(In)Forming: The Affordances of Digital Fabrication in Design Education

MARK CABRINHA
California Polytechnic State University

Introduction

Donald Norman popularized the term "affordances" in the design and use of everyday objects. Rather than seeing the use of digital fabrication as novelty, probing the affordances of digital fabrication is warranted as these tools increasingly become part of design education as well as practice. Norman summarized in the most simplistic terms that an affordance means "is for", as a chair "is for" support and therefore a chair affords sitting. (Norman 1988:9). If these tools "are for" more efficient means to make models and smoother topographies the affordances of digital fabrication can have little pedagogical influence. Although Norman first wrote on the affordances of everyday things before the computer was an everyday thing, he has become critical of the common misuse of affordances in digital culture. He has made further clarifications on affordances through the distinction between perceived affordances, material affordances, and conventions of use. Perceived affordances are the subjective understandings, skills, and perceptions of the user, while material affordances are the more objective qualities of a given material, tool, or object, and finally conventions are the habits of use developed by a community of practice which tend to obscure the potential of perceived and and material affordances. (Norman 1999). Conventions of use are already forming that instrumentalize these digital fabrication tools as printers of form, without engaging the material as a medium in itself. (Figure 1). These conventions of use only amplify the tendency in digital design to output to material at the end stage of design, rather than the *preparatory* and *evaluative* role of digital fabrication as material feedback into the design process. Rather than seeing digital fabrication as a means of novel output, the view taken here is that these technologies are foundational: informing the design process as a groundwork for tool-driven research as a critical practice.

Fig. 1. Irregular Forms are Habitually Sliced to be Materially Consumed

The Conventions and Politics of Numerical Control

> *"By far the greatest latitude of choice exists the very first time a particular instrument, system, or technique is introduced. Because choices tend to become strongly fixed in material equipment, economic investment, and social habit, the original flexibility vanishes for all practical purposes once the initial commitments are made. In that sense technological innovations*

> *are similar to legislative acts or political foundings that establish a framework for public order that will endure for many generations."*
>
> *(Winner 1986: 29).*

The technology critic, Langdon Winner, is most famous for his question, "Do Artifacts have Politics?" These politics are not so much in the affordances of objects, as they are in the conventions of use once these technologies become institutionalized. His particular interest in technology is in how they become forms of life, and furthermore, how the conventions of use restrict the very forms of life that the technologies were supposed to enable. The politics of computer numerical control have been exposed in David Noble's, *The Forces of Production*. Noble follows a thorough history of the development of numerical control in the United States, and yet his bias is clear: the case of computer numerical control is an example par excellence of technology's separation of execution from conception. Nobles' account of the adoption of numerical control at GE in the 1970's focuses on shifting the balance of power from the machinist to the manager through the adoption of numerical control. While Noble's account is thorough, it is clear that both his focus as well as the GE managers focus was based on the appearances of the material affordances of computer numerical control, rather than the perceived affordances developed through their use. In fact, using the very same data that Noble presents in his book, Andrew Pickering's book, *The Mangle of Practice*, focuses on the means by which this technology can likewise have a liberating effect. Due to the machinists resistance on the shop floor as a result of how these technologies were being deployed, an inverse tactic was used which gave the machinists complete control of the manufacturing process through numerical control blurring the roles of forman, planners, programmers, quality controllers etc. (Pickering 1995: 163). This was so liberating, one worker called it "the new way of life." (Pickering 1995: 172). Rather than seeing technology as a separation of conception from execution as Noble did, accepting the indetermancies of use and expansion of agency enable an opportunity to bring execution into conception.

