Contextual and Systemic Design

Changing Forms, Changing Processes

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Is it the form that drives the design and production process, or the processes themselves that determine forms? While often design expression pushes engineering ingenuity to invent new solutions, it is typically technological innovation that offers the tools to designers to explore new formalistic domains. Through the course of history, design practice has been integrating technology, people, and materials to invent new methods to increase form customization while decreasing production costs. We are witnessing a transformation within the building industry of what was previously known as empirical craftsmanship to today's highly controlled digital fabrication. Nevertheless, today's digital technology seems to raise as many questions in design practice and research as it answers.

The Industrial Revolution

The industrial revolution established standardization, mass production, and prefabrication in the building industry. Large machines effectively replaced manual labor in simple, repetitive tasks, while skilled workers concentrated on the cognitively complex tasks of assembling, handling, and distributing. Spurred by the machines' high setup costs, industries standardized components, processes, and shipping methods while production volume increased dramatically to benefit from economies of scale. Prefabrication factories used more sophisticated production and logistical processes to remotely fabricate, preassemble, and deliver building parts to the construction site for final assembly and installation. Panelized modules with universal interfaces could be combined in multiple ways like Lego blocks and flat-packed inside shipping containers to decrease project delivery time and supply-chain costs. Suppliers and fabricators specialized in products and services, formulating collaborative alliance clusters in geographically larger market networks.

Mass production and prefabrication systems created highly centralized supply chains, while their cost efficiency depended heavily on location and shipping volume. Design representation methods focused on Euclidean orthographic projections of floor plans, cross-sections and elevations to share technical information between contractors and designers, spreadsheets to order materials and estimate costs from suppliers, and perspective drawings or physical models to communicate ideas to clients. Furthermore, increasing standardization and repetition of building forms disengaged designers from studying custom structural details, as most technical specifications were now predefined by the industrial suppliers and building contractors, who could often change the design outcome significantly.

The Digital Revolution

The digital revolution has seamlessly integrated design and manufacturing, allowing designers to build a 3D CAD model on a computer and directly fabricate it using a CNC machine. Initially developed for the aerospace, naval, and automotive industries, digital design and fabrication are now transforming the building industry, reshaping processes, forms, and services. Widespread availability and decreasing cost of personal computers, fabrication machines, and software packages is making digital design and fabrication increasingly accessible to designers, engineers, contractors, material suppliers, and building product manufacturers.

Digital Design

Computer-aided design (CAD) replaced hand drafting by allowing designers to automatically create, modify, and reproduce digital drawings on demand.

The first CAD programs had a non-associative modeling approach, such that modifying a component of the model had no impact on the rest of the geometry. This made the design process rather tedious and time-consuming, as the designer had to manually adjust each component of the model. Modern CAD programs changed the designing process from a mere geometric representation of unassociated forms to a functional description of processes that can generate those forms. This shift from representation of forms to description of processes is a fundamental concept in modern computational design practice, as computer programs now follow the design instructions and remodel the resulting geometry for different input parameters. Modern computational design thus eliminates redundancy and opens the doors of complex geometric modeling to designers.

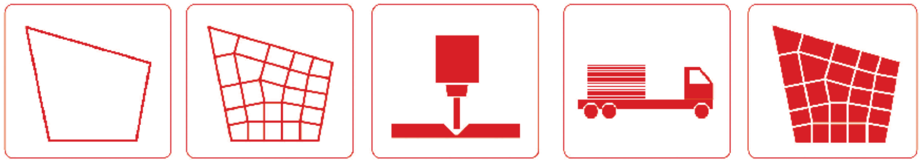
Computational modeling methods today can use either generative or parametric design approaches; often, however, a CAD model will combine both of them. Generative design focuses on algorithmically creating geometric forms by programming a list of instructions in a scripting language that, once executed by a CAD compiler, produces the resulting forms. The scripting language manipulates primitive geometric components such as points, lines, planes, and surfaces using variables, functions, conditional statements, loops, and grammar rules. Generative design deploys a bottom-up approach that can produce topologically different results, an aspect that makes it popular in form-finding and form-optimization techniques. Parametric design, on the other hand, is based on hierarchically associating geometric components of the model with mathematical equations such that modifying any input parameter of a component propagates changes in the entire model. Parametric modeling has a top-down approach, moving from the "parent" components (often called the driving geometry) to the "child" components, while their topological structure remains unchanged. Often an entire parametric model can be encapsulated and used as a component in another parametric model.

