Using Computer Numeric Controlled Equipment for Customizing Repetitive Manufacturing

In architecture, computer-aided manufacturing (CAM) has revolutionized the relationship between design and production. Proponents argue that CAM's computer numeric controlled (CNC) machines can make individual and unique architecture components that are not prohibitively expensive.[1] It would be difficult to imagine that works by Frank Gehry, Greg Lynn, and Zaha Hadid would be possible without CNC equipment fabricating the metal panels, carving the plywood, or re-rolling the steel structure. CNC equipment has a number of advantages—it has reconnected the process of design directly to the act of making, it has transformed architectural construction and thus architectural form. It has also decreased the entry into architectural fabrication, as many architecture students are able to experiment with CNC equipment because many educaiton programs have access to this equipment.

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Architects and architectural educators have been exploring the direct impacts of CAM, but have been ignoring the indirect effects of CNC equipment. CNC machines have made it more affordable to customize the tools for repetitive manufacturing processes and therefore large production runs are no longer necessary. CNC milling machines, electrical discharge machines (EDM), and hot-wire foam cutters are used to create tooling (e.g. molds, patterns, and jigs) for repetitive manufacturing. With the use of CNC equipment, repetitive manufacturing can be cost effective for small-volume productions and thus makes customizing repetitive manufacturing a viable option for architectural applications. Today, architects and manufacturers are working together to customize repetitive manufacturing to make building components for a specific project. I am proposing the term 'customized repetitive manufacturing', or CRM, to reference this type of work.

Using CNC equipment to make tooling for repetitive manufacturing creates tension between CAM and CRM. Repetitive manufacturing is dependent on the technology of CAM in order to reduce tooling costs, yet CRM is a competitor to CAM. This paper explores the indirect use of CNC equipment to fabricate tools and uses recent case studies of CRM in architecture. This paper uses those case studies to illustrate different approaches of using CNC equipment for CRM, discusses the design implications of CRM, and demonstrates that CRM is a viable alternative to CAM. The gathered case studies are located around the world and demonstrate a global application of using CNC indirectly in architecture component manufacturing.

DEFINITIONS

CAM refers to any manufacturing that makes use of CNC equipment for the purposes of manufacturing. CNC machines include a wide range of different devices and are categorized by how the device operates. Subtractive CNC equipment is those machines that remove material to make the object and include routers, electronic discharge machines (EDM), water-jet, laser and hot-wire cutters. Transformative CNC devices shape one form into another form without material loss; examples include wire benders and rollers. Additive CNC equipment (also known as rapid prototyping (RP) or 3D printing) form shapes by adding small layers of the media together to form the final object. Equipment includes selective laser sintering (SLS), fused deposition modeling (FDM), and stereolithography (SLA). The benefits of CNC equipment is its ability to make custom, unique shapes without slowing down the CNC machine or altering its operation.

Repetitive manufacturing makes similar products from raw materials, especially when done systematically. Repetitive manufacturing reuses its tools (e.g. jigs, molds, and patterns) to produce a run of similar products. