Digital Fabrication: Manufacturing Architecture in the Information Age

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Abstract
This paper addresses the recent digital technological advances in design and fabrication and the unprecedented opportunities they created for architectural design and production practices. It investigates the implications of new digital design and fabrication processes enabled by the use of rapid prototyping (RP) and computer-aided manufacturing (CAM) technologies, which offer the production of small-scale models and full-scale building components directly from 3D digital models. It also addresses the development of repetitive non-standardized building systems through digitally controlled variation and serial differentiation, i.e. mass-customization, in contrast to the industrial-age paradigms of prefabrication and mass production.

The paper also examines the implications of the recent developments in the architectural application of the latest digital design and fabrication technologies, which offer alternatives to the established understandings of architectural design and production processes and their material and economic constraints. Such critical examination should lead to a revised understanding of the historic relationship between architecture and its means of production.

Keywords
Digital Fabrication, Computer-Aided Manufacturing, Digital Construction
1 Introduction

“Integrating computer-aided design with computer-aided fabrication and construction [...] fundamentally redefines the relationship between designing and producing. It eliminates many geometric constraints imposed by traditional drawing and production processes—making complex curved shapes much easier to handle, for example, and reducing dependence on standard, mass-produced components. [...] It bridges the gap between designing and producing that opened up when designers began to make drawings.”

- W. Mitchell and M. McCullough in Digital Design Media

The Information Age, like the Industrial Age before it, is challenging not only how we design buildings, but also how we manufacture and construct them. In the conceptual realm computational, digital architectures of topological, non-Euclidean geometric space, kinetic and dynamic systems, and genetic algorithms, are supplanting technological architectures. Digitally driven design processes characterized by dynamic, open-ended and unpredictable but consistent transformations of three-dimensional structures are giving rise to new architectonic possibilities (Kolarevic 2000). The generative and creative potential of digital media, together with manufacturing advances already attained in automotive and airplane industries, is opening up new dimensions in architectural design. The implications are vast, as “architecture is recasting itself, becoming in part an experimental investigation of topological geometries, partly a computational orchestration of robotic material production and partly a generative, kinematic sculpting of space,” as observed by Peter Zellner in “Hybrid Space” (1999).

It was only within the last few years that the advances in computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies have started to have an impact on building design and construction practices. They opened up new opportunities by allowing production and construction of very complex forms that were until recently very difficult and expensive to design, produce, and assemble using traditional construction technologies. The consequences will be profound, as new digitally driven processes of design, fabrication and construction are increasingly challenging the historic relationship between architecture and its means of production.

2 Fabrication

The continuous, highly curvilinear surfaces that feature prominently in contemporary architecture brought to the front the question of how to work out the spatial and tectonic ramifications of such non-Euclidean forms. For many architects, trained in the certainties of the Euclidean geometry, it was the issue of constructability that brought into question the credibility of spatial complexities introduced by the new “digital” avantgarde. However, the fact that the topological geometries are precisely described as NURBS (Non-Uniform Rational B-Splines) and thus computationally possible also means that their construction is perfectly attainable by means of computer numerically controlled (CNC) fabrication processes, such as cutting, subtractive, additive, and formative fabrication, which are described in more detail in this section.

2.1 2D Fabrication

CNC cutting, or 2D fabrication, is the most commonly used fabrication technique. Various cutting technologies, such as plasma-arc, laser-beam, or water-jet, involve two-axis motion of the sheet material relative to the cutting head and are implemented as a moving cutting head, a moving bed, or a combination of the two. In plasma-arc cutting an electric arc is passed through a compressed gas jet in the cutting nozzle, heating the gas into plasma with a very high temperature (25,000°F), which converts back into gas as it passes the heat to the cutting zone (Figure 1). In water-jets, as their name suggests, a jet of highly pressurized water is mixed with solid abrasive particles and is forced through a tiny nozzle in a highly focused stream, causing the rapid erosion of the material in its path and producing very clean and accurate cuts (Figure 2). Laser-cutters use a high-intensity focused beam of infrared light in combination with a jet of highly pressurized gas (carbon dioxide) to melt or burn the material that is being cut. There are, however, large differences between these technologies in the kinds of materials or maximum thicknesses that could be cut. While laser-cutters can cut only materials that can absorb light energy; water-jets can cut almost any material. Laser-cutters can cost-effectively cut material up to 5/8”, while water-jets can cut much
thicker materials, for example, up to 15” thick titanium.