Although there are those in architecture that pursue pure form presuming execution is a given as a result of these technologies, the adoption of computer numerical control in architecture follows more closely the intent to bring execution into conception. More than 14 years ago on a x386 platform, the pioneering technological appropriation of Frank Gehry and his office makes this latter motive clear:

> *"The technology provides a way for me to get closer to the craft. In the past, there were many layers between my rough sketch and the final building, and the feeling of the design could get lost before it reached the craftsman. It feels like I've been speaking a foreign language, and now, all of a sudden, the craftsman understands me. In this case, the computer is not dehumanizing: its an interpreter." (Novitsky 1992: 105).*

The risk of following conventions and habits in use, is that the material affordances of digital fabrication are not understood to exploit the nature of materials the tools are working with. Perhaps the biggest challenge - and opportunity - in digital fabrication is that the material being manipulated is as much digital bits as it is physical atoms. In pursuing the material and perceived affordances of digital fabrication, the goal is to gain a foundational, even ontological, understanding of both the possibilities and intentions in formal conception. In bringing these advanced tools of execution into conception, new modes of execution change the nature of conception.

The Material Affordances of Digital Fabrication

Like watching a pen plotter in the early days, watching a CNC router can be mesmerizing - yet this is not where the work is being done. Watching the router, laser cutter, or rapid prototyper "work" and observing how they are used as discrete tools, tells very little about the affordances of digital fabrication. The material affordances of digital fabrication are largely driven by the constraints of the tools themselves. Constraints are not seen here as a negative, but enable the material affordances of the system - when one understands the material constraints of the system, the designers perceived affordances have friction to work from. While perceived affordances include the subjectivity of the user, material affordances are the objective criteria which restrict or enable the subjective use - understanding the material affordances focus the perceived affordances.

In each case of the three principle digital fabrication tools, the material stock able to be cut or built from and the tools' working volume are the principle constraints which become understood through use. Furthermore, subtractive fabrication is constrained by the 2, 3, 5 & 6 axes the tool can move within the working volume. Whereas additive subtraction is not constrained by these axes of movement, it is highly constrained by its small working volume, slow speed, and high cost of material. Despite the numerous intricacies of particular tools and materials, these few sentences outline the principle material affordances of digital fabrication.

Clearly the affordances of digital fabrication do not lie within these material affordances alone. These constraints enable the more significant material affordances of the simultaneous precision and flexibility of computer numerical control. Precision and flexibility are typically seen at opposite ends of the spectrum from the flexible hand to the precise machine. For example, Sigried Giedon's historical view of the precision of mechanization is formed around endless rotation - incredibly efficient and precise but the same thing over and over whereas the hand is a "prehensile tool, a grasping instrument" in which "flexibility and articulation are its key words." (Giedeon 1969: 46-7). From the view of the craftsman David Pye, this opposition between hand and machine is false - the machine is not simply about efficiencies of labor but an extension of the hand when precision is needed. (Pye 1995). Even Pye was optimistic about the diversity of shapes and surfaces through the use of computer numerical control. (Pye 129-130). In Malcom McCullough's Abstracting Craft, the relationship between the simultaneous precision and flexibility is afforded by the computer as "a means of combining the skillful hand with the reasoning mind." (McCullough 1998:81). The simultaneous precision and flexibility of digital fabrication, as CAD/CAM suggests, is the relationship between the material affordances of the computer and the material affordances of the data-driven fabrication tool. As the perceived affordances lie in this relationship, the significance of these tools is not self-evident in the tools themselves.

While efficiency is certainly an asset as well, the primary benefit of numerical control is not efficiencies of labor, but the efficiency of the simultaneous flexibility and precision which affords certainty in fabricating complex assemblies which precisely come together to form complex assemblages. The larger questions is not the means of efficiency that make formal complexity attainable, but the effectiveness of this formal complexity. Effectiveness develops from forming a broader context of the efficiencies of simultaneous precision and flexibility.

In fact, this is why the originator of the term affordances, coined by psychologist J.J. Gibson, took a wider ecological approach to his study of visual perception. This ecological approach is not an argument for sustainability as such, but a wider reciprocal relationship between organism and environment, accepting the subjective choice of the organism with the objective affordances in the broader environment or context of actions. He further describes the ecological concept of a niche, as a set of affordances, which refers more to how an animal lives than to where it lives. In suggesting that digital fabrication is just such a niche, a set of affordances, the suggestion is also how it is used, and in what context, more so than a new tool in the shop that needs to be exploited. Most significantly, Gibson's development of affordances takes the objective affordances of the environment relative to the perception of the user. The affordances of digital fabrication in design education should not only focus on the material affordances of digital fabrication - the invariant affordances in the given technology - but should be centered on the perceived affordances of the subjective user in relation to these given material affordances. However, one of the challenges of developing the perceived affordances of digital fabrication is that they are coupled to not only the material affordances of computer numerical control, but the material affordances of the digital surface.

