edge digital production tools and equipment as an integral part of their facilities, challenging the potential of the digital for the "making" of architecture.

As observed by Bill Mitchell[xxiv], "CAD/CAM design and construction processes require three types of intellectual investment". First - investment "in creating or acquiring code that establishes a design world of exploration". Second - "investment in deriving a digital model through the application of this code". Third - investment in "the design development for a particular CAD/CAM fabrication machine and the conversion of a digital model into a sequence of instructions for that machine". Explorations in Chapter 2 establish a methodology for integrating digital making into design exploration using sophisticated software, complex derivation processes of system components from geometrical configurations and CAD/CAM fabrication machines. Extending this, Chapter 3 examines the underlying issues related to Digital Making and suggests a procedure for integrating it into design exploration.

## 3.1 Production Strategies for Digital Making

Production strategies[xxv] are strategies that enable the production of geometrical configurations from digital representations using fabrication machines. Triangulation, contouring, faceting and the use of developable surfaces are different examples of production strategies. The challenge is to choose an appropriate geometric approximation that will preserve the essential qualities of the initial three-dimensional geometrical configuration. Experiments in Chapter 2 demonstrate how different production strategies are adopted for the digital making of various surfaces.

## 3.2 Design Rationalization

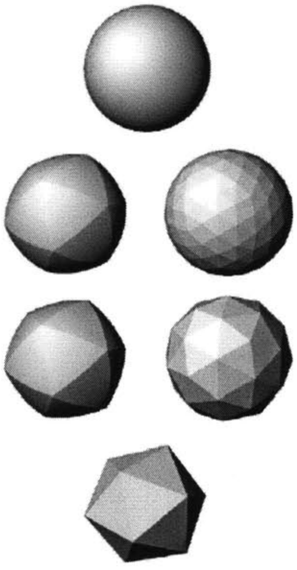

**Figure 3.1: Rationalization of a sphere**

"Rationalization is the resolution of rules of constructability into project geometry."[xxvi] It can be understood as the application of a production strategy to produce a constructible design for a given geometrical configuration. There are two broad approaches for developing constructible design through computational representations – the pre-rational and post-rational approach. A pre-rational system is a system in which "the construction system is defined before the design process happens."[xxvii] Here, the creation of geometry is constrained to happen within the limits of what is constructible under the adopted system. This system is extremely well controlled but can impose conceptual limitations. For example, in the faceted approximation of translational surfaces experiment (Chapter 2), the surface is programmatically created such that all the facets are quadrilateral and flat, and hence can be manufactured using two-dimensional fabrication devices. In a post rationale approach for digital making, "the design is conceived in a process that is for the most part divorced from considerations about construction."[xxviii] It is observed that adopting this system has several cost implications and often compromises are made to conform to a systematic means of construction. For example, in the cone experiment the construction system is designed after designing the geometrical composition.

## *3.3 Parametrics, Generative Methods and Automation*

For the digital making of a particular geometrical configuration, a detailed description of geometry is needed. A substantial operator effort is required in developing a system of elements, based on this detailed description. Furthermore, if digital making is to be integrated with the iterative design process, this operator effort grows exponentially. It is this operator effort that is the enemy of digital making and needs to be automated.

It is noted in the above explorations that in spite of the fact that every component is unique, several repetitive geometric operations are required for instantiating the description of these components. For instance, in the NURBS approximation exploration, the description of the NURBS surface, the mathematically defined contours (isoparm curves) are accessed one by one to create a supporting framework of ribs. This is the shortest possible way by which complex NURBS surfaces can be defined and coded as templates, with parameter values that can be expanded into explicit instances. Programming is used to automate the process of extracting the information required to define each rib from the underlying geometry of the NURBS surface. Thus, a repetitive geometry generation task is automated by procedural CAD modeling scripts. Similarly, in the triangulation exploration, the shortest possible way of defining complex surfaces is by parametrically describing the junction-nodes and connecting-bars. These components are modeled (parametrically) such that they can reconfigure to accommodate changes in explicit variables (parameters that are pre-defined while defining the code). Here programming is used for both generating the surface and extracting the information that is required to define the junctions and bars by accessing the underlying algorithm by which the surface is generated in the CAD system.

