

# Designing and Manufacturing Architecture in the Digital Age

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*The paper describes and 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. It offers a possibility of a revised understanding of the historic relationship between architecture and its means of production.*

**Keywords:** *Digital design, digital fabrication, CAD/CAM.*

## Introduction

“Having abandoned the discourse of style, the architecture of modern times is characterized by its capacity to take advantage of the specific achievements of that same modernity: the innovations offered it by present-day science and technology. The relationship between new technology and new architecture even comprises a fundamental datum of what are referred to as avant-garde architectures, so fundamental as to constitute a dominant albeit diffuse motif in the figuration of new architectures.”

Ignasi de Sola Morales (1997)

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, aerospace and shipbuilding

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 the historic relationship between architecture and its means of production is increasingly being challenged by new digitally driven processes of design, fabrication and construction.

## Digital Architectures

The new digital approaches to architectural design (digital architectures) are based on computational concepts such as topological space (topological architectures), isomorphic surfaces (isomorphic



*Figure 1. Isomorphic architectures: Bernard Franken's BMW Pavilion in Munich.*

architectures), motion kinematics and dynamics (animate architectures), keyshape animation (metamorphic architectures), parametric design (parametric architectures), and genetic algorithms (evolutionary architectures), as discussed in (Kolarevic 2000). New categories could be added to this taxonomy as new processes become introduced based on emerging computational approaches. For examples, new methods could emerge based on performance-based (structural, acoustical, environmental, etc.) generation and transformation of forms.

In his essay on "architectural curvilinearity" published in 1993, Greg Lynn offers examples of new approaches to design that move away from the deconstructivism's "logic of conflict and contradiction" to develop a "more fluid logic of connectivity." This new fluidity of connectivity is manifested through "folding," a design strategy that departs from Euclidean geometry of discrete volumes represented in Cartesian space, and employs topological, "rubber-sheet" geometry of continuous curves and surfaces, mathematically described as NURBS, Non-Uniform Rational B-Splines. What makes NURBS curves and surfaces particularly appealing is the ability to easily control their shape by manipulating the control points, weights, and knots. The NURBS make the

heterogeneous, yet coherent forms of the topological architectures computationally possible and their construction attainable by means of computer numerically controlled (CNC) machinery.

Isomorphic architectures (Figure 1), based on isomorphic polysurfaces, represent another point of departure from Platonic solids and Cartesian space. Blobs or metaballs, as isomorphic polysurfaces are sometimes called, are amorphous objects constructed as composite assemblages of mutually inflecting parametric objects with internal forces of mass and attraction. They exercise fields or regions of influence, which could be additive (positive) or subtractive (negative). The geometry is constructed by computing a surface at which the composite field has the same intensity – hence the name – isomorphic polysurfaces. The surface boundary of the whole (the isomorphic polysurface) shifts or moves as fields of influence vary in their location and intensity (fig 1).

In animate architectures, design, as described by Lynn (1998), "is defined by the co-presence of motion and force at the moment of formal conception." Force, as an initial condition, becomes "the cause of both motion and particular inflections of a form." According to Lynn, "while motion implies movement and action, animation implies evolution of a form and its shaping forces." In his projects, Lynn utilizes an entire

repertoire of motion-based modeling techniques, such as keyframe animation, forward and inverse kinematics, dynamics (force fields) and particle emission to generate the initial architectural form. In his House Prototype in Long Island, skeletons with a global envelope are deformed using inverse kinematics under the influence of various site-induced forces.

Metamorphic architectures rely on generative techniques such as keyshape animation (metamorphosis), deformations of the modeling space around the model using a bounding box (lattice deformation), a spline curve, or one of the coordinate system axis or planes, and path animation, which deforms an object as it moves along a selected path. In keyshape animation, changes in the geometry are recorded as keyframes (keyshapes) and the software then computes the in-between states. In deformations of the modeling space, object shapes conform to the changes in geometry of the modeling space.

In parametric architectures, it is the parameters of a particular design that are declared, not its shape. By assigning different values to the parameters, different objects or configurations can be created. Equations can be used to describe the relationships between objects, thus defining an associative geometry—the “constituent geometry that is mutually linked” (Burry 1999). That way, interdependencies between objects can be established, and objects’ behavior under transformations defined. As observed by Burry, “the ability to define, determine and reconfigure geometrical relationships is of particular value.”

Evolutionary architectures propose the evolutionary model of nature as the generating process for architectural form. In this approach to design, according to John Frazer (1995), “architectural concepts are expressed as generative rules so that their evolution and development can be accelerated and tested by the use of computer models.” Various parameters are encoded into the “a string-like structure” and their values changed during the

generative process. A number of similar forms, “pseudo-organisms,” are generated, which are then selected from the generated populations based on predefined “fitness” criteria. The selected “organisms,” and the corresponding parameter values, are then crossbred, with the accompanying “gene crossovers” and “mutations”, thus passing beneficial and survival-enhancing traits to new generations. Optimum solutions are obtained by small incremental changes over several generations.

