
CRITIQUING CAM: COMPARING COMPUTER-AIDED MANUFACTURING AND CUSTOMIZED REPETITIVE MANUFACTURING

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INTRODUCTION

As architects and designers promote the use of computer numeric controlled (CNC) equipment for off-site fabrication, they need to recognize that computer-aided manufacturing (CAM) is not cost neutral. The increased costs are both financial and environmental. Although there are some financial benefits to mass customization (e.g. increased customer loyalty, lower marketing costs, and lower product research costs),¹ mass customization does increase the monetary cost of production. Often, the consumer pays that higher price. Secondly, mass customization may increase environmental costs through increased production wastes. This is especially demonstrated by CNC equipment that is subtractive—such as routers, electronic discharge machines (EDM) and water jet cutters. Waste for these processes can be significant and, depending upon the material and process, unrecyclable.

In recent years, CAM has transformed off-site construction; however, it has not transformed all manufacturing. There are designers and architects who are customizing traditional repetitive manufacturing processes for their buildings. Examples include Carlos Jimenez's Data Service Building at Rice University (2007) and Alejandro Villarreal's Hesiodo in Mexico City (2005). Jimenez used reusable, custom fiberglass molds to form the Data Center's concrete walls and Villarreal used custom wood-molded, blown glass spheres as a rainscreen. In these examples, the designers relied on the repetitive use of molds to create multiple units. For these processes, the repetitive use of the mold is necessary as it distributes the mold's cost over a large number of products.

Customized repetitive manufacturing is a necessary alternative to mass customization for some manufacturing. Customized repetitive manufacturing allows for some customization from the designer, while offering lower costs—both monetary and environmental. Simultaneously, customized repetitive manufacturing places more restrictions on the designer than mass customization, because each produced element needs to be repeated a particular number of times in order to remain cost effective.

This paper examines the processes, benefits, and costs of using CNC equipment and compares that to traditional manufacturing processes for customized repetitive manufacturing. CAM is a strong

choice for some manufacturing processes, however for other manufacturing processes repetition is needed to reduce costs. In these cases, architects, designers, or students should consider customized repetitive manufacturing. This paper identifies different categories of manufacturing, as based on Chris Lefteri's categories in *Making It*. Those categories are Subtracting from Solid, Sheet and Sheet Manipulation, Continuous Cross-section and Continuous Cross-section Manipulation, Hollow, and Making Solid. In each category, I identify whether CAM or customized repetitive manufacturing is best. It is my belief that this assessment can offer designers more knowledge to choose alternative processes for the design and manufacturing for their building components.

COMPUTER AIDED MANUFACTURING

Mass customization is the concept that customers can customize products to meet particular specifications. Well-known examples of products that can be mass customized are Dell computers and Nike shoes. Costs associated with manufacturing mass-customized products are no longer cost prohibitive to the general consumer market. Many consider the cost differences between a mass-customized product and a mass-produced product is negligible compared to the benefit. Although mass customization offers the consumer more options than traditional repetitive manufacturing, there are limits to the offered options. Dell offers customers choices between a limited range of components and sometimes not all aspects of the product can be customized. For example, when I fill out a request from Dell for a personal laptop there is only one computer housing style and three colors offered.

Mass customization is different from CAM. Many of the mass-customized choices offered are manufactured repetitively. This is demonstrated by limited colors and singular housing style offered by Dell. Mass-customized products are customized during their assembly rather than in the manufacturing of their individual parts. Therefore, CAM is not necessary for the production of mass-customized products. This is similar to the difference between the terms 'fabricate' and 'manufacture'.² Fabricate is to make from standardized components and manufacture is to make from raw materials, especially when done systematically. Architects are familiar with the distinction between these terms because newly designed buildings although customized are often made of standardized components.

CAM refers to any manufacturing that makes use of any computer numeric controlled (CNC) machine for the purposes of manufacturing. CNC uses “a computer, specialized electronics and motors to control a machine in a precise and reproducible manner.”³ CNC machines include a wide range of different devices: drills, lathes, millers, router, surface grinders, electronic discharge machines (EDM), plasma cutters, water-jet cutters, laser cutters, knife cutters, hot-wire foam cutters, punch presses, oxyfuel welders and cutters, wire-benders, and 3-dimensional printers.