The Material Affordances of the Parametric Surface

With the popularization of NURBS surfaces, most can now recite the words behind the acronym - non-uniform rational b-splines - but

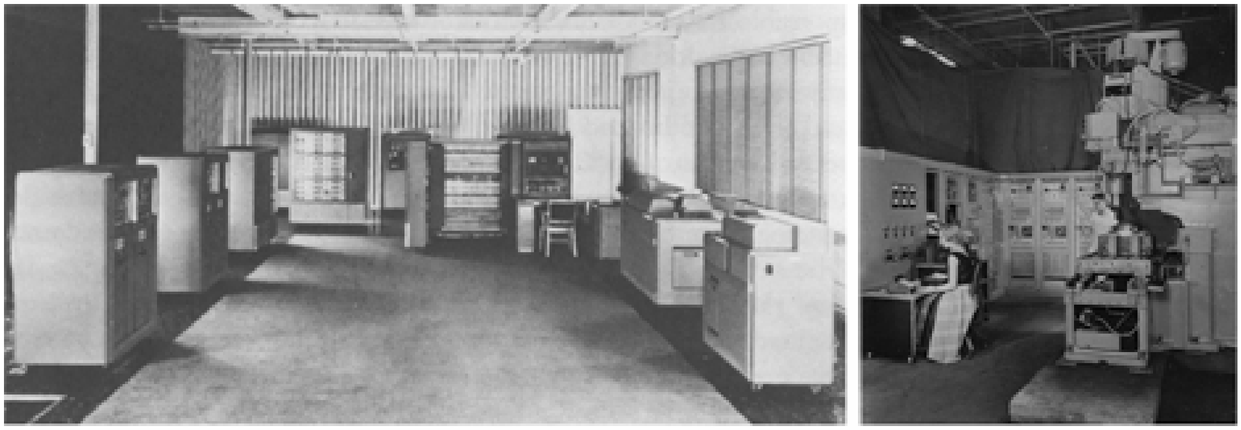

Fig. 2. 1952: The first commercially available computer and the first CNC mill at MIT.

do not understand the mathematical elegance in the simple parametrics that inform the complex surface. Although NURBS were popularized in architecture long before the current trend of digital fabrication, the computer and computer numerical control developed in lock-step in the 1950's. (Noble 1984). (Figure 2). Pierre Bezier was one mathematician among many who developed the mathematical basis of the parametric surface for the car industry in the 1960's as a consequence of the burgeoning development of computer numerical control. (Bezier 1972 Farin 1992). It is only in architecture that CAD was popularized at least 15 years before CAM, and that NURBS were introduced and theorized about without relation to the material system they were intended for.

Similar to the idea of the physical constraints of the apparatus in the tools of digital fabrication which yield their material affordances, understanding the very simple mathematical constraints of the NURBS surface yields its material affordances. While the variation of NURBS surfaces is considerable, derived from the mathematical development of NURBS their are principally only two means of developing these surfaces. One can start with a given surface or primitive shape and altering it through local and global transformations of the control vertices through moving, scaling, and rotating. The second means of developing a surface from a set of lines is quite determinate and yet enables a much larger degree of control and variation than the previous means. As already mentioned, the simplest surface, technically a patch, is formed from four given boundary curves connected at their endpoints. Similarly, a surface can be generated from four given boundary curves along with a number of given curves within that boundary. Lofting connects a set of given boundary curves as a surface. A rail or sweep develops the surface through a set of given curves along one or two given paths. A surface can be formed by revolving a given section about an axis, and similarly can be used in conjunction with a rail to revolve a given cross section connected to a given path around a given axis. While this may start to sound like a software tutorial, the importance here is to note that these properties develop from the mathematical basis of NURBS and therefore any NURBS based software will employ these functions although their names may be different. Secondly, in enumerating these determinate approaches, NURBS surfaces should not be seen as random but actually the complex outcome of fairly simple procedures. In other words, the mathematical elegance of NURBS surfaces affords complex behavior from a very simple structure. The tendency in architecture is to focus on the visual surface as the outcome, rather than understanding the simple structure that derives these forms. Furthermore, in every instance a surface is either given or developed from a set of given splines, and yet the fundamental question of what informs these "given" curves is rarely asked.

