

THE NEXT REVOLUTION: DIGITAL BUILDING KITS

Materializing Designs with Digital Fabrication

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Abstract. Novice designers are gaining increased access to CAD tools for design computing and digital fabrication that were once exclusively used by expert designers. As evidenced by the rise in manufacturing incubation facilities novice can prototype their ideas in ways similar to expert designers. Also available for novice designers are online rendering consultants, online manufacturing and online ecommerce as a way to distribute and sell products. Discussed here are the reasons for this emergence, complications when using design and digital fabrication as a standard mode of production and new focus for experts.

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1. Introduction

A recent article in *Wired Magazine* entitled “The Next Industrial Revolution” should be cause for concern for most people in design and manufacturing fields (Anderson, 2010). Fear of a revolution in manufacturing and design should follow the same concerns we once had over jobs and communication during the internet revolution. The fear is with good reason, so far the internet has shaken the foundation of news organizations and the traditional keepers of information. The United States has seen extermination of many local and international newspapers. Society now trusts information generated by non-expert sources (blogs) as much as they do expert sources. In many design fields, in particular architecture, the internet has given rise to drafting and rendering industries that generate images and construction documents overnight. The article in *Wired* should soon rock the foundation of any product maker because it illustrates the ease at which ordinary people can invent, prototype and manufacture their own goods. Novice inventors do not need sophisticated software, large factories,

high powered computers, high-tech design courses or instructors. Weekend designers are motivated by the availability of computer controlled machines, free CAD tools and more important decimation of ideas as real products through online ecommerce.

The article is not focused on new high powered robotics, gadgets that separate DNA strands or explain the latest technology around the faster computers. Instead it describes the phenomenon of human invention with manufacturing machines. It is about sharing design ideas and methods of making with product kits. It highlights automobiles, however with a bit of online probing one can find that small aircraft, hobby boats and small structures are ever more being sold as kits that everyday people can assemble and enjoy. In many cases novice designers are inventing, designing with free CAD tools, emailing a file to online prototyping companies, fabricating and selling their own products. Website such as alibaba.com and Maker Faires are filled with do-it yourself product maker who digitally design and customize their own products. Everyday people can manufacture one or one-thousand of the same product with ease from designed kits or sell their own kit for manufacture by other novice.

In spite the ease of fabrication there are rules and constraints that guide all digitally manufactured products. These rules are based on traditional design constraints such as form, function and appearance they also must consider machine constraints such as CAD/CAM tooling, the limits of component casting and assembly. The rules for self driven design follow similar rules derived from the do-it-yourself (DIY), a few are listed below:

- Design and manufacturing is limited by machines, modeling tools and materials
- Simple tools such as hammers and screw drivers are best for products sold as kits
- Good products are designed for replication opposed to one off products.
- Flat pack for ease of transportation

2. Fab Labs

Facilitating this movement is open CAD/database software and open prototyping labs for public access. Professional labs such as TechShop in San Francisco provide digital tools for physical creative play and learning. Alternatively community based workshops are also growing one in particular was founded at MIT defined as *Fab Labs*. They are small-scale workshops with an array of computer controlled tools that cover several different length scales and various materials, with the aim to make "almost anything". *Fab*

Labs are the brain child of Media Lab Professor Neil Gershenfeld in early 2002 (Gershenfeld 2005). They are equipped with the same computer controlled machines found in design schools such as laser cutters and large CNC machines. They also come with machines that allow for micro level milling as a way to build circuit boards with programmable chips for second generation internet accessibility. With a *Fab Lab*, household lights can be programmed with internet IP addresses making them smart and accessible from afar. It is possible to *Fab* a building from a *Fab Lab* outfit with furniture and finishes. In theory, a *Fab Lab* can be used to manufacture a *Fab Lab*. For houses *Fab Labs* can be used to manufacture furniture, electrical devices such as phones, ovens and someday solar panels. *Fab Labs* can be a sustainable reaction to natural disaster if *Fab Labs* are equipped with their own power source (solar power). It could be an addition to the western model of response that ships products to disaster sites as finished products. Alternatively a *Fab Lab* will empower manufacturing of finished goods on the battle field or disaster sites from raw goods. Sustainable relief is possible by employing local labor for manufacturing and product assembly.

3. Computation for Physical Production

After two decades of investment into design tools for computer visualization, a grand challenge for *The Next Revolution* is definition of new models of computation that support design for physical production. Challenges relate computing systems that transform ideas as 3D models into descriptions for machine manufacturing, material compliance and assembly (Sass 2005). Palladio used mathematics to describe best design and construction techniques for masons when translating his 2D plans and elevations to 3D masonry details (Palladio 1965). His rules could be used to successfully reconstruct moldings in 3D, structurally support all loads in 3D and subdivide geometry for best methods to assemble brick and stone components. For Palladio's villa designs wall construction required the top floor to be one brick less than walls on the first floor. He also wrote that walls at the basement should be twice the thickness of walls at the first floor. He had a complete language for masonry composition based on his own experience as a mason. The importance of his work system of construction procedures in text and drawings used to guide the fabrication of his villas.