CAM has transformed architectural form. Because CAM has lowered production costs by using CNC equipment, it has allowed architects and other designers to make use of the equipment to fabricate complex forms. CNC equipment has allowed architects to design complex forms for limited additional costs. It would be difficult to imagine that works by Frank Gehry, Greg Lynn, and Zaha Hadid would be possible without CNC equipment. Although CNC has allowed us to design and construct complex building forms, it does not necessitate those forms. A project such as Norman Foster’s Great Court at the British Museum makes us of CNC equipment to manufacture the components of the building’s roof.

The use of CNC equipment can greatly increase costs—both the soft costs of design and the hard costs of construction. For Gehry’s projects, the added costs can greatly exceed the industry standard. According to *Wired Magazine*, “The Stata Center came to \$400 per square foot, \$650 when you include design costs. The industry average for design and construction of a new science facility is \$260 a square foot.”⁴ The added soft cost is not just limited to the use of CNC equipment; it is also shared by mass customization. “The additional premiums of mass customization (compared to traditional mass-production) are challenged by additional costs associated with this system. Basically, higher costs occur both in sales and customer interaction as well as in manufacturing.”⁵

The costs associated with CAM are complex. Proponents of CAM may argue that the CNC machine does not care if it is making unique or repetitive pieces; however, there are the soft costs of designing and drafting each of the shapes and programming it into the machine. Time spent designing individual pieces and programming the machines is a cost that is passed on the consumer. CNC equipment can easily save labor costs when compared to traditional machining. This is especially true when architects have designed very complex components that could not be fabricated by traditional manufacturing. If more simple shapes were designed, or if complex designs were used repetitively, this would greatly reduce the production costs. In many cases, the costs of CAM could be lessened by using traditional manufacturing.

In addition to the added monetary costs, there are environmental costs associated with some CNC equipment. This is especially true of subtractive CNC equipment—machines that subtract material away to create the desired object. Examples of subtractive CNC equipment include plasma, water-jet, laser, and knife cutters, routers, drills,

presses, EDM’s, lathes, milling machines, hot-wire foam cutters, and surface grinders. Depending upon the material and the process, three things can happen to the waste that CNC equipment generates—it can be recycled, downcycled, or it sent to a landfill.

Recycling and downcycling are closely related.⁶ For purposes of this paper, I am defining recycling as reusing scraps to create a similar product (e.g. glass recycled to be glass) even though the quality may be reduced. I am defining downcycling as reusing scraps as a different material (e.g. wood dust used to make fiberboard) with different, lesser properties. Although recycling and downcycling create less landfill waste, they do use energy to transform from one material to another. If recycling or downcycling cannot be handled directly at the manufacturing site where the waste was created, then fuel costs and energy will be spent transporting materials for re-processing.

For some CAM processes with certain materials, the manufacturer can do nothing with the waste generated. Although the wood shavings and dust from a CNC router may be down-cycled, the plywood that is leftover between the router cuts cannot be recycled (unless processed). Shop coordinators and architectural instructors are familiar with this problem of waste. The leftover plywood scraps often line the hallways and fill the waste bins of architectural shops. If students do not use the scrapes, the coordinators send them off to the landfill. This is so much of a problem that instructors have been giving students the design problem of creating something using CAM equipment that produces as little waste as possible.⁷

Not only can the waste go to a landfill, the energy used to create that unused material is also wasted. This energy created for unused material must be included in the assessment of CAM processes, because some processes, such as EDM, create no physical waste. EDM uses an electronic charge to vaporize metal. The vaporized metal is not landfill waste, while at the same time it is unrecoverable. The energy spent to mine, smelt, and form the metal is forever lost.

CUSTOMIZED REPETITIVE MANUFACTURING

Repetitive manufacturing is the “continuous production of similar products on relatively fixed production lines.”⁸ Repetitive manufacturing reuses its tools (e.g. jigs, molds, patterns, etc.) to create similar products. Although repetitive manufacturing may use computers to run the machinery, it is not using computer to control the shape of the produced unit. The range of the production runs for repetitive manufacturing is varied and it can range from a prototype and small batch productions to over 1,000,000 units.

Production runs are a function of capital, tooling, and machining costs. Often the product’s production run offsets those costs, so that the number of units produced is higher to offset the costs. For example, if a mold costs \$50,000, but produces 100,000 units, the added cost of a custom mold would be just 50 cents per unit. Plastic blow molding, which is used to make prescription pill bottles, is a high volume production.