The mathematical elegance of NURBS surfaces allows either the simple manipulation of a given surface or shape or the generation of a complex surface from a few given curves. These simple manipulations are the result of the parametric structure as a result of the piecewise construction from the Bezier spline. The significance is that the simple manipulation of a few controlling elements yields a simple curve network with complex behavior. Yet the visual seduction of these formal surfaces on the screen has obscured the significant and very simple question: what informs form? Greg Lynn as the preeminent theorist and formal provocateur dodges the simplicity of this question through complex theorizing. Animate form is nothing other than the continual change of cross section along a path formed parametrically through animation software. "Force" manipulation is nothing other than simple surface manipulation controlled by simulation of gravity and soft and rigid bodies in the same animation software. (Lynn 1999). In other words, these two principle techniques are simply derived from the two families of manipulating NURBS surfaces made accessible through the software. With the idea of the performance envelope, Lynn's writing opens up the fundamental networked flexibility of the NURBS surface with the possibility of a determined yet flexible structure shaped through environmental influence. Though groundbreaking at the time, these influences are based on a visual simulation, rather than actual performance of real world constraints. In fact, Lynn has become critical of these earlier simulation tools as he explores more robust parametric tools such as Generative Components and Digital Project. (Ingebor 2006).

Appropriating Technology: Forming a Unifying Framework

Pierre Bezier developed his mathematical system to develop shape as a fluid and flexible parametric system in relation to the rigid cartesian world of machine tools. (Bezier 1972). Bezier's intent was not simply to draw or represent conventional means more efficiently, but to completely re-invent the design process as a unifying and interactive framework from design development to manufacture. (Bezier 1998). Bezier notes that a "stylist" could choose to work with sketches and small-scale mock-ups for their first intentions, but from that point on, the design process became part of this interactive parametric system. It was this connection to a material system that created a unifying and interactive framework from design through manufacture. Perhaps ironically, this sounds quite a bit like Gehry's design process. Yet it is not the forms derived from Gehry's process thatare significant, but rather the restructuring of practice enabled by this digitally enabled unifying framework. (Sheldon 2006).

The industrial trifecta of automotive, aerospace, and naval engineering are common analogies to advanced manufacturing in architecure as exemplified in *Refabricating Architecture*. While this comparison by analogy is productive, another way to understand the significance of digital fabrication in architecture is to understand its unique potential as a motivation for appropriating these technologies. In *Appropriating Technology*, three analytical distinctions of technological appropriation are reinterpretation, adaptation, and reinvention. "Digital fabrication" in architecture clearly meets the first two criteria: reinterpretation is the change of semantic use, such as from CAD/CAM to digital fabrication, and adaptation includes both this reinterpretation plus flexibility and the violation of the technologies intended purpose, such as taking tools for mass production to develop mass customization of the "one-off." However, the goal of appropriating technology is reinvention, which develops from reinterpretation and adaptation to a change in "structural use" enabled by this appropriation. Structural change in architecture has a double meaning: both the literal oppotunity of flexible and structural surfaces, and - more significantly - the change in social structure and agency of the architect. This conjoins the material implications of digital fabrication with the social impact of appropriating these technologies into a larger context of action. Following this analytical framework, the significance of these technologies is in the reinvention of the role of the architect through a structural change - a unifying and interactive framework between design and construction.