It is interesting to compare these two with the translational surface exploration, where the procedure for creating the surface is described programmatically. Thus, the geometry is intelligently created with an inbuilt flat panel solution; it is this internal elegance of the code that both creates the information and then extracts it, in the form of explicit parameters that are required to define the ribs of the translational surface. By adopting this method of designing the way in which the surface is created, like the CAD or software system, the designer has both more control and opportunity to design.

Procedural or scripted automation provides an element of modeling efficiency. The geometric scripts and any associated manual interactions can be re-applied on the same geometry, or any modified geometry, by changing certain explicit variables. For example, the number of isoparm curves in *U* and *V* directions are defined as explicit variables that can be controlled by the user in the NURBS experiment (Chapter 2).

Thus, repetitive operations, carefully abstracted to display the essential parameters to the designer in a well designed user interface and integrated into a well crafted script, simplify the designer's task and make it possible for him/her to entertain a much wider variety of possible explorations than would otherwise be possible.

## *3.4 Dimensional Tolerances*

Computer controlled fabrication makes it possible to manufacture system components with far greater accuracy than traditional model making techniques. It is difficult to generalize the exact tolerance values of machining, as it differs for various fabrication machines and their settings. For example, a laser cutter would have a different machining tolerance value for Plexiglas that is 1/16'' and 1/8'' thick because the power level required to cut through the material is different. Even though, very accurate CNC components could be fabricated directly from their digital representations, these CNC components still require assembly through traditional manual techniques.

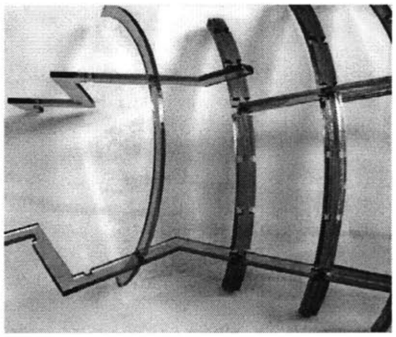

**Figure 3.2: Broken Plexiglas model due to tolerance failure**

These accurate representations would be of little advantage (in fact more of a disadvantage) unless these components are accurately positioned exactly as in the digital model. For example, if a CNC component is at a particular orientation with respect to a fixed origin point, and does not exactly match with the system component digital representation, all other components that would be assembled in relation to this component would be located such that their positions do not match the corresponding digital model. At some point the errors could multiply such that the assembly cannot proceed. To avoid this, appropriate tolerance values have to be accommodated in all members. It is difficult to achieve this kind of accuracy in positioning members using manual assembly process. Also, as seen in the approximated NURBS surface exploration, the members are twisted to follow the *UV* lines. Therefore, the grooves must be designed such that tolerances for the twists and the resulting bending stresses can be accommodated. Such tolerances are tested by making quick physical mockups. Similarly, in the triangulated approximation exploration the pieces have to be located such that they are both in appropriate three-dimensional location and orientation, which is very difficult to achieve due to the small scale of models. Even if such exacting in the position of digital and CNC components is presumed, the relative fabrication tolerances of adjoining system components can require adjustable connection strategies for resolving dimensional discrepancies.

Tolerances for digitally made architecture greatly differ from traditional methods. For example, the plug-in panels in the translational surface exploration are dependant on the location of grooves in the sub-frame, which is dependant on the main frame. Thus, any error in the components of the main frame affect the sub frame and the panels. As a result, main frame members need tighter tolerances and consequently, different tolerance values are required from different system components. This method contrasts with the traditional methods in which the secondary structure is typically measured relative to the primary structure. Also, as observed in the cone exploration, as the scale increases, corresponding changes have to be accommodated in the tolerance values for the various system components.

Tolerance decisions cannot be divorced from computer modeling strategies of the various system components. These decisions have implications on the manufacturability and assembly of the physical models which are sometimes difficult to predict. A judicious use of tolerance and flexibility in the dimensional control of the project geometry is very important. A parametric definition of tolerances that can accommodate change in tolerance variables for different scale models is found particularly useful.

