Design for Manufacturing in Architecture
Mapping in between Curved Surfaces Design and Fabrication

Eduardo Lyon
College of Architecture
Georgia Institute of Technology
eduardo.lyon@coa.gatech.edu

Abstract. *This paper explores new ways to integrate manufacturing processes information in to design phases. Through the analysis of related fields and looking at the relations between its design methods and production processes, we analyze design processes and design representations that already have embedded in them specific ways to materialize through production the artifacts they define. Subsequently, we explore curved surface fabrication using cutting and bending technologies. As a summary, we conceptualize from this top-down development approach to design a framework that integrates design and construction in architecture, based on three possible applications fields:*

- *Design processes improvement*
- *Building production process improvement*
- *CAD-CAM Tools development*

Keywords. *Design Computing, Design Cognition, Digital manufacturing.*

1. Introduction

The aspiration motivating this work is to better understand an alternative approach to traditional design process formulation that currently is receiving increasing attention. Traditional design has been based on a clear-cut division between the generation of information to describe artifacts followed by the provision of information to construct them. Design for manufacturing (DFM), on the other hand, tries to resolve within the design process how the artifact is to be constructed. Considering construction knowledge during design becomes especially important when exploring alternatives to traditional construction methods, where the space of construction alternatives is not well understood. The benefits of integrating design with construction knowledge can be understood through study of the cost of resolving problems as they occur early or later in the design process. Problem resolution late is expensive, early is cheap (Ahmadi and Wurgraft, 1994).

To better understand and effectuate this change of process, we recognize that the resources available for rethinking architecture are to be found in a reformulation of its theory and design practice, based on:

- new design representations that integrate considerations of design of the artifact with its fabrication,

- new design tools invested with analytical and operational capabilities allowing designers to explore new ways to both conceptualize and produce artifacts,

- new competences that focus not only on increasing ways to create forms but also in alternatives ways to build artifacts.

2. What we can learn from other fields:

Representations are domain specific and almost all design activities rely on specific design representations. Fashion design and boat design contain specific conventions to describe objects and embedded process descriptions to manufacture those objects.

2.1. Clothing Design Process:

Clothing design is a craft older than architecture. Design may start with a sketch or by directly draping material on a human body or mannequin. Material is temporarily attached using pins. Tucks, folds, vents and other features may be applied to gain the desired form and drape of material. Buttons, snaps, zippers and other hardware is also added. The above-described process is called drafting and draping. Drafting consists in obtaining the pattern from specific body measurement, and draping consist in manipulating the fabric attaching it to a real model or a mannequin, possibly inspired in a sketch (Glock and Grace I., 2000, Carr and Latham, 1994, Eckert et al., 2000). Clothing design is heavily based on fashion pattern drawings; see figure 1 and figure 2.

2.2. Boat Design Process:

Boat design also starts with a carefully developed design, in plan and longitudinal and transverse sections. See figure 3 and figure 4

Boat design process consists in producing 2D shapes from a sequence of object cuts. The sections must be produced along the hull axis, shown in figure 4. Because a boat hull is symmetrical, only half of the hull section is needed. In addition, because the hull is made up of two portions, one expanding up to the boat's maximum girth, then declining to the aft, the sections from the bow to the maximum girth can be shown on one side of the symmetric plane, and those declining to the aft can be shown on the other side of the symmetry plane (Chapelle, 1941).

3. Design for Manufacturing

The design for manufacturing approach considers manufacturability as part of design constraints, and explicitly includes information to feed construction process. Furthermore, designers are required to have a good understanding of manufacturing processes in order to provide detailed and accurate information to feed those processes.

The use of CNC manufacturing technologies in buildings is already giving us a sense of how building production may change in the future. In some ways, digital manufacturing technology is a definite shift away from Contractor-led models, and as such the organization of building production will no longer be limited to traditional forms of construction (Kieran and James Timberlake, 2004). Moreover, digital manufacturing represents a substantial change from conventional methods of mass production where repetition was the basis of economy. With Computer Aided Manufacturing variation and customization no longer require an increase in costs due to specialized labor or exceptional manufacturing techniques (Kieran and James Timberlake, 2004).