Customized repetitive manufacturing balances the value of repetitive manufacturing with the ability of the designer to customize the repeated product. Customized repetitive manufacturing can make best use of those processes that require low-to-mid production runs. For example, because of the low costs to make a pattern, sand-casting can be used for small batches. Since architects are most likely to use customized repetitive manufacturing on a building-by-building basis, I focused on those repetitive processes that have production runs under 10,000 units. If we consider exterior facing materials such as brick, terra cotta tiles, or metal panels, 10,000 units is easily achieved. Villarreal uses 7,723 blown glass spheres on the Hesiodo, a 27,000 square foot apartment building in Mexico City.

Customized repetitive manufacturing has a number of valuable benefits. First, this process reuses its tools during production. Depending upon the mold, the process, and the material a mold's lifetime can include up to 500,000 produced units. Secondly, these processes typically only use as much medium as the mold, pattern, or jig needs. By reusing tools and reducing raw material requirements, customized repetitive manufacturing reduces waste. Next, manufacturing tolerances are high and have the potential to rival the tolerances of CNC equipment. Fourth, because each unit uses the same design, the soft cost most likely will be lower in customized repetitive manufacturing than CAM. Finally, as this paper will demonstrate, there is a wide range of materials and processes available for the designer.

CAM VERSUS CUSTOMIZED REPETITIVE MANUFACTURING

Both CAM and customized repetitive manufacturing include a number of different processes. I have organized the processes in categories in order to compare more easily CAM to customized repetitive manufacturing. The categories are Subtracting from Solid, Sheet and Sheet Manipulation, Continuous Cross-section and Continuous Cross-section Manipulation, Hollow, Making Solid. Each of the categories contains both CNC equipment and traditional repetitive manufacturing equipment. I include only those repetitive processes with production runs under 10,000 units and could be easily customizable. I have based process assessments on waste, tolerances, and design parameters.

In all of these examples, the soft costs associated with CAM will most likely be higher than that of customized repetitive manufacturing.

Subtracting From Solid

This category includes the manufacturing processes that subtract material away from a solid in order to reveal the final object. Available materials include metal, wood and wood products, ceramics, plastic, and glass. The CNC equipment in this category include drills, lathes, millers, routers, surface grinders, EDM's, plasma cutters, water-jet cutters, laser cutters, knife cutters, hot-wire foam cutters, punch presses, and oxyfuel cutters. Traditional manufacturing includes traditional machining by hand with tools such as drill presses, lathes, routers, saws. Because of the introduction of CNC equipment repeti-

tive manufacturing is currently limited to jiggering and jollying, which is used to mass-produce round ceramics (e.g. plates and bowls)

For these processes, CNC has an advantage over traditional manufacturing. CNC offers greater production tolerances than hand machining, jiggering, or jollying. In general all of the Subtracting from Solid processes produce waste. Depending upon the material used, that waste might be recycled, downcycled, or placed in a landfill. In the repetitive manufacturing processes in this category, the product can be created with a jig. For example, the jiggering of ceramic plates uses a jig as a profile. The profile is dragged along the surface of the plate to carve one side of the plate's profile. However, because of the available CNC equipment, a machine say with a moving knife can do this subtraction just as easily as the jig. The added advantage of the CNC equipment is that the jig would not be necessary. The CNC equipment eliminates tooling and thus reduces the amount of materials required for the manufacturing processes.

Even though CNC equipment is better for subtracting materials from a solid in comparison to traditional manufacturing, I caution the architect from using it. In general, the waste from all Subtracting from Solid processes is high. My question to the designer is: should subtractive processes be used at all in manufacturing? I challenge architects to redesign their building components so that subtractive processes are not used.

Sheet and Sheet Modification

This category includes manufacturing sheet goods and the modification of sheet products. Materials in this category include sheet metal, glass, wood products, plastic and fiber reinforced plastic (FRP). Products in this category include gel-coated fiberglass bathtubs, bent plywood furniture, steel kitchen sinks, and slumped glass. Examples of customized repetitive manufacturing of sheets are contact molding (both hand-layup and spray), vacuum infusion processing (VIP), and hydraulic pressing to create bent plywood. Sheet modification processes for customizable repetitive manufacturing include sheet metal forming, thermoforming, vacuum forming, slumping, metal spinning, deep drawing, and explosion forming.

