MANUFACTURING MATERIAL EFFECTS
RETHINKING DESIGN AND MAKING IN ARCHITECTURE
EDITED BY BRANKO KOLAREVIC AND KEVIN KLINGER
THE (RISKY) CRAFT OF DIGITAL MAKING
NOTES
2 The abbreviation CNC stands for computer numerical control and refers to a computer control unit that reads the digitally encoded instructions and drives a machining tool used in fabrication based on the selective removal of material (as in subtractive fabrication).
4 Ibid., p. 22.
6 McCullough, op. cit., p. 21.
8 Parametric explorations by Nia Garner; Performative Architecture design studio, Branko Kolarevic, University of Pennsylvania, Graduate School of Fine Arts, Philadelphia, fall 2003.
10 The underlying computational processes are actually highly deterministic; it is our inability to anticipate the outcomes of these processes that gives them the qualities of unpredictability and indeterminacy.
11 For more information, see Kolarevic, op. cit, Chapter 3, “Digital Fabrication.”
13 The different techniques of crafting surface effects using parametrics and digital fabrication technologies were explored in a four-week project within elective courses at the University of Pennsylvania in the spring of 2005 and at Ball State University in the fall of 2005 and the spring of 2007.
14 Striations, by Carmen McKee and Fuyuan Su; Digital Fabrication course, Branko Kolarevic, University of Pennsylvania, School of Design, Philadelphia, spring 2005.
15 NURBS stands for Non-uniform Rational B-splines.
16 Field Explorations, by Jill Desimini and Sarah Weidner; Digital Fabrication course, Branko Kolarevic, University of Pennsylvania, School of Design, Philadelphia, spring 2005.
17 The parametric setup was extremely simple: the size of the dots for halftoning, and the angle and distance for the motion blur image transformation in Photoshop, and the extent of height deformation in Rhinoceros. The point is that complex effects could be produced with simple, parametrically driven tools, that are more or less readily available in every “digital craftsman’s” toolkit.
19 Kinetic Hyposurface, by Dustin Headley and Mickel Darmawan, Contemporary Praxis: From Digital to Material course, Branko Kolarevic, Ball State University, College of Architecture and Urban Planning, Department of Architecture, Muncie, Indiana, fall 2005.
20 Even though only a simple prototype was produced, this project could be further developed into a shading screen, or a highway acoustic barrier; producing in both cases an intricate, dynamic effect as one moves along.
21 Expanded Topographies, by Dustin Headley, Parametric Constructions course, Kevin Klingler and Branko Kolarevic, Ball State University, College of Architecture and Urban Planning, Department of Architecture, Muncie, Indiana, spring 2007.
22 As in the Kinetic Hyposurface project, only prototypes were produced as a test of the concept. The project could be further developed into a facade rain or shading screen by working with aluminum metal sheets that could be cut and expanded (albeit through a different process from what is currently done in the industry).
An architect must be a craftsman. Of course any tools will do; these days, the tools might include a computer, an experimental model, and mathematics. However, it is still craftsmanship — the work of someone who does not separate the work of the mind from the work of the hand. It involves a circular process that takes you from the idea to a drawing, from a drawing to a construction, and from a construction back to idea.

(Renzo Piano)

Architecture as a material practice implies that making, the close engagement of the material, is intrinsic to design process. Making, however, is increasingly mediated through digital technologies: today, it is the CNC machines and not the hands of the maker that mostly shape materials and their properties. Digital making — the use of digital technologies in design and material production — is blurring the sharp discontinuities between conception and production established in the twentieth century. New techniques based on close, cyclical coupling of parametric design and digital fabrication are restructuring the relationships between design and production, enabling a closer interrogation of materials during the earliest stages of design.

For example, designers today, like resurrected craftsmen of the past, are increasingly using new digital techniques and technologies to explore surface effects, such as pattern, texture, relief, or variable properties, as a means through which building surfaces manifest the design intent, at a range of different scales. As surfaces become more complex in form, shape, composition, and appearance, the generation and manufacturing of material and surface effects become a locus of design and production efforts.