A computational design model can thus be considered a black box that takes input arguments and outputs a resulting geometry. Such black-box models can be linked to external databases to store and exchange properties that in turn can be further linked to other models, programs, or collaborators, creating dynamic workflow chains that automatically update, each time a change in one of the links occurs. Designers thus can model complex geometric forms and instantly change the thickness of the walls, the profile curve of a beam, or the density of a structural grid, updating in real time the entire model and the exported properties lists, without endless hours of rework.

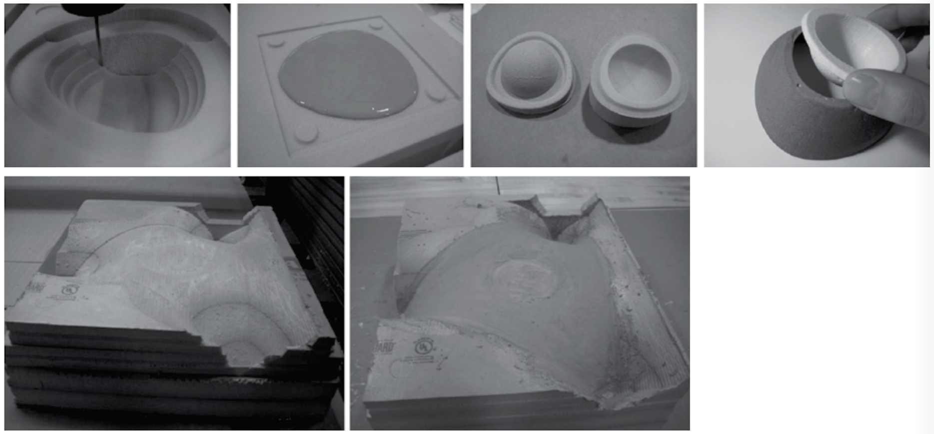
Computational modeling, however, is also an experience-based skill. In contrast to traditional non-associative geometric modeling, there is no single approach to building a computational model: the same result can be reached by different parametric or scripting approaches, but the level of control will be different in each case. Selecting the appropriate design method to build a computational model depends on thoroughly understanding the design requirements and available data; availability of a clear project scope and contextual parameters can distinguish a good modeling strategy from a bad one.

Digital Fabrication

Digital fabrication or computer-aided manufacturing (CAM) uses computers to digitally control high-precision fabrication machines (CNC) to build physical prototypes from CAD files. A special computer program translates the input CAD file into a tool path, while a control system in the machine drives the motors of the tool tip along the path during fabrication. Digital fabrication methods can be either subtractive or additive, depending on whether they remove material from a monolithic block (milling, laser-cutting, plasma-cutting, etc.), or instead deposit material into stratified layers (3D printing, fused deposition modeling, etc.). Depending on the number of axes and motors that move the tool tip, a fabrication machine can have two, three, four, or five degrees of freedom, with a significant impact on fabrication capabilities. Typically the tool tip is moving relative to a stable bed, the dimensions of which limit



Digital fabrication production workflow



CNC milled molds and formwork can be used to cast plastics or composite materials

the maximum size of a part that can be machined. However, research today uses autonomous mobile robots equipped with CNC fabrication machines and sophisticated geo-positioning systems that can navigate in space fabricate similar to the drawing turtles of the classic LOGO language.[1]

Computers, digital fabrication machines, and assembly stations can be combined to create very efficient production systems. Workflow starts from the development of a master model, rationalization and decomposition of the master model into detailed part files, distribution of the part files to the fabrication units for machining, shipping of the finished parts to the construction site, and final assembly. These processing steps can be linked through programs, computers, machines, and humans, creating a dynamic production system that can make almost anything, anywhere, and at any time at a cost depending mainly on material, equipment type, machining time, and shipping distance.