4. Curved Surfaces:

Even though stone craftsmen built wonderful geometries and stone cutting methods developed

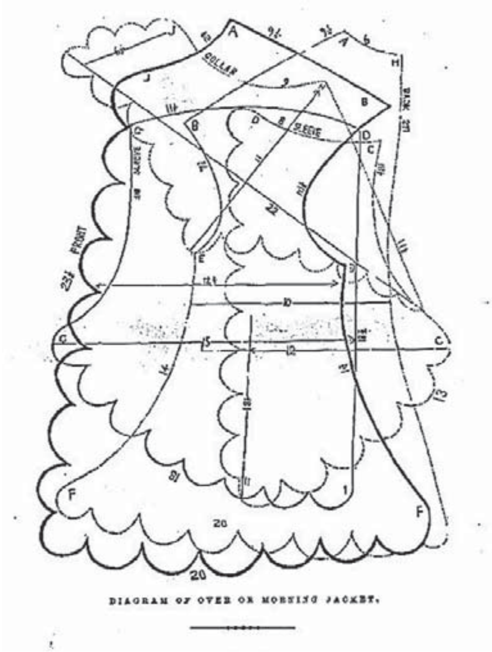
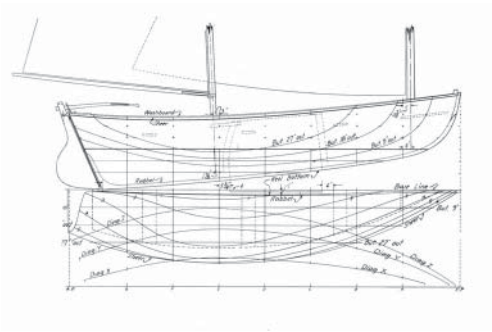


Figure 1. Example dress from The Lady's Book, Louis A.Godey 1850

Figure 2. Pattern for dress at left from The Lady's Book, Louis A. Godey 1850



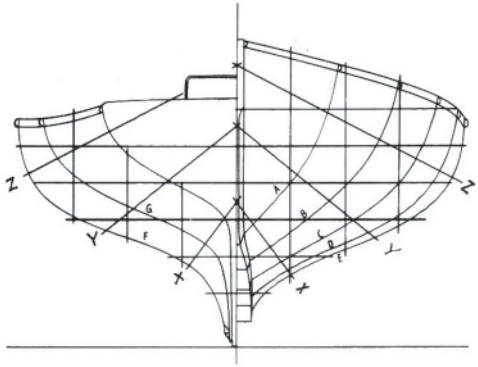


Figure 3. Lines of 17-Foot Hampton Boat from Chapelle, H.I., Boatbuilding Boatbuilding.1941

Figure 4. Lines of 17-Foot Hampton Boat from Chapelle, H.I., Boatbuilding Boatbuilding.1941

powerful heuristics generation methods for decades architectural representation methods were limited to Euclidean geometry constrains. It was not until 1868 that Beltrami proved that non-Euclidean geometries were as logically consistent as Euclidean geometry (Mlodinow, 2002).

Lately and because of the widespread use of solid modeling, a notable increase in the use of curved surfaces in architecture has been noticed. Designers considering curved surfaces perform Gaussian analysis of its curvatures, trying to reduce -expensive to built- double curvatures.

4.1. Non Uniform Rational B-Splines (NURBS)

Before computers, architects would draw their designs for buildings and the like by using pencil, paper, and various drafting tools. These tools included rulers and T-squares for drawing straight lines, compasses for drawing circles and circular arcs, and triangles and protractors for making precise angles. In addition curve sets were found in each design field, see from figure 5 to figure 6.

Of course, many interesting-shaped objects couldn't be drawn with just these instruments.

As computers were introduced into the design process, the physical properties of such curves were investigated. Curved surfaces by means of computers are produced using polygonal meshes or NURBS surfaces. Because of their flexibility and accuracy, NURBS models are intensively used in processes from illustration and animation to manufacturing (Farin, 1999).

5. Cutting and Bending as Production Processes:

As we reviewed in the previous chapters curved surfaces can be transformed into flat shapes to be fabricated. Manufacturing of those shapes includes two main production processes, cutting and bending. Each manufacturing process needs a specific set of information. In the following section, we review some of those manufacturing considerations in relation to cutting and bending operations.