## *3.5 Eight Steps for Digital Making*

1. *Define tasks*
2. *Search for production strategies*
3. *Establish a system of manufacturable components*
4. *Divide into realizable modules*
5. *Identify and prepare layouts for key modules*
6. *Complete overall layout*
7. *Prepare production and assembly instructions*
8. *Assembly process*

## *Step 1 Define Tasks*

It is critical to define the intention for digital making; this will help determine the output that is required. For example, making sketch models as a part of the iterative design process, design of manufacturability, design of assembly, representing production of architecture by making scaled versions of building components, etc.

## *Step 2 Search for Production Strategies*

A production strategy is a strategy that needs to be adopted so that a given geometrical configuration can be constructed using a fabrication machine or a combination of fabrication machines. The use of developable surfaces, contouring, projecting grids, triangulation, and tessellation are examples of production strategies. The challenge is to choose an appropriate geometric approximation that will preserve the essential qualities of the initial three-dimensional geometrical configuration. A number of factors play an important part while selecting an appropriate production strategy, for example aesthetics, cost and structural performance.

It is to be noted that in a pre-rational system, such strategies are embedded in the internal elegance of geometrical definition of the form.

## *Step 3 Establish a System of Manufacturable Components*

Based on the chosen production strategy, the next task is to establish a construction system — with a set of manufacturable components that are interrelated and work together as a system. This system can simply be assumed for the rest of the digital making process. For instance, in a traditional column-slab system, the columns and slabs are the essential system components. These system components have a certain relationship with one another, for example the slabs rest on the columns. In the same way in the triangulation exploration, initial tests are done to identify components that are required to make a physical representation of the triangulated surface (i.e. the joints, bar members and the face panels) and establish a system for the various components (joints and bar member are assembled in a tongue and groove fashion to form a supporting frame on which the panel faces rest).

### *Step 4 Divide into Realizable Modules or Parts*

Having established a construction system based on a given production strategy, the next step is to map this onto a given geometrical configuration. For example, if tessellation is chosen as the production strategy for a given surface, the tessellation pattern has to be mapped onto the surface. This could be done in many ways — the underlying algorithm of the surface modeling system could be used to tessellate the surface, a two-dimensional tessellation pattern could be projected onto the surface or a custom tessellation pattern could be developed for the surface. The wire frame model that is generated must be further manipulated to create a complete abstraction of the construction system and to generate the precise definition of each and every system component.

### *Step 5 Identify and Prepare Layout for Key Modules*

Repetitive tasks or procedures are required to create both simple and complex configurations. The shortest procedure that can expand pre-declared parameter values into explicit instances is defined as the layout of the key module. It may be possible to define several such short procedures for the same geometrical configuration. For example, in the NURBS approximation exploration the rib components in the *U* and *V* directions are the key modules; in the Triangulation exploration the frame, with the joints and bars, and the panel faces are key modules.

## *Step 6 Complete Overall Layout*

Having defined the layouts for the key modules, the next task is to assign different values to the parameters, such that different objects or instances required to complete the overall layout can be created. For example, in the panels for the cone exploration, the user can manually input these parameters for each panel such that the layout with the system components is created for each panel. It is also possible to automate this process, either by creating an interface for interactively selecting points on the computer screen or, even better, by programming a procedure for automatically selecting various parameters required to create the layout for each key module. A good example of such automation is by the use of programming in the NURBS surface approximation exploration. In that case, End-user programming is first used to define the shortest repetitive procedure, that is, the creation of a rib component, and then automatically creates various instances of the ribs by extracting information from the NURBS surface. Thus, all the instances required to complete the overall layout are generated automatically. Similarly, in the translational surface approximation exploration, the information required to create the key modules is first generated programmatically by defining the geometry and is then stored in a list. A procedure for creating system components for each module is then defined programmatically. The information stored in the list is accessed to create different instances constituting system components (facet panels, sub-frames and main frames), thus automating the generation of the overall layout.