The digital fabrication supply chain is spatially and functionally decentralized. As local fabrication facilities and internet communication means spread around the world, a CAD model being developed in North America can be electronically sent to fabrication shops in Asia for prototyping and shipped to a nearby construction site for assembly, significantly decreasing transportation costs. Furthermore, as digital fabrication machines become smaller, smarter, and cheaper, an entire fabrication unit can fit inside a shipping container and be sent directly to a construction site, further lowering shipping and rework costs.

New Forms

The digital revolution has had a tremendous impact on both building forms and design strategies, giving designers new perspectives, but also creating new construction challenges. From the doubly curved titanium-clad forms of the Frank Gehry's Guggenheim Museum in Bilbao to the interlocking plywood panels of the Instant House of MIT in the Museum of Modern Art in New York, the typical digitally fabricated building is a geometrically complex assembly of both customized and standardized parts. Generally speaking, the greater the number of standardized parts, the less flexible the design, but the easier the construction due to repetition and economies of scale; on the other hand, the greater the number of customized parts, the more flexible the design but the harder the construction. Based on this trade-off, a typical challenge in digital fabrication is to determine the line between standardized and customized parts in a geometrically complex design: at one extreme, complexity is uniformly distributed in the parts, such that each part is slightly different from the other; at the other extreme, complexity is strategically concentrated in few highly customized parts, while the rest of the parts are standardized and repetitive.

Phaeno Museum in Wolfsburg:
CNC milled formwork

Guggenheim Museum, Bilbao: Complex geometric forms decomposed into developable surfaces (photo used under Creative Commons from Jaume d'Urgell)

Another design challenge in construction of free-form geometries is to ensure that all complex surfaces are decomposed into smaller developable surface panels that can be easily fabricated through cutting, bending, and forging flat sheet materials. This means that surfaces cannot have double curvature; their unidirectional curvatures should not exceed the maximum bending curvature that can be achieved by the available materials and techniques; the angles of polygonal panels should not be overly acute; and surface continuity between individual panels must often be retained to provide a smooth finish.

DRL pavilion in London: Complex assembly of interlocking planar parts (photo used under Creative Commons from jimmiehomeschoolmom)

Another compelling design constraint is to ensure that converging planar ribs at either the nodes or other boundaries of a free-form structural grid will retain to the greatest extent possible their topological and angular relationships as the overall driving geometry of the model is modified. This is necessary to simplify and standardize joint and fastener detailing as well as to transfer loads smoothly between parts. For example, often the planar ribs of a quadrilateral structural grid must be locally perpendicular to both the skin surface they support and the other ribs that converge in the nodes. The list of constraints in computational design for complex

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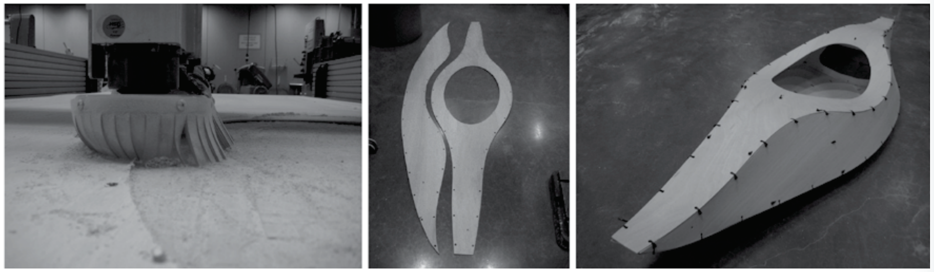
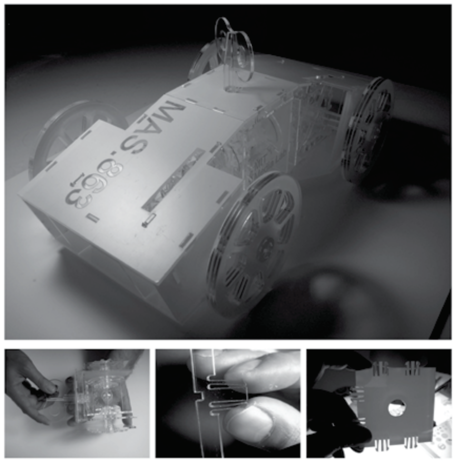
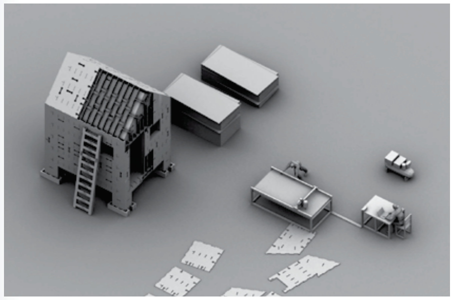
1. www.hexapodrobot.com;
http://el.media.mit.edu/logo-foundation/logo/turtle.html