Perceived Affordances: Informing Form

The primary challenge of achieving this unifying framework is not a technical challenge, but a cultural one. The current emphasis on plastic form places emphasis on shape as the ultimate aim of architectural design. Emphaziziing the verb tense of form, forming is proposed as an active exploration that has both an effect on the object formed, and an affect on the individual forming. Forming, then, is Janus faced: looking out to the artifacts that are formed, while looking into

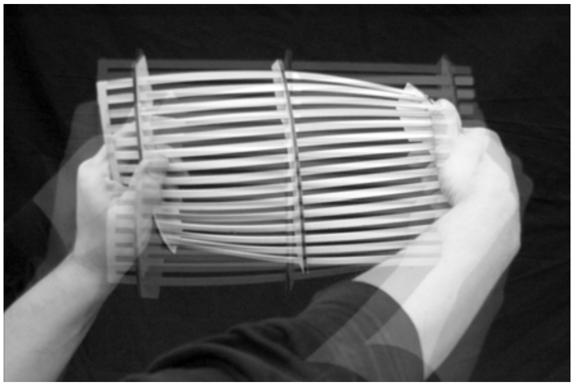

Fig. 3. Finding Shape in Material.

forming the skills, identity, and values of the designer. Through informing, form and content are not separate, nor is content absorbed into formalism, but as Henri Focillon has developed "form is the record of dynamic organization." (Focillon 1992). "Content" then is not objective fact that need packaging, but is the dynamic organization that informs form. Through the idea of form as a record of activity, Focillon asks "what is the bounds of art?" (Focillon 1992). Rather than predetermine the bounds of digital fabrication, probing the affordances of digital fabrication identifies form as the record between the perceived and material affordances in a given context.

The material affordances of digital fabrication have been presented as the simultaneous flexibility and precision of these tools in conjunction with the ability to develop complex behavior from a simple structure through the parametric surface. These can be understood through use, but it is the perceived affordances of the design student that is of critical importance to design education. As schools across the country tool-up, it is critical to not instrumentalize the technology as printers of form, but rather to develop the perceived affordances through the *relationship* between the digital and the physical in a given context.

As digital fabrication is still new in many places, these technologies develop frequently in seminars that place focus on the technologies. However, it is also not uncommon to see design studios focused on digital technique. Both the boutique seminar and the digital technique based studio place technology at the foreground – and so it should be no surprise that these reinforce form as the primary aim of design. Following Focillon, the question is not about form, but how form demonstrates the dynamic organization of design. This would require that these technologies move from the foreground to the background. Placing the tools in the foreground allow a critical appreciation of the material affordances of the tools. However, it is also necessary to allow these tools to recede into the background such that the perceived affordances of their use can engage a broader context of design issues and the potential solutions the material affordances of the tools enable. As the perceived affordances develop through the relationship of these tools in a given context, the significance of digital fabrication is on the interactivity between material and the digital. As result of formal emphasis, a satisfactory solution is typically the output of form and material. Focusing on interactivity, the question is how material can become both an input and a means of feedback into the design process.

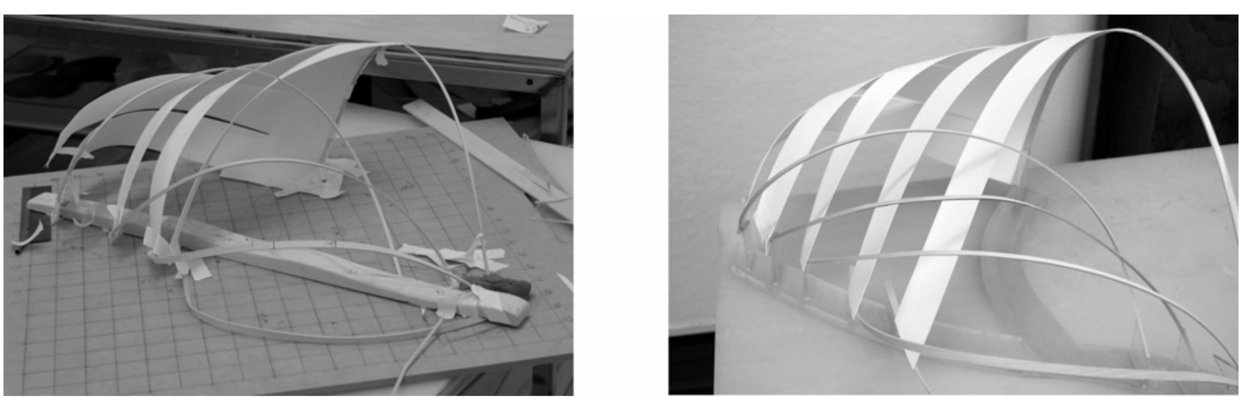

Fig. 4. Materials First: Surfaces and Splines are digitized, refined and then unrolled for verification.