Currently, CNC equipment does not make sheet goods; there is only CNC equipment for sheet modification. The majority of the CNC tools that are in this category are similar to the Subtracting from Solid group. The difference between the categories is that the CNC equipment in the Sheet category only modifies surfaces of sheet goods, rather than fully cutting objects from the sheets. Typically, the CNC equipment in this category creates 2½ dimensional objects—objects in which the machine carves a relief into the sheet's surface. The equipment includes CNC routers, surface grinders, and mills, EDM, plasma, water-jet, laser, and knife cutters.

Subtractive CNC can offer the designer an infinite range of 2½D surface designs for any sheet modification, but with any subtractive method there is an environmental cost. Repetitive manufacturing

processes in this category use molds to modify sheets without any loss of material. In all of the repetitive manufacturing processes, the capital investments are low and so a large production run is unnecessary but could be accommodated. Some of the repetitive processes (e.g. slumping, thermoforming, vacuum infusion process, and bending plywood) are simple and can be accomplished by both industrial manufacturers and shop hobbyists.

Because of the subtractive nature of the CNC equipment in this category, I do not recommend using them; however, there is one exception—roll bending. Roll bending uses three CNC rollers to roll sheets (often metal) into desired shapes. The spacing of the rollers determines the amount of sheet bend. There is no loss of material with the process and CNC equipment has reduced labor costs typically associated with traditional roll bending.

Continuous Cross-Section and Manipulation of Continuous Cross-Section

This category is the production of continuous cross-sections of material or the manipulation of those cross-sections. A continuous cross-section uses a constant profile along its entire length. Architectural products in this category include vinyl siding, aluminum mullions, and bricks. Materials in the category include clay, metal, plastic, and FRP. Customized repetitive manufacturing processes for producing continuous cross-sections include extrusion, pultrusion, and roll forming. The manipulation of the cross-section is a post-production process, in which the completed continuous cross-section is manipulated into another shape. Examples include roll bending, wire forming, swaging, and pulshaping. CNC equipment is available for wire forming and roll bending.

Similar to Sheet and Sheet Modification, in this category, only repetitive manufacturing can be used create the continuous cross-section. The modification of the cross section via post-production can be done by either CNC equipment or by traditional manufacturing. Similar to the modify sheet products, using the CNC equipment of roll or wire formers is preferred over that of traditional manufacturing as it will reduce labor costs, give better tolerances, and will allow full flexibility of design. For processes such as swaging and pulshaping, a CNC option is not available.

Hollow

This category is the production of hollow, thin-walled objects. Examples include plastic drink bottles, mason jars, plastic garden flamingoes, and Boeing's 787 fuselages. Materials include glass, plastic, FRP, metal, clay, and rubber. The production runs in this category ranges from small-batch to large production runs in the millions. The customizable repetitive processes are blown glass (either by hand or by mold), rotational molding, centrifugal casting, slip casting, and backward impact extrusion.

CNC equipment in this category is very limited and is a part of filament winding. Filament winding is the creation of FRP by winding

the reinforcing strands and the plastic resin around a static mandrel. A computer typically controls the winding pattern of the FRP around the mandrel. Although the CNC equipment may change the pattern (and the strength) of the reinforcing strands, the CNC equipment does not change the object's shape.

Making Solid

This category is the production of solid objects from either a liquid or pellet medium. Examples of products manufactured in this category are the rubber soles of Patagonia shoes, Legos, fire hydrants, and pre-cast concrete. Materials typically include plastic, FRP, rubber, metal, paper, concrete, and glass. The customizable repetitive processes are compression molding, transfer molding, forged metal, injection molding (including reaction injection molding (RIM), gas-assisted injection molding, and metal injection molding), investment casting, sand casting, concrete casting, and pressed glass. CAM processes include 3D printers such as selective laser sintering (SLS), direct metal laser sintering (DMLS), fused deposition modeling (FDM), stereolithography (SLA), laminated object manufacturing (LOM), electronic beam melting (EBM), and powder and inkjet 3D printing. Manufacturing tolerances in both the repetitive manufacturing and CAM are very high.

Some of Making Solid customized repetitive manufacturing processes does have waste associated with the process. For example, forging metal and compression molding creates flashing between the dies. The flashing is small, but will be machined away through post-production. Depending on the material used, the flashing may be recycled. Some processes such as sand casting and injection molding have a system of runners to get the medium from the injection site into the mold. The medium often solidifies within the runners as the mold cools. The object is then removed from the runners. The runners are most often recycled and in many cases (e.g. sand casting and injection molding) the runners are recycled directly on site.