As argued later in the chapter, these effects are designed and produced with an iterative precision, where the final outcome is carefully crafted through cyclical interactions between the conceptual and representational articulation of geometry, its performative dimensions and material manifestation, and the economic and technological realities of manufacturing and assembly. In this context, craft is no longer entrusted to the realm of production, which was its operative domain historically; it is manifest everywhere — in the definition of geometry and its manipulation, the engagement of the material and its production process, and in the multiple circular feedback loops that these emerging non-linear processes entail.

THE CRAFTSMANSHIP OF RISK

Any discussion of craft in general in a contemporary context requires an apt definition of this, as some would argue, rather obsolete term, and in particular, of what is meant by the notion of craft in architecture. In the book Abstracting Craft, Malcolm McCullough provides an excellent examination of contemporary meanings of craft, both as a noun and as a verb, and describes the technological and cultural origins of what he calls “digital craft,” an emerging set of material practices based on digital media that engage both the eye and the hand, albeit in an indirect way. He refers to this as “the seeming paradox of intangible craft.” McCullough argues that “digital craft” as a term is not an oxymoron, but that today the craft medium need not have a material substance, and the craftsperson need not touch the material directly.

Although McCullough’s book offers a seminal examination of the contemporary meanings of craft, it is David Pye who has provided, more than 30 years earlier, in his book entitled The Nature and Art of Workmanship (published in 1968), a definition of craftsmanship that is particularly suitable for our contemporary “digital age:”

Craftsmanship ... means simply workmanship using any kind of technique or apparatus, in which the quality of the result is not predetermined, but depends on the judgment, dexterity and care which the maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making.

David Pye distinguishes manufacturing from craftsmanship, defining manufacturing as the workmanship of certainty and craftsmanship as the workmanship of risk. According to Pye, an artifact is manufactured (industrially or by hand) if the risks involved in its creation are minimal; on the other hand, an artifact is crafted if there are risks involved in its
creation and production, i.e. if "the quality of the result is not predetermined, but depends on the judgment, dexterity, and care which the maker exercises as he works," as quoted above.

The *craftsmanship of risk* – the notion of craft in which an outcome "is continually at risk" – has particular resonance today. In contemporary practices that have fully adopted digital technologies into the processes of design and production, digital media is often deployed to *discover* a promising formal configuration or spatial organization. In other words, results of a particular design process are not predetermined or anticipated – they are to be discerned among many alternatives and variations produced in carefully articulated, structured investigations, often in a circular, non-linear fashion. As the unanticipated design outcome hinges on discovery – and the discovery is by no means certain – there is an implied element of risk in the entire process. This notion of risk, stemming from the inherent lack of predetermined design outcomes, is how we could interpret Pye's seminal work in a contemporary context. McCullough affirms this essential idea: "In digital production, craft refers to the condition where [we] apply standard technological means to unanticipated or indescribable ends."6

CRAFT IN PARAMETRIC DESIGN

In contemporary architectural design, digital media is used not only as a representational tool for visualization, but as a generative tool for the derivation of three-dimensional constructs and their transformation.7 In a radical departure from centuries-old traditions and norms of architectural design, digitally generated forms are not designed or drawn as the conventional understanding of these terms would have it, but they are calculated by a chosen generative computational method, most of which are based on some form of parametric design.

In parametric design, the parameters of a particular design are initially declared, not its shape or form. By assigning different values to parameters, different geometric configurations emerge. Parametric variation can be automatic (figure 10.1), or can be controlled manually, in discrete, incremental steps; when specific values are assigned to parameters, particular instances are created from a potentially infinite range of possibilities. Furthermore, equations are used to describe the relationships between objects, thus defining an associative, linked geometry. This way, interdependencies between objects are established, and objects' behaviors under transformations are defined. These interdependencies become the structuring, organizing principle for the generation and transformation of the geometry. How these interdependencies are structured and reconfigured depends to considerable extent on abilities of the designer to *craft* these relationships precisely.