What is common to all these approaches is an almost exclusive use of topological geometries, which appear to be almost de rigueur regardless of the underlying computational foundation. “Topology is the science of self-varying deformation,” observes Brian Massumi (1998). Topological space opens up a universe where essentially curvilinear forms are not stable but may undergo variations, giving rise to new possibilities, i.e., the emergent form. Designers can see forms as a result of reactions to a context of forces or actions, as demonstrated by Lynn’s work. There is, however, nothing automatic or deterministic in the definition of actions and reactions; they implicitly create fields of indetermination from which unexpected and genuinely new forms might emerge—unpredictable variations are generated from the built multiplicities.

The capacity of digital architectures to generate new designs is therefore highly dependent on designer’s perceptual and cognitive abilities, as continuous, dynamic processes ground the emergent form, i.e., its discovery, in qualitative cognition. Their generative role is accomplished through the designer’s simultaneous interpretation and manipulation of a computational construct (topological surface, isomorphic field, kinetic skeleton, field of forces, parametric model, genetic algorithm, etc.) in a complex discourse that is continuously reconstituting itself - a ‘self-reflexive’ discourse in which graphics actively shape the designer’s thinking process. It is precisely this ability of “finding a form” through dynamic, highly non-linear, indeterministic processes

that gave the digital media a critical, generative capacity in design. Even though the technological context of design became thoroughly externalized, its arresting capacity remains internalized (McCullough 1996).

### Digital Fabrication

The continuous, highly curvilinear surfaces that feature prominently in digital architectures brought to the front the question of how to work out the spatial and tectonic ramifications of such non-Euclidean forms. It was the issue of constructability that brought into question the credibility of spatial complexities introduced by the “digital” avantgarde. However, the fact that the topological geometries are precisely described as NURBS 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 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, 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. The production strategies used in 2D fabrication often include contouring, i.e., sequential sectioning (Figure 2), 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 (fig 2).

As its name implies, subtractive fabrication involves removal of specified volume of material from solids using multi-axis milling. In CNC (Computer Numerical Control) milling a dedicated computer system performs the basic controlling functions over



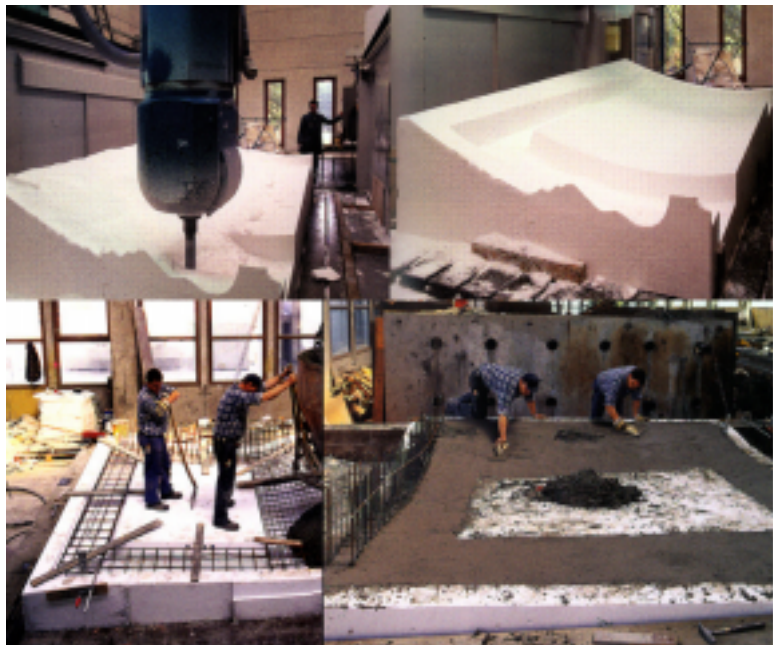
*Figure 2. Structural frames in Frank Gehry’s Experience Music Project in Seattle, produced by contouring.*

the movement of a machine tool using a set of coded instructions. This decades old technology has been recently applied in innovative 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 Gehry's office buildings in Dusseldorf, Germany (Figure 3), 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.

In a process converse of milling, additive fabrication (often referred to as layered manufacturing, solid freeform fabrication, or rapid prototyping) involves incremental forming by adding material in a layer-by-layer fashion. 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. 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. 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.

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



*Figure 3. Milling of Styrofoam molds for the casting of reinforced concrete panels for Gehry's Zollhof Towers in Dusseldorf, Germany (Rempen 1999).*

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 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. 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. As LeCuyer notes in her article, this processes are common practice in the aerospace industry, but relatively new to building.

### **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. 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."

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).

### 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 unsuitable. 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'être* as infinite variability becomes as feasible as modularity and as mass-customization offers alternatives to mass-production.

Digital architectures are profoundly changing the processes of design 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).

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