## *Step 7 Prepare Production and Assembly Instructions*

The system components could be derived from the geometrical configuration, however, they have to be manufactured using CAD/CAM machines. The design development procedure for producing an output is different from one CAD/CAM fabrication machine to the other. For example, in the triangulation exploration, the joints are to be fabricated using the milling machine or the ZCorp printer. Both of these machines require the surface information of joints in "stl" format. In the case of the milling machine, each joint is milled individually along with certain other modifications (for instance, additional projections in the surface geometry of the joints are required for holding it while being milled; the size of the stock from which the joint is being milled). However, for the ZCorp machine a number of joints could be 3D-printed together. Again, these joints should be compactly placed within the limits of the printing bed (for example the 8.5'' x 8'' bed) to economize both the cost of machining and the time required.

The system components also have to be assembled to fabricate the final form. It is essential to bar code or label each component both in the 3 dimensional construction layout and the cut sheet layout. Bar coding/labeling helps to track the pieces during the manufacturing and assembly process. CNC fabrication machines often support the development of registration information as part of the fabrication process. For example, laser or plasma cutting tools can be operated at lower power levels than required to burn through material and can allow dimensionally accurate registration marks and even textual annotation as a part of the cutting process.

## *Step 8 Assembly Process*

Various system components could be manufactured using fabrication machines, but these system components eventually have to be assembled together exactly like the digital model. It is interesting to note from the explorations that it is sometimes possible to both derive system components from digital representations and manufacture them, but it may not be possible to assemble them due to the internal constraints of the particular geometrical configuration. The sequence of assembly is another aspect that is critical: for example, in the cone exploration the pieces can be assembled only in a particular sequence, which evolved with the design. Thus, the assembly process is very critical for testing if the system components could be physically assembled and to derive a sequence in which the various components should be assembled.

Another issue closely related with the assembly process is that of dimensional tolerances. The exacting of system components locations in the digital and physical realms is critical, but also very difficult to achieve using manual methods. Assembly process could help us to determine and assign appropriate tolerances for the different system components.

Note that these eight steps for digital making are very broad divisions. At times it may be difficult to separate one step from the other, or depending on a particular geometrical configuration, all eight steps may not be required.

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[xxiv] William J. Mitchell, *Design Worlds and Fabrication Machines*, in *Architecture in the Digital Age, Design and Manufacturing*, Branko Kolarevic

[xxv] Branko Kolarevic, *Architecture in the Digital Age, Design and Manufacturing*

[xxvi] Dennis R. Shelden, *Digital Surface Representation and the Constructibility of Gehry's Architecture*, PhD thesis, MIT

[xxvii] Hugh Whitehead, quoted by Yanni Loukissas in *Rulebuilding, Exploring Design Worlds through End-User Programming*, SMArchS thesis, MIT

[xxviii] Hugh Whitehead, quoted by Yanni Loukissas in *Rulebuilding, Exploring Design Worlds through End-User Programming*, SMArchS thesis, MIT

# Chapter 4

## *Conclusions*

> *"It was constructability that brought into the question the creditability of spatial complexities introduced in the new "digital" avant-garde. But as constructability becomes a function of computability, the question is no longer weather a particular form is buildable, but what new instruments in practice are needed to take advantage of the opportunities opened up by the digital modes of production."*
>
> *- Branko Kolarevic*[xxix]

Various explorations in this document describe methods of fabricating architecture using a combination of digital modeling with generative methods and computer controlled fabrication machines. With the established methodology and suggested procedures for digital making, it is possible to simulate CAD/CAM design and manufacturing processes in architectural studios and offices. Directly engaging in the activity of digital 'making' enables the thoughtful and creative designer to come up with innovative solutions for challenging design problems and engage in activities of construction earlier in the design process.

## *Post-Script*

### *Embedding Digital making into the Iterative Design Process*

Digital 'making' for architecture cannot be divorced from the activity of design. Explorations in this document suggest the need for the integration of digital making into the iterative design process. It is noted that such integration helps the designers be more informed about the constructability implications of a digital model.