The production strategies used in 2D fabrication often include contouring, triangulation (or polygonal tessellation), use of ruled, developable surfaces, and unfolding. They all involve extraction of two-dimensional, planar components from geometrically complex surfaces or solids comprising the building’s form. Which of these strategies is used depends on what is being defined tectonically: structure, envelope, a combination of the two, etc.

In contouring, a sequence of planar sections, often parallel to each other and placed at regular intervals, are produced automatically by modeling software from a given form and can be used directly to articulate structural components of the building, as was the case in a number of recently completed projects (Figures 3 and 4).

Complex, curvilinear surface envelopes are often produced by either triangulation (or some other planar tessellation) or conversion of double-curved into ruled surfaces, generated by linear interpolation between two curves (Figures 5 and 6). Triangulated or ruled surfaces are then unfolded into planar strips, which are laid out in some optimal fashion as two-dimensional shapes on a sheet (in a process called nesting), which is then used to cut the corresponding pieces of the sheet material using one of the CNC cutting technologies. For example, Frank Gehry’s office used CATIA software in the Experience Music Project in Seattle to “rationalize” the double-curved surfaces by...
converting them into “rule-developable” surfaces, which were then unfolded and fabricated out of flat sheets of metal (Linn 2000).

The surface data could be also used to directly generate a wireframe abstraction of the building’s structural framework, which could be then processed by the structural analysis software to generate the precise definition of all structural members. In Gehry’s Bilbao project the contractor used a software program from Germany called Bocad to automatically generate a comprehensive digital model of the structural steel, including the brace-framed and secondary steel structures for the museum (Stephens 1999). More importantly, that same program was used to automatically produce the fabrication drawings or CNC data to precisely cut and pre-assemble the various components (LeCuyer 1997).

The surface model could be also used to design, analyze, and fabricate the envelope components from sheet material. In designing the Guggenheim Museum in Bilbao, Gehry’s office used the Gaussian analysis to determine the areas of excessive curvature as there are limits as to how much the sheets of metal could be bent in two directions; the same technique was used on other projects by Gehry (Linn 2000). The analysis produced a colored image that indicated through various colors the extent of the surface curvature (Figure 7).

2.2 Subtractive Fabrication

Subtractive fabrication involves removal of specified volume of material from solids (hence the name) using multi-axis milling. In CNC (Computer Numerical Control) milling a dedicated computer system performs the basic controlling functions over the movement of a machine tool using a set of coded instructions (McMahon and Browne 1998).

Early experiments in using CNC milling machines to produce architectural models were carried out in early 1970s in the United Kingdom. Large architectural firms in the United States, such as Skidmore Owens Merrill’s office in Chicago, have used CNC milling machines and laser cutters extensively in the production of architectural models and studies of construction assemblies. Automated milling machines were used in late 1980s and 1990s to produce construction components (Mitchell and McCullough 1995), such as stones for New York’s Cathedral of Saint John the Divine and columns for Sagrada Familia Church in Barcelona. Frank Gehry’s project for Disney Concert Hall in Los Angeles represents the first comprehensive use of CAD/CAM to pro-
duce architectural stonework: for the initial 1:1 scale model the stone panels with double-curved geometry were CNC milled in Italy and then shipped to Los Angeles, where they were positioned and fixed in place on steel frames (Mitchell and McCullough 1995). Gehry’s office used this same fabrication technique for the stone cladding in the Bilbao project.

The CNC milling has recently been applied in new ways in building industry – to produce the formwork (molds) for the off-site and on-site casting of concrete elements with double-curved geometry, as in one of the Gehry’s office buildings in Dusseldorf, Germany, and for the production of the laminated glass panels with complex curvilinear surfaces, as in Gehry’s Conde Nast Cafeteria project and Bernard Franken’s BMW pavilion (Figure 8).