5.1. Cutting operations:

Cutting operations can be differentiated according to the way that cuts are produced; one is removing material from the panel, the second is melting it. Material removing processes in construction are normally performed using saws or CNC routers, and more extensively applied to wood, non-flammable plastics like acrylic, and some soft alloys. In general, thermal cutting operations are more suitable for metals and have wide-

Figure 5. Copenhagen Ship's Curve Set from http://www.reuels.com.

Figure 6. Fashion Design Curves Set from http: //www.reuels.

spread use in building industry (Callicott, 2000).

5.2. Bending Operations:

In bending operations, desirable shape is obtained from pressing a working piece with a forming tool against a die or passing the work piece through a series of rolls, being the former known as press Brake (Stacey, 2001) and the later roll forming (Kalpakjian and Schmid, 2002).

Plastics, wood plies and some metals are also possible to bent by applying localized heat allowing material re-distribution and bending. This method is often known as heat forming and is used for smooth bending of plywood, large pipes, plastic and steel sheets.

6. Design Representation for Curved Surface Fabrication:

Essentially, we will analyze a process to design and manufacture NURBS surfaces using 2D cutting and bending technologies. This process will be structured in four major steps Form Generation, Form Analysis, Form Optimization, and Manufacturing in figure 7.

6.1. NURBS Surface generation

Form generation is a very flexible process; so multiple paths are possible and combination of them allowed. The first step is to identify major sources of information for form generation, being the most common formats like paper drawings, digital models, or physical models. Furthermore, different methods are provided to produce, with some level of accuracy, digital models out of them. Even though NURBS surface are widely adopted by surfaces modelers, we provide alternatives paths for transformations from mesh models to contours or sections, and then to B-Splines in figure 8.

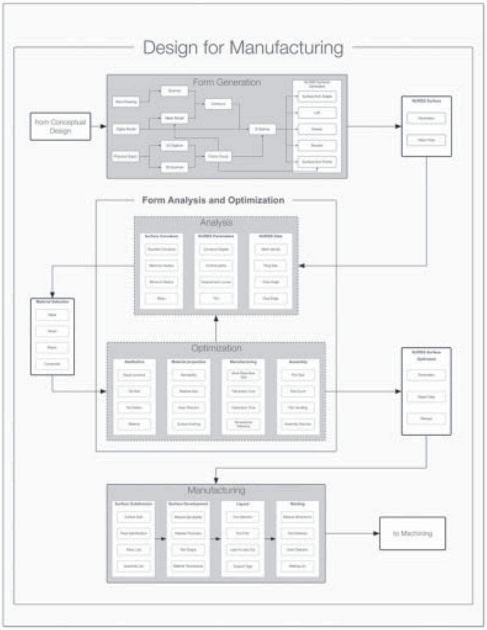


Figure 7. Process diagram showing complete Design for Manufacturing process.

6.2. NURBS Surface Analysis

Initial purpose of doing surface analysis is to better understand surface properties and specific parameters controlling it. Even though there are multiple connections between them, we divided the analysis phase according to most common properties in NURBS curved surfaces. These are Surface Curvature, NURBS Surface Parameters, and NURBS Surface Data. Surface modelers provide powerful tools to analyze NURBS surface geometry and its curvature. But most surface modelers available for architects, are oriented to visualization and ignore material properties of NURBS surfaces. See figure 9

6.3. NURBS Surface Optimization

Curved surface aspects considered in our optimization phase were; Aesthetics, material properties, manufacturing and assembly. Aesthetic is by far the most idiosyncratic value for optimization and for that reason it is the most unpredictable one. Material properties include multiple aspects like bendability, material size, grain direction, and surface finishing. Manufacturing and assembly considerations include the most common decision criteria factors found in field literature (Ahmadi and Wurgraft, 1994, Kalpakjian and Schmid, 2002, Chang et al., 1998, Boothroyd, 2002, Schodek et al., 2004).