### *CAD/CAM and Fabrication Machines*

Through some derivation processes CAD/CAM machines can translate a digital model into material realization. We can describe the process of design development as one of translating a digital model into a sequence of instructions for some particular fabrication machine. Directly working with fabrication machines helps designers to better relate to CAD/CAM design and construction processes by understanding the limitations and possibilities of fabrication machines.

### *Generative Fabrication*

> *"A plasma cutter can produce a hundred identical pieces or a hundred different pieces at the same price per kilogram. The difference here is whether one single data record is sufficient for all pieces, or if a new record must be created for each piece — the costs are transferred to the immaterial work."*
>
> *Bernhard Franken*[xxx]

It is interesting to note in the above explorations how generative methods support iterative design and the automation in manufacturing of system components for the making of a digital model. Such methods also have the potential for creating architectural forms characterized by a greater depth of geometrical reasoning and greater control over actual fabrication aesthetics.

## *Design of Fabrication Machines*

As observed by William Mitchell "architects drew what they could build, and built what they could draw."[xxxi] This reciprocity between means of representation and production has disappeared entirely in the digital age. Today, knowing the production capabilities of a particular fabrication machine, designers specifically tailor their designs according to the capabilities of those machines. Consequently, it is "the capability of a machine" that is the limiting factor for design exploration worlds. If the fabrication machine could be designed for a given task, this would remove the formal constraints imposed by the limitations of an existing fabrication machine. For example, in the automobile industry, fabrication machines are designed or customized for specific task or requirement. Thus, designers can engage in the design of both the specific output they want and a corresponding production line for producing that output.

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[xxix] Broko Kolarevic, Architecture in the Digital Age, Design and Manufacturing

[xxx] Bernhard Franken, Real as Data, in Architecture in the Digital Age, Design and Manufacturing

[xxxi] William J. Mitchell, Roll Over Euclid: How Frank Gehry Designs and Builds, in J. Fiona Ragheb, Frank Gehry, Architect

# *Appendix*

For more information on fabrication machines used in this exploration please refer to the following websites:

Laser Cutter : http://www.ulsinc.com/english/laser_systems/product_line/x660.html

Stratasys : http://www.stratasys.com/NA/index.html

ZCorp : http://zcorp.com/

Paper Cutter : http://www.rolanddg.com/products/cx2412.html

For tutorials on how to use the machines refer to:

http://web.mit.edu/ddfg/devices/index.html

## *Glossary*

CAD/CAM: Computer aided design and Manufacturing

Production strategy: These strategies enable the production of geometrical configurations from digital representations, using 2 dimensional fabrication devices. For example, triangulation, faceting, contouring

Layout for key module: The shortest procedure that can expand pre-declared parameter values into explicit instances could be defined as the layout of the key module.

System components: Refers to a series of components that constitute a construction system

Variables: An entity that is subject to variation A symbol that represents a numerical quantity that is prone to change

Explicit model: A geometric model that has attributes with fixed values

Stl: File formatter required by certain fabrication machines

Parameter: a factor that determines the range of variations of a system. An entity that controls the value of a variable through some type of relationship

Parameterization: the process of transforming fixed values into variables
Design Representation: An image, model or drawing that communicates visually a design or design intent

Parametric system: a group or collection of interrelated components that have a specific behavior, and describe process subject to change.

Cartesian geometric space: used in a system of representing geometric quantities, invented by Descartes.

Programmatically: Following an overall plan or schedule: *a step-by-step, programmatic approach to problem solving.*

Operator effort: effort put in by one who operates a machine or device

Iterative design process: repetitive (changing) design process

Batch process: A set of data or jobs to be processed in a single program run

Tolerance: Allowed amount of variation from the standard or from exact conformity to the specified dimensions, weight, etc., as in various mechanical operations

Exacting: Characterized by accurate measurements or inferences with small margins of error; not approximate: *an exact*

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*The Reality Center*: http://www-europe.sgi.com/global/uk/centre

*Z Corporation*: http://www.zcorp.com