In Gehry’s project in Dusseldorf (Zollhof towers) the undulated forms of the load-bearing external wall panels, made of reinforced concrete, were produced using blocks of lightweight polystyrene (Styrofoam), which were shaped in CATIA and CNC milled (Figure 9) to produce 355 different curved molds that became the forms for the casting of the concrete (Rempen 1999, Slessor 2000).

2.3 Additive Fabrication

Additive fabrication involved incremental forming by adding material in a layer-by-layer fashion, in a process converse of milling. It is often referred to as layered manufacturing, solid freeform fabrication, rapid prototyping, or desktop manufacturing. All additive fabrication technologies share the same principle in that the digital (solid) model is sliced into two-dimensional layers. The information of each layer is then transferred to the processing head of the manufacturing machine and the physical product is incrementally generated in a layer-by-layer fashion (Jacobs 1992).

Since the first commercial system based on stereolithography was introduced by 3D Systems in 1988, a number of competing technologies now exist on the market, utilizing a variety of materials and a range of curing processes based on light, heat, or chemicals (Kochan 1993, Chua and Leong 1997). Stereolithography (SLA) is based on liquid polymers that solidify when exposed to laser light. In Selective Laser Sintering (SLS) laser beam melts a layer by layer of metal powder to create solid objects. In 3D Printing (3DP) layers of ceramic powder are glued to form objects. Sheets of material (paper, plastic), either precut or on a roll, are glued (laminated) together and laser cut in the Laminated Object Manufacture (LOM) process. In Fused Deposition Modeling (FDM) each cross section is produced by melting...
a plastic filament that solidifies upon cooling. *Multi-jet manufacture* (MJM) uses a modified printing head to deposit melted thermoplastic/wax material in very thin layers, one layer at a time, to create three-dimensional solids.

Because of the limited size of the objects that could be produced, costly equipment, and lengthy production times, the additive fabrication processes have a rather limited application in building design and production. In design they are mainly used for the fabrication of (massing) models with complex, curvilinear geometries (Novitski 2000). In construction, they are used to produce components in series, such as steel elements in light truss structures, by creating patterns that are then used in investment casting (Figure 10). Recently, however, several experimental techniques based on sprayed concrete were introduced to manufacture large-scale building components directly from digital data (Khoshnevis 1998).

### 2.4 Formative Fabrication

In *formative fabrication* mechanical forces, restricting forms, heat, or steam are applied on a material so as to form it into the desired shape through reshaping or deformation, which can be axially or surface constrained. For example, the reshaped material may be deformed permanently by such processes as stressing metal past the elastic limit, heating metal then bending it while it is in a softened state, steam-bending boards, etc. Double-curved, compound surfaces can be approximated by arrays of height-adjustable, numerically-controlled pins, which could be used for the production of molded glass and plastic sheets and for curved stamped metal. Plane curves can be fabricated by numerically-controlled bending of thin rods, tubes, or strips of elastic material, such as steel or wood, as was done for one of the exhibition pavilions designed by Bernhard Franken (ABB Architekten) for BMW.

### 2.5 Assembly

After the components are digitally fabricated, their assembly on site can be augmented with digital technology. Digital three-dimensional models can be used to determine the location of each component, to move each component to its location, and finally, to fix each component in its proper place.

Traditionally, builders took dimensions and coordinates from paper drawings and used tape measures, plumb-bobs, and other devices to locate the building components on site. New digitally-driven technologies, such as electronic surveying and laser positioning, are increasingly being used on construction sites around the world to precisely determine the location of building components. For example, as described by Annette LeCuyer (1997), Frank Gehry’s Guggenheim Museum in Bilbao “was built without any tape measures. During fabrication, each structural component was bar coded and marked with the nodes of intersection with adjacent layers of structure. On site bar codes were swiped to reveal the coordinates of each piece in the CATIA model. Laser surveying equipment linked to CATIA enabled each piece to be precisely placed in its position as defined by the computer model.” Similar processes were used on Gehry’s project in Seattle (Figure 11). As LeCuyer notes in her article, this processes are common practice in the aerospace industry, but relatively new to building.