To make solid objects with repetitive manufacturing technologies a mold has to be used. The advantage to customizable repetitive manufacturing is the production speed. In using 3D printers, the advantage is that a mold is not necessary. The 3D printer is an additive processes. It adds layers of material for the production of its objects. In most 3D printing technologies, the printer uses only the amount of material needed in production so that no material is wasted. By eliminating the mold and most reducing the materials waste with most of the 3D printers, this environmental waste produced by 3D printers is less than repetitive manufacturing.

There are some drawbacks of 3D printing compared to repetitive manufacturing. First, depending upon the process and the materials uses, the printing layers can be visible on the printed object. This is to say that the printed surface is often not smooth and can require post-production finishing. Finishing processes can include sanding or chemical baths. In many traditional repetitive manufacturing processes, the mold surface is imprinted on the manufactured object,

and so little post-production may be required. Secondly, not all 3D printing technologies are waste-free. In FDM, the printer prints two different media—one for the object and the other for any necessary support structure. The support structure is then removed from the object and is discarded. In LOM, the printer laminates layers of paper or foil together and cuts away the unwanted parts. Next, there can be less choice in materials for 3D printing. For example, glass and rubber are available with repetitive manufacturing but not CAM. Finally, the technology of 3D printers is still developing and the available quality of printed objects may not match the available quality of traditionally manufactured objects. For example, better shapes and qualities of surfaces are available in precast concrete than CRAFT's proposals for 3D printed concrete.

CONCLUSION

Architects today have embraced CAM, and CNC tools have transformed architects' education and practice. CNC equipment has allowed architects to design and construct complex building forms, however the equipment is not cost neutral. Manufacturing experts have cited that mass customization comes with increased design costs and those costs are often passed to the consumer. Additionally there are environmental costs associated with CAM. Those costs include physical production waste as well as energy wastes associated with downcycling, recycling, producing, and transportation.

Architects should be better familiar with the possibility of customizing repetitive manufacturing for their building components. For this paper, I focused on those repetitive manufacturing processes that have small to mid-range production runs. Highlighting those processes that can accommodate production runs fewer than 10,000 units allows the possibility that an architect could customize a particular process for an individual building. In almost all cases, repetitive manufacturing has lower soft costs than CAM. For some repetitive manufacturing processes there is little to no production waste. Repetitive manufacturing is not limiting and can offer a wide range of materials, finishes, and sizes to meet our customized design needs at a lower cost.

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ENDNOTES

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- 2 Webster defines fabricate as "to construct from diverse and usual standardized parts" and manufacture as "to make from raw materials by hand or by machinery;... especially when carried on systematically with division of labor". *Webster's Ninth New Collegiate Dictionary*, (Springfield, MA: Merriam-Webster, Inc., 1988)

- 3 Hess, E, *The CNC Cookbook: An Introduction to the Creation and Operation of Computer Controlled Mills, Routers Tables, Lathes, and More* (Scited Publications, 2009), 11
- 4 Scanlon, Jessie, "Frank Gehry for the Rest of Us", *Wired Magazine*, November 2004. <http://www.wired.com/wired/archive/12.11/gehry.html>. Accessed 9 July 2012
- 5 Piller, 438
- 6 McDonough, William and Michael Braungart, *Cradle to Cradle: Remaking the Way We Make Things*, New York: North Point Press, 2003.
- 7 Matt Gines, University of New Mexico Shop Coordinator and Instructor, gave an assignment that specifically targeted eliminating waste from the laser cutter. Frank Jacobus, University of Idaho Assistant Professor, writes that eliminating waste is an assignment parameter ("The 2to3 Chairs: An Exploration of CNC Assemblies", *Assembling Architecture: 2009 BTES Conference Proceedings*, (2010), 225-232). Mark N. Carbinha, Cal Poly, San Luis Obispo Assistant Professor, also acknowledges this point and shifts his assignments in order to reduce waste ("Material Imagination in Digital Culture", *Made: Design Education and the Art of Making* (School of Architecture, The University of North Carolina at Charlotte: 2011), 85-92
- 8 Steiner, Joseph C., "Requiem for the Manufacturing Order", *Repetitive Manufacturing Seminar Proceedings*, (Falls Church, VA: American Production and Inventory Control Society, 1981), 35