3.1 COMPUTING BUILDING ELEMENTS

Materializing is a rule based system with procedures that enables physical production from 3D shapes in CAD with CAD/CAM machining. Materialization is a mathematical process of shape decomposition resulting

in 2D interlocking components shapes from 3D models. The aim of the system is support for manufacture of 3D models with 2D CAD/CAM tools and common sheet goods. As a set of computational functions, *materializing* follows similar methods of manufacturing found in layered manufacturing or rapid prototyping (Dolenc 1994). As a building system of comprised of components, *materializing* follows assembly goals found in integral attachment design (Messler 2007). *Functions* start by subdivision of a 3D shape into surface parts for small artifacts. For larger artifacts functions are used to subdivide the exterior of the shape and a second set of functions generate internal layers of a typical thickness. Secondary functions subdivide exterior sections and sliced layers into smaller parts based on material machine stock sizes. Assembly functions add features to the ends of each subdivided part to join components. The end product of a materialized 3D shape are components as 2D geometries ready for CAD/CAM manufacturing and hand assembly.

3.2 MESOSTRUCTURES

Software for rapid prototyping machinery has similar outcomes focused on building artifacts as a series of assembled objects. Research in this field has focused on discovery of efficient functions for slicing shapes in CAD into layers for manufacturing. New research explores ways to generate geometry as internal meshing or structuring defined as mesostructures tailored for a specific performance (Chen 2008) opposed to layers. In one example, Yong considers application of these mesostructures for finished manufacturing of cushions designed to vary in areas of firmness and softness. His method builds foam pads with micro structures as a way of varying foam density. A mesostructure is non-uniform sectioning thorough a 3D file as a way to generate of tool paths for layering of material. Yong's computation allows for manufacturing of non-solid objects manufactured with rapid prototyped machines, the artifact is composed of an open web structure and an external solid surface.

3.3 MATERIALIZING A SHAPE

Materializing is generation of geometry for manufacturing in layers along three axes opposed to horizontal only sectioning found in rapid prototyping software. The desired physical size of the final artifact determines the number of functions needed to decompose an initial shape and the degree to which each function can be automated. For example, a function that copies of all sides of a three dimensional shape from 3D to 2D for laser cutting can be an automated function. In contrast, once each side is drawn as a 2D shape sorting thousands of parts for material efficiency may be best as a non-automated function. For a very tall structure manufactured components at the

foundation should be manufactured first, components at the top of the structure should be manufactured last.

3.4 SIZE MATTERS

The size and material thickness of the finished artifact determines the investment computation. For example, manufacturing of a very large artifact requires three to five core functions along with many sub-functions in order to transform a 3D shape to 2D cut patterns. Subdivision and organization of the 2D cut patterns are guided by *rules of construction*.

Materializing an artifact the physical size of sports balls is computation and digital fabrication with physically thin material. The first function set organizes the subdivision of outer shape into panels developed prior to the computation. The second set of functions is aimed at adding features to previously subdivided geometries for assembly. These features aid physical assembly between components after CAD/CAM manufacturing. Characterization and generation of features in CAD are designed for connectivity between parts with assemblies sustained by friction. The third set of functions creates 2D shapes from the 3D model. Fourth is sorting and packing of 2D shapes within the boundary of a sheet.

Materializing large artifacts such as buildings where an internal structure is required a similar set of functions are used to decompose the surface first, next create internal structure. Three core sets of functions are employed; the first decomposes the exterior surface into components, second generates an internal structure and the last set of functions integrates the surface and internal structure. Both sets of functions are determined separately, later integrated with functions create features for connection between surface and structure. For building structures materializing three dimensional shape(s) provides a virtual skeleton for design and integration of other systems such as plumbing, electrical and energy.

3.5 CONSTRUCTION RULES

Layered manufacturing software generates surfaces from a 3D model as horizontal sections for manufacture one layer at a time. The software assumes physical manufacturing and assembly parameters as part of the subdivision process. *Materialization* generates manufacturing and assembly data as part of the subdivision and object creation process. *Construction rules* are imposed constraints that limit subdivisions and guide the generation of geometry based on the material and machining and assembly limits (Sass 2007). For larger structures non-automated steps allow for calculation and planning for manufacturing and assembly efficiency. For example, structural testing and materials ordering can be challenged during the subdivision process. Areas of material under high stress loads can be

fabricated of high strength plastic or steel, while parts under low strength can be fabricated of recycled material. Also a systematic approach to the design integrated assemblies is possible. Integral assembly design is commonly found in the plastics industries in the design of snap-fit assemblies (Genc, et al. 1998). Limits in assemblies between components and assembly mechanisms can be designed as part of the generative process.