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**Figure 10.** Trypiramid, a fabricator in New York, used rapid prototyping to manufacture truss elements for Polshek’s Rose Center for Earth and Sciences in New York.

**Figure 11.** Global Positioning System (GPS) technology was used on Gehry’s Experience Music Project in Seattle to verify the location of components (Linn 2000).
In Japan, a number of robotic devices for moving and fixing of components was developed, such as Shimizu’s Mighty Jack for heavy steel beam positioning, Kajima’s Reinforcing Bar Arranging Robot, Obayashi-Gumi’s Concrete Placer for pouring concrete into forms, Takenaka’s Self-Climbing Inspection Machine, Taisei’s Pillar Coating Robot for painting, and Shimizu’s Insulation Spray Robot.

3 Implications
The digital design and production techniques based on CAD/CAM technologies were widely adopted over the past two decades in many fields, such as product design, automotive, aerospace and shipbuilding industries. The impact was profound – there was a complete reinvention of how products in those respective industries were designed and made. Boeing 777, “the first 100% digitally designed aircraft,” is probably one of the best-known examples.

While the CAD/CAM technological advances and the resulting changes in design and production techniques had an enormous impact on other industries, there has yet to be a similarly significant and industry-wide impact in the world of building design and construction. The opportunities for the architecture, engineering, and construction (AEC) industries are there and the benefits were already manifested in related fields.

By integrating design, analysis, manufacture and assembly of buildings around digital technologies, architects, engineers, and builders have the opportunity to reinvent the role of a “master-builder” and reintegrate the currently separate disciplines of architecture, engineering and construction into a relatively seamless digital collaborative enterprise, thus bridging “the gap between designing and producing that opened up when designers began to make drawings,” as observed by Mitchell and McCullough (1995).

The legal framework within which AEC professionals operate still requires drawings, often tens of thousands of them for a project of medium size and complexity. As new synergies in architecture, engineering, and construction are emerging, the need to externalize representations of design, i.e., produce drawings, is bound to wane. As production of (unnecessary) drawings declines, i.e., as digital data is increasingly passed directly from an architect to a fabricator, so will the building design and construction processes become more efficient. By some estimates, there is a potential for building construction to become 28–40 percent more efficient through better (digital) information and coordination (Cramer 2000). But for that process to begin, the AEC legal framework, in which the drawings establish the grounds of liability, would have to change. In other words, the 19th century AEC practices would have to change for architects to work directly with fabricators, i.e., subcontractors; this “disintermediation” (Cramer 2000) should bring new efficiencies. As observed by James Cramer, Chairman/CEO of Greenway Consulting, “designers and contractors will no longer be the custodians of traditional assets but the creators of new value in a new industry.” According to Cramer, architects will find themselves “moving from linear to non-linear changes – from information that is shared by teams, rather than individuals, and communication that is continuous, rather than formal and fragmented.”

3.1 New Materiality
As new digital processes of conception and production begin to permeate building design and production, there is an increasing interest in “new” materials, well known in other production fields and only recently discovered by architects.

Much of the interest among architects in new materials stems from the new geometric complexities. In dealing with tectonic ramifications of non-Euclidean forms a particular challenge is how to avoid the usual translation into structural bays, often done by contouring, described in the previous section. This had lead to a renewed interest in surface or shell structures, or monocoque or semi-monocoque constructions in which the skin absorbs all or most of the stresses. The principal idea is to conflate the structure and the skin into one element thus creating self-supporting forms that require no armature. That in turn prompted a search for “new” materials, such as high-temperature foams, rubbers, plastics, and composites, which were until recently rarely used in building industry. As observed by Giovannini (2000b), “the idea of a structural skin not only implies a new mate-
rial, but also geometries, such as curves and folds that would enable the continuous skin to act structurally, obviating an independent static system: The skin alone does the heavy lifting.” Thus an interesting reciprocal relationship is established between the new geometries and new materials: new geometries opened up a quest for new materials and vice versa. Kolatan and MacDonald’s house addition project in Connecticut nicely illustrates that reciprocity: the building is made of polyurethane foam sprayed over an egg-crate plywood armature that was CNC-cut, thus forming a monocoque structure that is structurally self-sufficient without the egg-crate, which will remain captured within the monocoque form (Figure 12).