The Stitchyak: a digitally fabricated kayak using a stitching technique to facilitate assembly



The Fabcar: a digitally fabricated 4WD toy car whose complex mechanical assembly consists of 234 unique parts



The Instant House (image courtesy of Lary Saas)

The built Instant House at MoMA's back yard (photo used under Creative Commons from C-Monster)

geometries can be long, depending on the requirements of each project, making digital design and fabrication a highly specialized and challenging field.

Design for Manufacturing and Design for Assembly

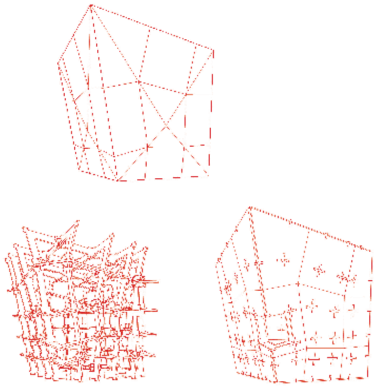
Seamless integration of design with production has led designers to consider how the latter could benefit from the former. Emerging from the fields of industrial design and product development, design for manufacturing (DfM) and design for assembly (DfA) are strategies that utilize design intelligence as a means of facilitating fabrication and assembly processes. For example, the studs (the small raised portions of Lego bricks) allow a child to easily position and assemble a series of Legos even with closed eyes. An excessive increase of the number of contact points between two parts, however, can make positioning and assembly difficult and time consuming. Similarly, using snap-fit joints, self-locating tabs and grooves, and registration marks facilitates assembly while minimizing the need for required joints, fixtures, and formwork. DfM and DfA engage designers in thinking of the assembly process as an integrated part of the design, a rather forgotten art since the advent of industrialization.

The following examples illustrate cases in digital design and fabrication where processes, tools, and materials inspired new forms and strategies. Stitchyak is a digitally fabricated kayak created at the MIT Media Lab utilizing a stitching technique with temporary zip-ties that helped with positioning and alignment of the curved cut sheets during assembly, without any fixtures or formwork. The stitched sheets were afterward covered by fiberglass for waterproofing and structural durability, and the zip-ties were removed. Such a process would otherwise have taken considerable time and effort, without taking into account the construction of the formwork itself. Stitchyak was parametrically modeled, allowing for customization in form, size, and curvature to fit different body types and styles. Special consideration was given during the design process to the curvature and grain direction of the plywood surfaces to guarantee that they would be easily bent without cracking.

Fabcar is a digitally fabricated four-wheel-drive toy car made at the MIT Media Lab entirely out of plexiglas sheets shaped with a laser cutter and manually assembled without adhesives or fasteners. Fabcar's complex mechanical assembly consists of 234 unique parts organized into three differential gear mechanisms to unevenly distribute torque applied from a top central shaft to each of the four wheels based on their relative torque resistances. The design of Fabcar used snap-fit flexure joints that bend to ensure easy installation and spring back to trap the installed parts and prevent accidental disassembly. Material stiffness and tolerance were empirically estimated to take into account the material removed during the machining process.