6.4. NURBS Surface Subdivision

The first manufacturing operation is surface subdivision and consists in the surface split according to NURBS surface tiling. The tiling pattern is considered as a manufacturing feature and we proposed a direct mapping with the mesh subdivision that is an editable property of NURBS sur-

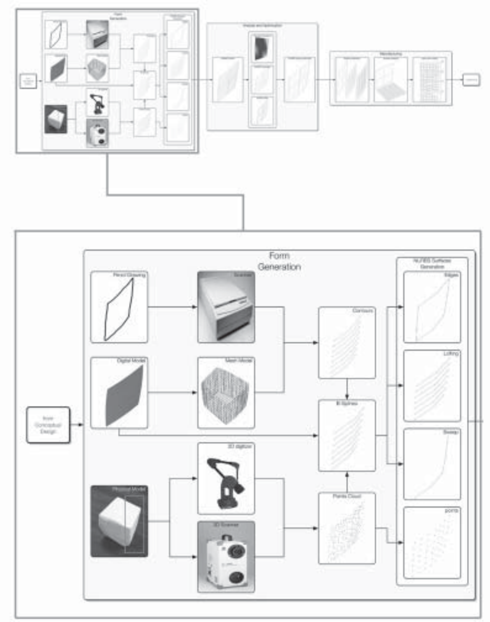


Figure 8. Design Representation for Form generation stage

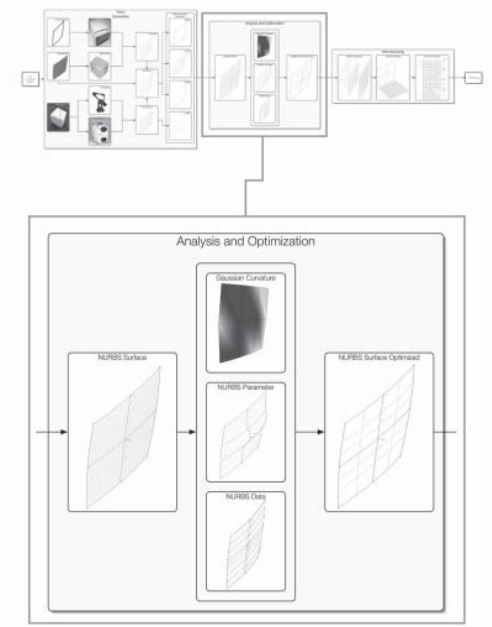


Figure 9. Design Representation for analysis and optimization stages.

faces. Even though surface modelers provide tools to edit mesh subdivision there is a lack of accurate tools to split the surface according to mesh module or pattern, keeping NURBS editable properties. Finally a tile numbering sequence is also included.

6.5. NURBS Surface Development

Our next Manufacturing operation is Surface development. Methods for generating a flat pattern of a general 3D surface depends on the shape of the surface and the material of the surface cover (Elber, 1992). Nevertheless, available tools for developing surfaces, included in the CAD software used in this study, ignore material thickness, or even worse, all material properties.

6.6. Shape Layout and Nesting

These operations are the first ones in the process in which NC code or machining code is produced. Layout consists in preparing the developed shapes for machining assigning specific machining information like tool description, tool path, tool lead in and lead out, and support tags to hold the pieces in place during machining operations. Arranging parts on the working piece or panel, known as nesting, is being studied by researchers employing several methods and implementing them using computers (Babu and Babu, 2000, Lamousin and Warren N Waggenspack, 1997). While developing the nesting method for a given set of parts and sheets, it is important to consider geometrical and technical aspects (Babu and Babu, 2000).

7. Conclusions and Future Research:

Transferring knowledge from manufacturing processes to design processes is becoming increasingly important. CAD systems mostly ignore that reality, even though some remarkable exceptions exist. In the other side CAM systems relies mostly on redraw or feature recognition algorithms to obtain manufacturing knowledge from design

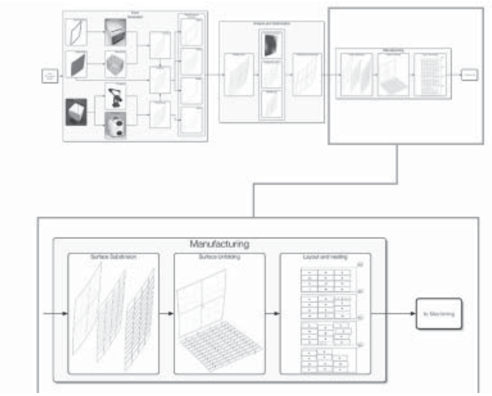


Figure 10. Design Representation for manufacturing stages.

stages. The alternative process selected in this study consists of linking manufacturing knowledge with manufacturing features using a manufacturing process model. Subsequently design features are mapped to manufacturing features using design representations.