In parametric design, the conceptual emphasis shifts from particular forms of expression (geometry) to specific relations (topology) that exist within the context of the project. Using parametrics, designers create an infinite number of similar objects, which are geometric manifestations of a previously articulated schema of variable dimensional, relational or operative dependencies. Shapes and forms become variable, giving rise to new possibilities, i.e. the *emergent form*. Instead of working on a *parti*, the designer constructs a generative, parametric system of formal production, controls its behavior through parametric manipulation, and selects forms that emerge from its operation for further development (figure 10.2). For instance, designers can see forms as a result of reactions to a context of "forces" or actions, as demonstrated by Greg Lynn's work.9 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.10 Structural and formal complexity is also often deliberately sought, and this intentionality oftentimes motivates the processes of construction, operation, and selection in parametric design.

The capacity of parametric computational techniques to generate new design opportunities is highly dependent on the designer's perceptual and cognitive abilities, as continuous, transformative processes ground the emergent form, i.e. its discovery, in qualitative cognition. The designer essentially becomes an "editor" of the generative potentiality of the designed system, where the choice of emergent forms is driven largely by the designer's aesthetic and plastic
sensibilities. The designer simultaneously interprets and manipulates a parametric computational construct in a complex design development process that is continuously reconstituting itself. This “self-reflexive” process relies on the visual results of the deployed generative parametric procedure to actively shape the designer’s thinking process. The potential for crafting the parametric processes of conceptual production—and the outcomes of those processes—lies precisely in the designer’s capacity to effectively edit the minutiae of the underlying parametric generative system. This capacity comes with experience and dexterity—knowing intuitively which small quantitative change could potentially produce a qualitatively different outcome (the so-called “threshold” effect). This is precisely how many of the conventional, creative crafts operate.

By stressing the discovery of form, the determinism of traditional design practices is abandoned for a directed, precise indeterminacy of innovative digital, parametric processes of conception. There is an explicit recognition that the admittance of risk—the unpredictable and unexpected—paves the way to poetic invention and creative transformation. Non-linearity, indeterminacy, and emergence are intentionally sought, with a considerable degree of risk involved, as the successful outcomes (however determined) are anything but certain.

**CRAFT IN DIGITAL FABRICATION**

While the digital techniques of parametric design have redefined the relationship between conception and representation, enabling the designers to carefully craft the formal outcomes through iterative processes, the technologies of digital fabrication have facilitated a closer investigation of material outcomes at the earliest stages of design.

The various computationally numerically controlled (CNC) processes of shaping and reshaping, based on cutting, subtractive, additive and formative fabrication, have provided designers with an unprecedented capacity to control the parameters of material production, and to precisely craft desired material outcomes. Knowing the production capabilities and availability of particular digitally driven fabrication equipment enables designers to design specifically for the capabilities of those machines. The consequence is that designers are becoming much more directly involved in the fabrication processes, as they create the information to be translated by fabricators directly into control data that drives the digital fabrication equipment.

For example, using digital fabrication technologies in sheet-metal production, corrugated, flat, and curved profiles can be perforated, drilled, milled, etc. in a wide variety of ways. Virtually any corrugation profile can be produced including variations in frequency and amplitude; perforations of any pattern can be produced by mechanical milling. A very good example of what could be attained with flat sheets is the recently completed de Young Museum in San Francisco (2005), designed by Herzog & de Meuron. The large surfaces of the rain screen that wraps the building are made from over 7,000 copper panels (12 ft by 2½ ft in size), each of which features unique halftone cut-out and embossing patterns abstracted from images of surrounding tree canopies. The circular perforations and indentations produce abstract patterns and images when seen from a distance, similar to how halftone patterns of dots of varying size fool the eye into seeing different shades of gray in newspaper images. A number of geometric and material alternatives were developed in an iterative fashion (figure 10.3), in early...
10.5. Striations, a paneling system by Carmen McKee and Fuyuan Su.