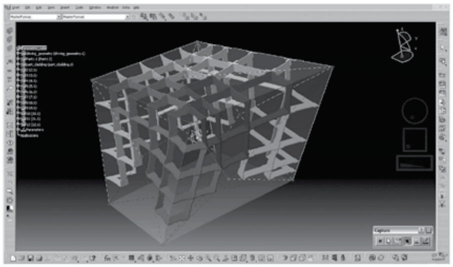
In the same spirit, the MIT Digital Fabrication Group designed and built the Instant House, a digitally fabricated house that was exhibited at the Museum of Modern Art in New York as part of the "Home Delivery" exhibition in 2008. The Instant House was a proof of concept of a new design and construction system that uses a generative shape grammar to create customized connection details for each plywood panel based on its location within the overall house geometry, and a portable three-axis CNC mill that can be transported in a shipping container to the construction site to fabricate the panels.
The Instant House was made entirely of plywood sheets using glue-less, friction-fit, notch-and-groove connections; assembly was done on site by two nonskilled workers in a few days. The structural system of the envelope consisted of a dense quadrilateral grid firmly connected to an external and internal sheeting layer. Instant House had one main design constraint: since three-axis milling machines can only cut perpendicularly to the surface of a sheet, the structurally connected parts must be either perpendicular to each other or coplanar. As a consequence, since the planes of the structural ribs should always be perpendicular to the internal and external sheeting layers, they should also be perpendicular to the envelope's edges, where neighboring wall faces meet. Furthermore, the structural grid should be continuous for smooth load transfer between parts. Although successful in principle, the Instant House generative system had several limitations: there was no firm geometrical solution in the CAD model to parametrically adjust the structural grid's layout as the envelope's geometry changed; the assembly hierarchy was not organized into subassemblies, a fact that made the assembly process tedious and difficult.

Further studies at MIT developed YourEnvelope, a generalized computational solution to this problem that parametrically readjusts the structural grid configuration as the envelope geometry changes ensuring that the perpendicularity constraints are always met. YourEnvelope could take as input the angles of the faces, the desired grid density, and the thickness of the material and output the cut sheet files with customized connection details. Furthermore, the overall structural grid was cleverly organized into nested subassemblies such that the assembly process could be conducted more quickly and easily.



YourEnvelope: Parametrically adjustable structural envelope consisting of 252 custom parts organized into: (a) structural grid consisting of 12 subassemblies of 8 parts each and 48 connecting joints; (b) skin paneling consisting of 108 panels (54 interior and 54 exterior).

Cut sheet layout of the 252 parts of YourEnvelope

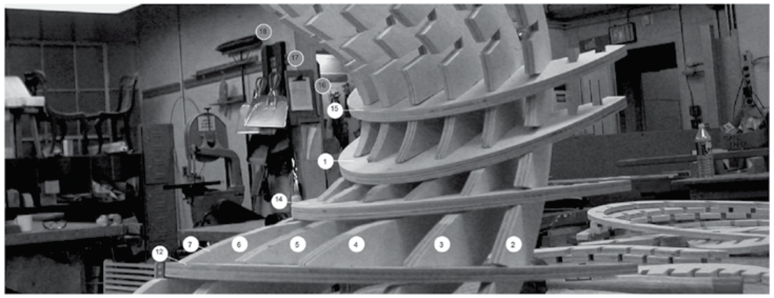


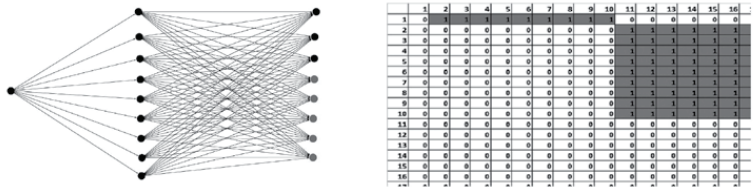
Parametric variations of YourEnvelope's geometry and grid organized into different subassemblies

New challenges

Despite the positive impact on design and production, the digital revolution also brought new challenges to construction. Not surprisingly, many digital fabrication projects have been construction nightmares, either due to logistical mismanagement of the numerous tasks and practitioners or assembly incompatibilities at the construction site. Many fabrication projects take more time than originally planned, are more expensive than expected, involve great risk and uncertainty, and prove to be too complex to plan, understand, and manage. Moreover, most problems are discovered at the construction site, when it is already late for corrective actions.