The second issue is the complexity found in exchanging between multiple data formats along the process (Rosso et al., 2002). Programming for CNC machine tools is normally done by using ISO 6983. This standard dates back to the time of punched cards and does not cover the demands of modern CNC technology. Programming with ISO 6983 results in huge programs, which are difficult to handle; last-minute changes or correction of machining problems on the shop floor are hardly possible and control of program execution at the machine level is severely limited. Even worse, due to many different languages and vendor-specific add-ons to the programming language, part programs are not interchangeable (Maeder et al., 2002).

The third topic of interest arises from the fact that providing feasible design and manufacturing process representations opens the option to feed the process in the reverse direction i.e. to obtain a three dimensional objects from a set of manufacturing features, and finally opens the question can be this process feed with alternative parameters to obtain alternatives design or manufacturing solutions? Some of these questions has been already made and labeled under the concept of “generative manufacturing” and grouped in Feature Based Manufacturing field (Shah et al., 1994).

References:

Ahmadi, R. H. & Wurgraft, H. (1994) Design for Set Manufacturability. IN DASU, S. & M.EASTMAN, C. (Eds.) Management of design: engineering and management perspectives. Boston, Kluwer Academic Publishers.

Babu, A. R. & Babu, N. R. (2000) A generic approach for nesting of 2-D parts in 2-D sheets using genetic and heuristic algorithms. Computer-Aided Design, 33, 879-891.

Boothroyd, G. D., Peter. / Knight, W. A. (2002) Product design for manufacture and assembly, New York, Marcel Dekker.

Callicott, N. (2000) Computer-Aided Manufacture in Architecture - The Pursuit of Novelty, Elsevier Science & Technology.

Carr, H. & Latham, B. (1994) The technology of clothing manufacture, London; Boston, Blackwell Scientific Publications.

Chang, T.-C., Wysk, R. & Wang, H.-P. (1998) Computer-aided manufacturing, Upper Saddle River, N.J, Prentice Hall.

Chapelle, H. I. (1941) Boatbuilding: a complete handbook of wooden boat construction, New York, W.W. Norton.

Eckert, C. M., Cross, N. & Johnson, J. H. (2000) Intelligent support for communication in design teams: garment shape specifications in the knitwear industry. Design Studies, 21, 99-112.

Elber, G. (1992) Model fabrication using surface layout projection. Computer-Aided Design, 27, 283-291.

Farin, G. (1999) NURBS: from projective geometry to practical use, Natick, Mass., A.K. Peters.

Glock, R. E. & Grace I., K. (2000) Apparel manu-

facturing: sewn product analysis, Upper Saddle River, NJ, Merrill.
Kalpakjian, S. & Schmid, S. (2002) Manufacturing processes for engineering materials, Upper Saddle River, N.J., Prentice Hall.
Kieran, S. & James timberlake (2004) Refabricating Architecture, New York NY, McGraw-Hill Companies.
Lamousin, H. & Warren N Waggenspack, J. (1997) Nesting of two-dimensional irregular parts using a shape reasoning heuristic. Computer-Aided Design, 29, 221-238.
Maeder, W., Nguyen, V. K., Richard, J. & Stark, J. (2002) Standardisation of the Manufacturing Process: the IMS STEP-NC project. Saas-Fee, STEP-NC Publications Page.
Mlodinow, L. (2002) Euclid's Window: The Story of Geometry from Parallel Lines to Hyperspace, Simon & Schuster Adult Publishing Group.
Rosso, R., Allen, R. D. & Newman, S. (2002) Future Issues for CAD/CAM and Intelligent CNC Manufacturing. 19th International Manufacturing Conference – IMC-19. Belfast North Ireland, Queen's University.
Schodek, D., Bechthold, M., Griggs, J. K., Kao, K. & Steinberg, M. (2004) Digital Design and Manufacturing: CAD/CAM Applications in Architecture, Hoboken NJ, Wiley.
Shah, J., Mäntylä, M. & Nau, D. (1994) Advances in feature based manufacturing, Amsterdam; New York, Elsevier.
Stacey, M. (2001) Component Design, Oxford; Boston, Mass., Elsevier Science & Technology.