10.6. Striations: isoparametric curves were used directly as CNC toolpaths.

In the *Striations* project\(^\text{14}\) (figure 10.5), Carmen McKee and Fuyuan Su modeled a simple time-based parametric process, based on force physics simulation, using *Maya* animation software that resulted in different undulations of a rectilinear surface. Isoparametric curves, used in visualizing NURBS\(^\text{15}\) surfaces, were extracted from selected frozen frames of the time-based animation and translated directly into CNC toolpaths for milling (figure 10.6). The density and number of isoparametric curves were carefully explored (figures 10.7a–c), as were the sizes of milling bits, and whether round or flat bits should be used (figure 10.8). Equally important were the hardness and texture properties of the wood to be used in production. Thus, the process was defined by parameters related to designed geometry, parameters pertaining to production (such as the size and shape of the milling bit, the feed-rate, etc.) and parameters related to the material itself, such as wood hardness, grain size, etc. These parameters were interrelated, thus numerous design opportunities were explored through several iterations informed by continuous feedback loops between design and production. In the end, the panels were manufactured at the rate of 15 minutes per panel, each of which was 1' by 2' in size (figure 10.9), and assembled in a linear configuration (figure 10.5).

In the *Field Explorations* project\(^\text{16}\) (figure 10.10) by Jill Desimini and Sarah Weidner, the parameters that defined the geometry of panels were based on image processing techniques using *halftoning* and *motion blur* operations. Selected sequences of images were first halftoned using *Photoshop* and then a motion-blur filter was applied to the halftones, resulting in what appeared as a grayscale image of an undulating surface (figures 10.11a–b). These bitmap images were translated into height-deformation maps once imported into *Rhinoceros* modeling software to define the extent of deformation of a flat, meshed square surface.\(^\text{17}\) The deformed surface configuration was used to compute milling paths using *MasterCAM*.

A number of different material studies (figures 10.12a–c) were conducted, involving a plywood panel (found acceptable because of the intricate surface effects resulting from the revealed layering of the material), laminated wood dowels (rejected because the dowels were visually
and a composite made of acrylic over plywood (rejected primarily because of difficulties in production). In the composite configuration, the intent was to superpose halftone patterns over the undulating topography resulting from the motion-blur images (figure 10.13); the halftone pattern was laser-etched in acrylic as a top layer thermally slumped over the topographical surface CNC-milled in plywood.

The final field configuration was achieved using CNC-milled plywood, with the intent of using the material's lamination (its inherent material property) to produce a subtle and intricate surface effect, both locally, within each panel, and globally, over the entire panel assembly. The initial production attempt was unsuccessful (figure 10.14), as the grain of the wood was not taken into account. To further aggravate the production process, the milling feed-rate (the speed with which the milling bit is moved through the material) was too high, resulting in complete destruction of the material. Minor adjustments in the geometry, careful selection and positioning of the laminated sheet of plywood, and careful setting of the production parameters, yielded in the end rather compelling surface effects. As in the previous project, the parameters related to the production (size of the milling bit, etc.) and the properties of the material (texture, hardness, etc.) were crucial to the overall success of the project; the feedback loops between design and production were essential for the success of the project. After several, quick iterations, the final field configuration (figure 10.15) was carefully and quickly produced.
In the *Kinetic Hyposurface*, Dustin Headley and Mickel Darmawan were interested in carving out a complexly shaped volume from a stack of layered sheets, with members spaced apart to reveal an inner void (figure 10.18). The outcome was quite surprising, i.e. purely incidental: as one’s eyes moved along the side of the resulting construct over time, a subtle, dynamic effect emerged. This performative aspect of the resulting “kinetic hyposurface” was fine-tuned by exploring different values for key parameters, such as the thickness of the layers, and the size of the spacing between the layers. As with previous projects, the parametric definition of the geometry was fairly simple, as well as the production of the individual panels. After several quick iterations, the (virtually kinetic) result was more than the sum of the (static) panels, carefully arranged in a linear sequence.

