MANUFACTURING DIGITAL ARCHITECTURES

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Abstract
This paper addresses recent digital technological advances in design and fabrication and the unprecedented opportunities they created for architectural practices by allowing design, fabrication and construction of very complex forms that were until recently very difficult and expensive to design, produce, and assemble using traditional construction technologies. The paper 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.

Introduction
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 of the changes brought about by the introduction of CAD/CAM technologies in building design and construction are likely to be profound, as the historic relationship between architecture and its means of production is increasingly being challenged by new digitally driven processes of design, fabrication and construction. 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 amalgamation of what were until recently separate enterprises has already transformed other 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 as architects find themselves increasingly working across the disciplines of architecture, material science, and computer-aided manufacturing,

Digital Fabrication and Assembly
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. The fact that those surfaces are precisely described in 3D modeling software 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, briefly described in this section.

CNC cutting, or 2D fabrication, is the most commonly used fabrication technique. Various cutting technologies, such as plasma-arc, laser-beam, or water-jet (Figure 1), involve two-axis (2D) motion of the sheet material relative to the cutting head [Kolarevic, 2001]. The production strategies used in 2D fabrication involve extraction of two-dimensional, planar components from geometrically complex surfaces or solids and are often based on contouring (Figure 2), triangulation or polygonal tessellation (Figure 3), use of ruled, developable surfaces (Figure 4), and unfolding [Kolarevic, 2001]. Which of these strategies is used depends on what is being defined tectonically: structure, envelope, a combination of the two, etc.

Subtractive fabrication involves removal of specified volume of material from solids (hence the name) using multi-axis CNC milling, which was used to various extent by large architectural practices over the past two decades. Frank Gehry's project for Disney Concert Hall in Los Angeles represents the first comprehensive use of CNC milling to produce the stone panels with double-curved geometry. The CNC milling, however, has recently been applied in new ways in building industry – to produce the formwork (molds) in lightweight polystyrene (Styrofoam) for off-site and on-site casting of concrete elements with double-curved geometry (Figure 5), and for the production of the laminated glass panels with complex curvilinear surfaces (Figure 6).

In a process converse of milling, additive fabrication involves incremental forming by adding material in a layer-by-layer fashion. All additive fabrication technologies share the same principle in that the digital (solid) model is sliced into two-dimensional layers, which are then transferred to the processing head of the manufacturing machine and the physical product is incrementally generated in a layer-by-layer fashion. 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. Because of the limited size of 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. They are mainly used in design for the fabrication of massing models with complex, curvilinear geometries. 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. Recently, however, several experimental techniques based on sprayed concrete were introduced to manufacture large-scale building components directly from digital data [Khoshnevis, 1998].

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. 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 Bernard Franken for BMW.

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. In Frank Gehry's building in Bilbao structural components were identified with bar codes which were swiped on-site to reveal the location of each piece in the digital 3D model; laser surveying equipment linked to the same 3D model was used to precisely place each component [LeCuyer, 1997]. These digital assembly processes are common practice in the aerospace industry, but relatively new in building industry.

Digital Continuum from Design to Construction

While CAD/CAM technological advances and the resulting changes in design and production techniques had enormous impact in many fields, such as product design, automotive, aerospace and shipbuilding industries, there has yet to be a similarly significant and industry-wide impact in the world of building design and construction. As mentioned earlier, by integrating design, analysis, manufacture and assembly of buildings around digital technologies, architects, engineers, and builders have the opportunity to reintegrate the currently separate disciplines of architecture, engineering and construction into a relatively seamless digital collaborative enterprise – a digital continuum.

As new synergies in architecture, engineering, and construction begin to emerge, the need to externalize representations of design, i.e., produce drawings, is bound to wane. As production of 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 in building design and construction.

As new digital processes of conception and production begin to permeate building design and production, there is also an increasing interest in "new" materials, well known in other production fields and only recently discovered by architects. Much of that interest stems from the new

Fig 1. Aluminum cutting using CNC water-jet technology.

Fig 2. Structural frames in Gehry's building in Seattle produced by contouring.

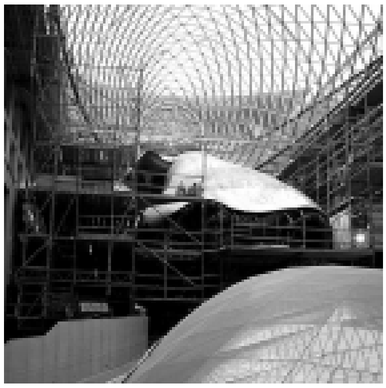

Fig 3. Glass envelope in Gehry's building in Berlin produced by triangulation.

geometric complexities, which has led to a renewed interest in surface or shell structures in which the skin absorbs all or most of the stresses. 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. Thus an interesting reciprocal relationship is established between the new geometries and new materialities: new geometries opened up a quest for new materials and vice versa. More importantly, the "new" materiality promises a radical departure from Modernism's ideals, as noted by Giovannini [2000]:

"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. [...] Complex surfaces with integrated structures promise a quantum leap of engineering elegance and intellectual satisfaction."

The CNC-driven production processes have also introduced into architectural discourse the new "logics of seriality," i.e., the local variation and differentiation in series, and "mass-customization" instead of mass-production, i.e., the ability to mass-produce irregular building components with the same facility as standardized parts. It is now possible to produce "series-manufactured, mathematically coherent but differentiated objects, as well as elaborate, precise and relatively cheap one-off components," as observed by Peter Zellner [1999]. The implications are potentially far-reaching. As Catherine Slessor [1997] notes, "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 – a "machine for living." Mass-production of the house would bring the best to a wide market and design would not cater to the elite. Today 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].