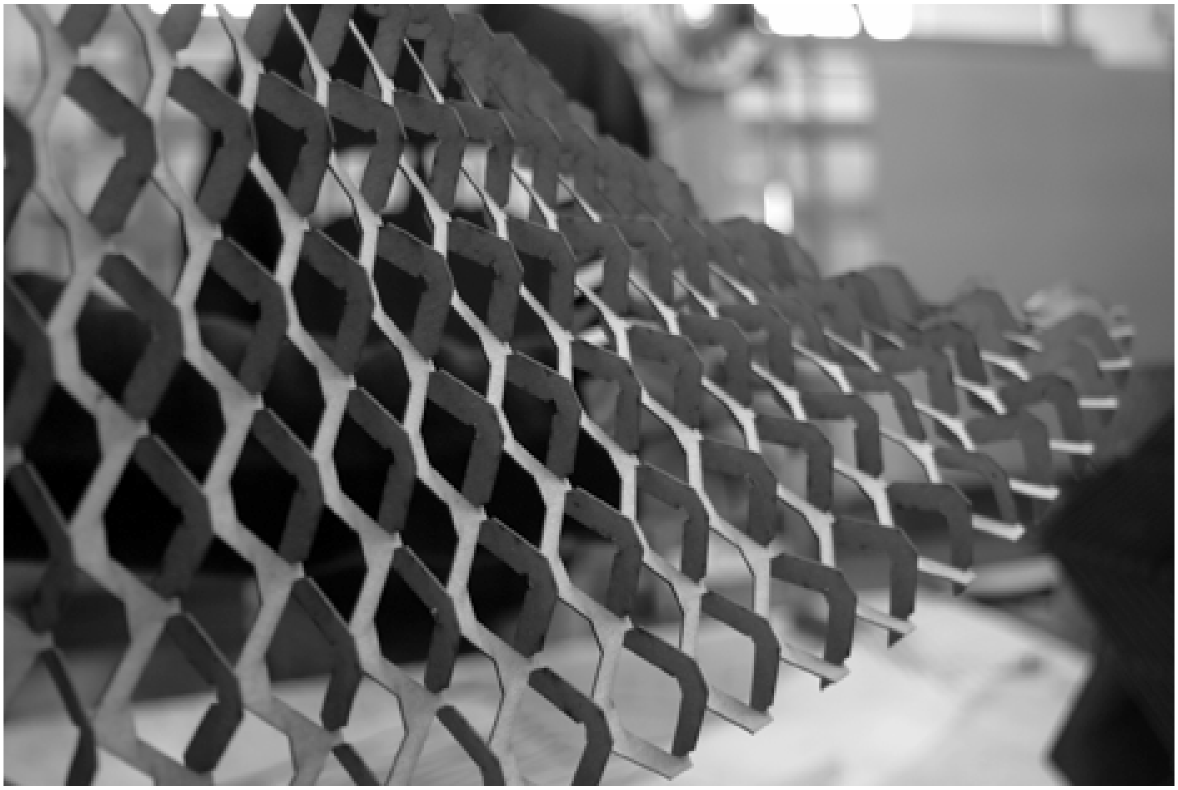

Fig. 5. Expanding Surface.

As an opposite tactic from the habitual and conventional slicing, a distinction can be made that moves from cutting shape out of material to finding shape in material. (Fig. 3). As there are two ways to manipulate surface in NURBS, one building up from the piecewise curve and the other from manipulating a given surface, presented here are two approaches to finding shape in material.