**ECONOMY OF METHOD**

An important design and production dimension of the described projects was a certain “economy of method,” introduced as “less effort, less machine time, less material, less waste,” and summed up in the end as “less for more” – a thinly veiled reference to Mies van der Rohe’s famous aphorism, but with an entirely different connotation. This design/production dimension was an attempt to introduce *resource economy* (time-, material-, and energy-wise) into the design and production processes. Complex effects were to be achieved through simple means; the underlying ethos being that complexity need not be synonymous with complicated, i.e. that conceptual and production simplicity can produce a perception of complexity in the outcome.

*Expanded Topographies* (figure 10.19), a project by Dustin Headley, offers a particularly successful demonstration of such a resource economy approach to design and production. It was inspired by research into expanded metal meshes, which are produced by simultaneous slitting and stretching of a flat sheet of metal, resulting in a regular, repetitive pattern of diamond-shaped holes. What is interesting about this process is its geometric and production simplicity, and that nearly zero metal waste is generated during the process; in addition, the final product – the expanded mesh – is stronger (by kilogram) and lighter (by meter) than the original sheet.

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The *Parametric Weave* screen (figure 10.16) by Virginia Little and Maggie McManus was modeled using a simple time-based, force-physics simulation process using *Maya* animation software resulting in slight, ripple-like undulations of a rectilinear surface. Isoparametric curves were extracted in both U and V directions from each surface configuration, and used as sweeping paths for circular profiles of gradually increasing radii. The resulting configuration of “tubes” was cut with a flat plane, revealing the internal voids in the tubes, and producing an intricate surface effect (figure 10.17). This subtle effect was produced by accident, due to the fact that solids were represented in the modeling software as enclosed voids. The “parametric weave” was then milled quickly in ordinary insulation foam panels, which were then coated with a layer of white hi-gloss latex house paint, resulting in an intricate latticework screen configuration.
The project’s premise was that variegated surface patterns, i.e. apertures of gradually increasing or decreasing sizes, could be produced by simply varying the values of expansion parameters including the length of cut, aligned spacing between the cuts, and spacing between the successive lines of cuts. Using scripting with Rhinoceros, a simple parametric procedure automatically generated different cutting patterns (figure 10.20), which could be directly transmitted to a digitally controlled cutting machine. Various prototypes were produced by laser-cutting flat, rectangular sheets of acrylic, which were then heated and expanded by applying equal force (in opposite directions) to the two shorter sides of the sheet. The sheets would deform in the process, depending on the density and the lengths of the cuts, producing topographic surfaces, with apertures that vary in size across the length of the surface. Precise topographies were produced by controlling the length of each cut and X and Y spacing between the adjacent cuts. In addition, by making non-parallel cuts, i.e. by introducing angle as an additional parameter, further possibilities for surface articulation opened up. The design and production processes were simple and straightforward, with nearly zero material waste, resulting in an artifact with intricate surface effects, subtle undulations and series of apertures that change in size across the length of the panel.22

CONCLUSIONS
In design and production processes driven by digital technologies – digital making – craft is understood as a set of deliberate actions based on continuous, iterative experimentations, errors, and modifications that lead to innovative, unexpected, and unpredictable outcomes, discovered in the intertwined processes of conception and production. More precisely, craft in this context is associated with slight adjustments and subtle changes to parameters that define processes of design and production in search of such an outcome. Knowing what, why, and how to adjust requires deep knowledge of the processes, tools, and techniques, just as it did in the pre-digital era.

Designers – contemporary craftspersons – are in continuous control of design and production and rely on iterative, cyclical development based on feedback loops between the parametric definition of the geometry and the digital fabrication of material artifacts. The discoveries are in most cases directly dependent on unanticipated outcomes and are anything but ascertained (and to reiterate, therein is the contemporary understanding of Pye’s “workmanship of risk”). Designers are constantly looking for particular affordances that a chosen production method can offer, or unexpected resistances encountered as they engage a particular tool and a piece of material. This constant, cyclical interaction between the “work of the mind” and the “work of the hand,” in the words of Renzo Piano, is what provides a particularly rich and rewarding context for design and production. This highly iterative process is the essence of the contemporary understanding of craft – the craft of digital making.

10.20.
Expanded Topographies:
a simple parametric procedure automatically generates different cutting patterns.