Bibliography

Cramer, J. http://www.greenwayconsulting.com/, 2000.
Giovannini, Joseph, Building a Better Blob, Architecture, vol. 89 no. 9, pp. 126-8, September 2000.
Khoshnevis, B., Innovative Rapid Prototyping, Material Technology, vol. 13(2), p. 53- 56, 1998.
Kolarevic, Branko, Digital Fabrication: Manufacturing Architecture in the Digital Age, Proceedings of the ACADIA 2001 Conference (forthcoming), 2001.
Kvan, Thomas and Branko Kolarevic, Rapid Prototyping and Its Application in Architectural Design, Automation in Construction special issue on rapid prototyping in architecture, Elsevier (forthcoming), 2001.
LeCuyer, Annette, Building Bilbao, Architectural Review, vol. 102 no. 1210, pp. 43-45, December 1997.
Mitchell, W. and M. McCullough, Digital Design Media, 2nd ed., Van Nostrand Reinhold, New York, 1995.
Slessor, Catherine, Atlantic Star, Architectural Review, vol. 102 no. 1210, pp. 30-42, December 1997.
Zellner, Peter, Hybrid Space: New Forms in Digital Architecture, New York: Rizzoli, 1999.

Fig 4. Use of ruled surfaces in the Water Pavilion by NOX.

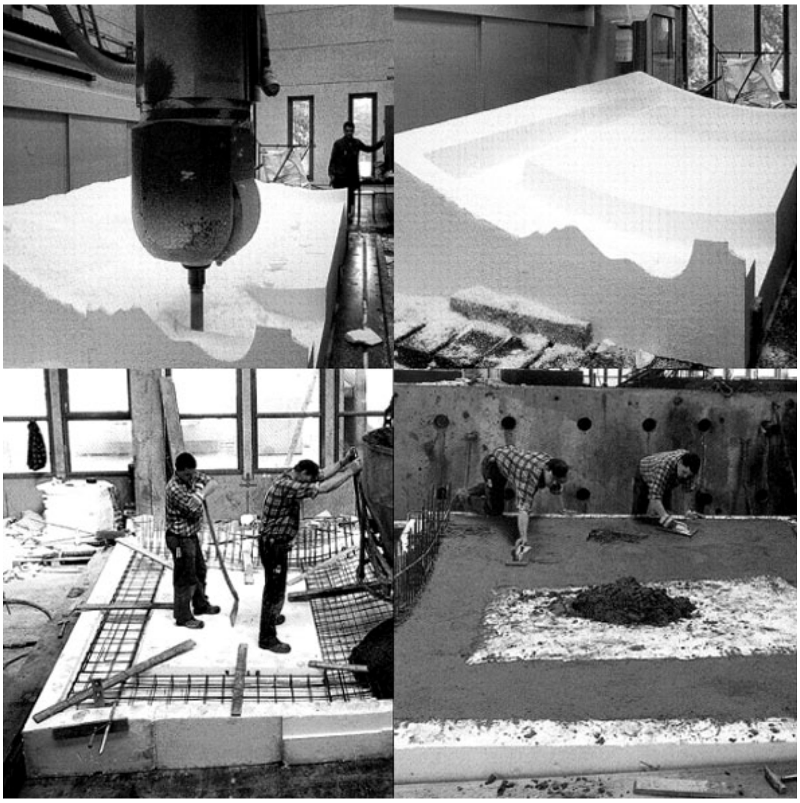

Fig 5. Milling of molds for concrete casting in Gehry's building in Dusseldorf.

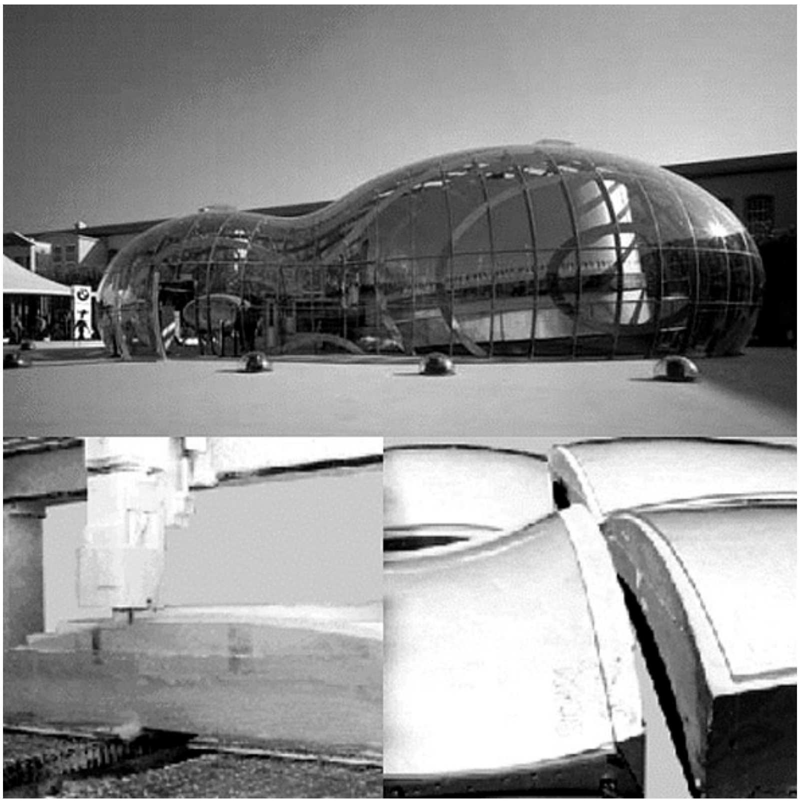

Fig 6. Milling of molds for acrylic glass panels in Bernard Franken's BMW pavilion.

Note

This paper is based on the paper presented at the ACADIA 2001 conference, referenced as [Kolarevic, 2001] in the bibliography.