Evaluating the constructability of design can be a hard task, requiring skills and tools that we are just beginning to explore. It depends on the installation vectors of the parts during assembling and also on the number of connections between different parts. In practice, assemblies are studied through CAD modeling and physical mockups. 3D CAD modeling represents the final state of the assembly, however, when all parts have been put together, but not the process of putting these parts together. The order of constraint delivery in parametric CAD models is not necessarily the same as the constraint delivery of the actual assembly. As a consequence, by studying a 3D CAD model, the designer cannot easily tell if a design is constructible or estimate the difficulty of the assembly sequence. Physical mockups are typically used during design development to test constructability, but with a significant loss in time and cost. Testing is empirical, understanding the solution to the geometrical problem is obscure, and design development becomes intuitive. While considerable research and technology have been invested in digital design and fabrication, empiricism and intuition characterize assembly at the construction site. Studying assembly is a matter of analyzing the topology of the assembly graph of the connected components. The following example illustrates a case where the liaison graph, which shows the order of constraint delivery between the parts, was used as a means to understand assembly incompatibilities.





	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
5	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
7	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
8	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
9	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
10	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Assembly sequence analysis of the Fabseat highlighting the parts that could not be installed

Fabseat was a project done at MIT in 2007 to explore constructability assessment problems. Fabseat is a digitally fabricated and manually assembled chair consisting of 29 interlocking plywood profiles that together formulate a doubly curved structural surface. Fabseat was designed using conventional non-associative 3D modeling software. During assembly, about a quarter of the parts could not be installed without warping the material, an issue that was impossible to detect during 3D modeling development. A network analysis of the assembly sequence using the liaison graph that was done afterward showed that some of the nodes were impossible to install because they required more than two simultaneous installation vectors that were not parallel.

New practices

Digital design and fabrication have significantly affected professional practices, as the designers of complex geometric assemblies must holistically take into account the machine, material, and computational constraints during design process. The complexity of design and construction of digitally fabricated buildings creates a new type of professional specialist who combines educational knowledge from design, computational geometry, programming, manufacturing, and structural engineering, among others fields. Many design firms around the world have formulated special interdisciplinary groups of experts who work as the interfaces between designers and industry to bring the most demanding projects to life.

Other emerging professional practices are specializing as external consultants on building information modeling (BIM), offering technical expertise and project management to traditional offices that lack this knowledge. This emerging type of specialist creates an unprecedented need for changes in the educational system, as the multidisciplinary nature of the field does not fit within any existing engineering or design discipline. Furthermore, digital technologies in design have affected contractual relationships between architects, engineers, and digital design specialists, as determining liabilities and intellectual property rights in cross-collaboration platforms such as BIM is not always straightforward.

From Digital Fabrication to Digital Materials

Our digital design and fabrication capabilities are already able to materialize the most complex geometric forms that our modeling skills and imaginations can create. As we expand the scale and scope of our fabrication technology and decrease its cost, we will soon be able to equip those forms with intelligence for sensing, thinking, and reacting to better respond to changing environmental needs.

Today new additive digital fabrication methods can print composites with variable structural and chemical properties by fusing materials with different properties. New digital electronics fabrication methods can place circuits with microcontrollers, sensors, and actuators into building components that can sense applied loads through force or vibration and realign their molecular fiber structure to better withstand those loads via electric signals. Moreover, smart building components can talk to each other and propagate messages through the entire assembly, turning potential buildings into habitable distributed computing platforms. Our future goal should be to apply these emerging technologies in meaningful ways in architecture.

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Bibliography

Anderson, David M. *Design for Manufacturability and Concurrent Engineering*. Cambria: CIM Press, 2006
Bergdoll, Barry, and Peter Christensen. *Home Delivery: Fabricating the Modern Dwelling*. Basel: Birkhäuser, 2008.
Bechthold, Martin, Kimo Griggs, Martin Kao, Daniel Schodek, and Marco Steinberg. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design*. Newark: John Wiley and Sons, 2005.
Huang, Jeffrey. “Interorganizational Information Systems in Design.” Doctor of Design thesis. Graduate School of Design, Harvard University, 1997.
Mitchell, William J., and Malcolm McCullough. *Digital Design Media*. New York: John Wiley and Sons, 1995.
Ohno, Taiichi. *Toyota Production System: Beyond Large-Scale Production*. New York: Productivity Press, 1988.
Sass, Lawrence, Dennis Michaud, and Daniel Cardoso. “Materializing a Design with Plywood.” ECAADE, Frankfurt, Germany, September 2007.
Shingo, Shigeo. *A Study of the Toyota Production System*. New York: Productivity Press, 1989.
Whitney, Daniel E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York: Oxford University Press, 2004.