Through understanding the principles of the Bezier curve in relation to a material system, the larger development of NURBS can be materially derived. Bezier took his inspiration for the spline from the 18^{th} Century spline, in which the material of the spline was analogous to the curve used in shipbuilding. Beginning with a material spline, the relationship between material resistance and the principles of NuRBS are developed in tandem. Through the basswood spline, binary, quadratic, and cubic degrees of curvature are introduced, such that the physical curve on a laser engraved grid can be recorded by its control points, two measurements for linear, three for quadratic, and four measurement points for cubic curves. Beginning with material in the physical world, these material tests are digitized, developed more accurately in the computer, and then outputted again as a test of verification of this process. Taking this materials first approach, material resistance is taught in tandem with understanding NURBS surfaces. (Fig. 4).

Another approach is taken in expanding sheet material through the precision of laser cut patterns. This takes an inverse tactic to the typical material waste in cutting shape out of material and expands the shape 2-3 times from sheet material. (Fig. 5.)

[Author Note: These results are from a design build studio in progress. It is my intention to add the final results.]

Conclusion

As digital fabrication becomes part of the everyday tools of design education, critical attention is needed on how the affordances of these technologies impact not only design methods but the very motivations of design. If they are treated as printers of form or more efficient means of model making, the risks of deskilling are warranted. However, through the history of the development of these technologies, and the fundamental and historical relationship between CAD and CAM, the opportunity they present is a restructuring of the architect's agency in the design process. The fundamental question is not what they output, but how these outputs become feedback into the design process.

References

Bezier, Pierre. *Numerical Control (Wiley Series in Computing)*. John Wiley and Sons Ltd, 1972.

Bezier, Pierre. "A View of the CAD/CAM Development Period." *IEEE Annals of the History of Computing*. Vol. 20, No. 2 (1998): 37-40.

Eglash, Ron, Jennifer L. Croissant, Giovanna Di Chiro, and Rayvon Fouche. *Appropriating Technology: Vernacular Science and Social Power*. University of Minnesota Press, 2004.

Farin, Gerald E. *Curves and Surfaces for Computer-Aided Geometric Design: A Practical Guide (Computer Science and Scientific Computing Series)*. Academic Press, 1992.

Focillon, Henri. *The Life of Forms in Art*. New York, New York: Zone Books, 1996 (1934).

Gibson, James J. *The Ecological Approach to Visual Perception*. Lawrence Erlbaum Associates, 1987.

Giedion, S. *Mechanization Takes Command*. W W Norton & Co Inc, 1969.

Kieran, Stephen, James Timberlake, Stephen Kieran, and James Timberlake. *Refabricating Architecture: How Manufacturing Methodologies are Poised to Transform Building Construction*. McGraw-Hill Professional, 2003.

Lynn, Greg ed. *Folding in Architecture (Architectural Design Profile)*. John Wiley & Sons, 1993.

Lynn, Greg. *Animate Form*. Princeton Architectural Press, 1998.

Lynn, Greg. *Folds, Bodies & Blobs : Collected Essays*. La Lettre Volee, 1998.

McCullough, Malcolm. *Abstracting Craft: The Practiced Digital Hand*. The MIT Press, 1998.

McCullough, Malcolm. *Digital Ground: Architecture, Pervasive Computing, and Environmental Knowing*. The MIT Press, 2005.

Noble, David F. *Forces of Production*. Knopf, 1984.

Norman, Donald A. *The Design of Everyday Things*. New York, New York: DoubleDay, 1988.

Norman, Donald A. "Affordances, Conventions, and Design." *Interactions*. May/June (1999): 38-42.

Novitsky, B.J. "Gehry Forges New Computer Links." *Architecture*. August (1992): 105-110.

Pickering, Andrew. *The Mangle of Practice: Time, Agency, and Science*. University Of Chicago Press, 1995.

Pye, David. *The Nature and Art of Workmanship (Design Handbooks S.)*. Herbert Press Ltd, 1995.

Rocker, Ingeborg M. "Calculus-based form: an interview with Greg Lynn." *Programming Cultures (Architectural Design)*. Vol. 76, Issue 4 (2006): 88-95.

Sheldon, Dennis R. "Tectonics, economics and the reconfiguration of practice: the case for process change by digital means." *Programming Cultures (Architectural Design)*. Vol. 76, Issue 4 (2006): 82-87.

Winner, Langdon. *The Whale and the Reactor: A Search for Limits in an Age of High Technology.* University of Chicago Press, 1988.