Materializing a design as a computational process is used to prepare a CAD model for manufacturing of 2D components, key aspects of the process are described below:

- 2D machine compliant shapes are generated for manufacturing from 3D models
- Functions can be automated and non-automate
- Construction rules set limits for generative functions and component composition
- Functions generate components as surfaces for the artifact and components as internal structure
- Integration functions assure a relationship between the surface and structure
- Each component includes an assembly feature that relates to an adjacent components
- Shaping of components and component assemblies is based on rules from a construction grammar

4. Sustainable Design Production

Novice involvement in production of manufactured buildings is possible by materialized geometry directly from 3D design models files. This process of making small and large products offers some hope for real development of local economies by situating design and production in one place. Situated production benefits developing nations and sites of natural disaster in most cases they require permanent product production rapidly. In many cases non-western societies cannot support large building factories (prefab) and importation of building materials such as dimensional lumber or shaped steel. Needed is a flexible design and production system as a way to introduce new design possibilities and ways to think about non-western product development.

In response to new methods of construction, not all countries will have or should have access to westernized construction systems. Digital fabrication machinery is small, portable and simple to run. Digital fabrication and materialization functions provide access to a production system supporting ongoing interest in regional or individualized design and fabrication. The

benefits are worldwide sustained production at a low startup cost. Socially sustainable design solutions make better use of local labor and knowledge.

Materialized design data also allows for physical construction with few tools. Rapid assembly is possible by inclusion of designed building assemblies into the manufacture of each component. Structural safety is also assured by enabling virtual testing with algorithms for finite element analysis of components. Typical methods to challenge a building's structural stability require that components are designed for efficiency first, after more material is added to the component to increase its strength for safety. Over structuring compensates for the communication gap and material variability between the design model, the shop and field conditions. This gap in communication has been solved in automobile and Aerospace engineering from CAD/CAM machining with advanced CAD tool applications such as finite element analysis. Materializing a design is an efficient process of production the question continues to be tool development.

5. Physically Integrated Components & Systems

For western societies this New Revolution in production and design exploration supports sustainable design practices for novice. It will also empower partnership with design and engineering schools for development and innovation of new building components for experts. We have seen great promise with *building information systems* (BIM) providing a surface for designers, engineers and builders to integrate their intentions. Effective computing (materializing), flexible manufacturing (direct manufacturing) and new forms of communication are critical for the following emerging fields.

- *Materializing Systems for Whole Building Models* for all materials from steel to wood and concrete
- *Integrated Energy Solutions* into BIM Models –Solar Paneling, Wind and Geothermal.
- *Analysis Modeling* – Assured relationship between structural loading, seismic, 4D and 3D BIM modeling for higher levels of fidelity

Materialization of the building structure and integration of associated engineering fields will offer pathways to challenge building performance during the design process. Emphasis is placed on computing of the actual objects in construction opposed to representations or intentions on screen.

7. Next Generation Building Kits

Production of houses as ecommerce products has been promised for many decades. Architects have posted drawings and CAD models online for others to view and purchase. Alternatively *materializing* and *BIM* modeling demonstrate the potential of buildings as a kit of parts that could result in a well thought out product. Home kits can be high quality products delivered as a collection of snap-fit components once assembled result in an integrated product. Best is the flexibility of digital fabrication can empower localized designs and localized manufacturing.

The idea of housing kits has been available since 1902 from Sears and Roebuck, to the Lustron House and the General Panel Company started by Walter Gropius and Konrad Wachmann. Currently there are panelized, dome and green home kits also available online. Companies that make these houses claim their systems to be easy and simple to build. A related question is, if they are so simply why house kits not contributed solutions to the world's problems on home delivery? Why have home kits not had the same impact on society as cell phones have on communication? Is it to expense ship house kits, assembly with few tools, create a variety of building styles or vary the cost?

There are a number of home kit providers on line that offer standard home products they sell kits that include most of the elements needed to build a house. A current example of a conventional building kit is the Katrina Cottage offered by Lowes Home Stores intended for sale as a kit of parts. Unlike a digital set of components for sale is a materials list for contractors and tradesmen to follow along with a set of drawings. The owner is required to hire an architect, specialized labor, with specialized tools and purchase space. Home building kits calls for many service workers from the various trades and consultants – plumbers, electricians and carpenters.

An important comparison can be made between building kits with car and airplane kits that are also sold online. These kits are made for assembly by hand with few tools. The benefit of the kit is that reduced labor lowers the cost of the end product. These automobile and aerospace kits are integrated product kits that manage the assembly of complex systems from braking and engine to electrical and mechanical. Another advantage is that kit producers offer a variety of styles, car kits range from low grade sports car kits to Hummer car kit.

A *materialized* building kit could arrive as a complete product of parts, ready for assembly with a few basic tools. Structure and building skin could be manufactured of interlocking parts. Mechanical systems as a series of flexible conduits and pipes and electrical lines as solid state snap together tracks and lines are possible. Lighting, plumbing fixtures and kitchens can be integrated products as well easy to assemble with few tools. Most

important is involvement of the kit owner at all levels from plumbing to painting.

Building a house from a *kit of materialized* components could simplify home delivery for worldwide access. With this we also have to face the fact that complexity remains in design and rethinking home delivery with digital tools. Manufacturing can be simplified with Fab Labs and flexible building systems. Required a redesign and refocus on integration and manufacturing of complete and finished homes that also include new energy systems such as solar and geothermal systems. In the end the next revolution is integration mixed with manufacturing as a way to produce products for general consumers to build as well as experts.

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