The implications of the “new” materiality are significant, as noted by Giovannini (2000b), as “new” materiality promises a radical departure from Modernism’s ideals:

“In some ways the search for a material and form that unifies structure and skin is a counterrevolution to Le Corbusier’s Domino House, in which the master separated structure from skin. The new conflation is a return to the bearing wall, but one with freedoms that Corb never imagined possible. Architects could build many more exciting buildings on the Statue of Liberty paradigm, but complex surfaces with integrated structures promise a quantum leap of engineering elegance and intellectual satisfaction.”

3.2 Mass Customization

The ability to mass-produce irregular building components with the same facility as standardized parts introduced the notion of mass-customization into building design and production (it is just as easy and cost-effective for a CNC milling machine to produce 1000 unique objects as to produce 1000 identical ones). Mass-customization, sometimes referred to as systematic customization, can be defined as mass production of individually customized goods and services (Pine 1993), thus offering a tremendous increase in variety and customization without a corresponding increase in costs. It was anticipated as a technological capability in 1970 by Alvin Toffler in Future Shock and delineated (as well as named) in 1987 by Stan Davis in Future Perfect (Pine 1993).

In addition to “mass-customization,” the CNC-driven production processes, which afford the fabrication of non-standardized repetitive components directly from digital data, have also introduced into architectural discourse the new “logics of seriality,” i.e., the local variation and differentiation in series. It is now possible to produce “series-manufactured, mathematically coherent but differentiated objects, as well as elaborate, precise and relatively cheap one-off components,” according to Peter Zellner (1999), who argues that in the process the “architecture is becoming like ‘firmware,’ the digital building of software space inscribed in the hardwares of construction.” That is precisely what Greg Lynn’s “Embryologic Houses” manifest: “mass-customized” individual house designs produced by differentiation achieved through parametric variation in non-linear dynamic processes.

The implications of mass-customization are profound. As Catherine Slessor (1997) observed, “the notion that uniqueness is now as economic and easy to achieve as repetition, challenges the simplifying assumptions of Modernism and suggests the potential of a new, post-industrial paradigm based on the enhanced, creative capabilities of electronics rather than mechanics.” In the Modernist aesthetic, the house was to be considered a manufactured item (“machine for living”), drawing upon the engineering logic for the design to be clarified and reduced to the essential. Mass production of the house would bring the best to a wide market and design would not cater to the elite (Le Corbusier 1931). At the start of the twenty-first century the goal remains, although reinterpreted, with the process inverted. No longer does factory production mean mass production of a standard item to fit all purposes, i.e.,
one size fits all. Instead, we now strive for mass customization, bringing the benefits of factory production to the creation of a unique component or series of similar elements differentiated through digitally controlled variation (Kvan and Kolarevic 2001).

4 Conclusions

The paradigm shifts currently at play in contemporary architectural design are fundamental and inevitable, displacing many of the well-established conventions. In a digitally-mediated design, as manifested in Gehry’s buildings and projects of the “digital avantgarde,” the practices of the past suddenly appear irrational. Models of design capable of consistent, continual and dynamic transformation are replacing the static norms of conventional processes. The predictable relationships between the design and representations are abandoned in favor of computationally generated complexities. The topological, curvilinear geometries are produced with the same ease as Euclidean geometries of planar shapes and cylindrical, spherical, or conical forms. Plan no longer “generates” the design; sections attain a purely analytical role. Grids, repetitions, and symmetries lose their past raison d’etre as infinite variability becomes as feasible as modularity and as mass-customization offers alternatives to mass-production.

As architects find themselves increasingly working across the disciplines of architecture, material science, and computer-aided manufacturing, the historic relationship between architecture and its means of production is increasingly being challenged by the emerging digitally driven processes of design, fabrication and construction. The amalgamation of what were until recently separate industries such as aerospace, automotive, and ship building, but there has yet to be a similarly significant and industry-wide impact in the world of building design and construction. That change, however, has already started, and is inevitable and unavoidable.

Bibliography


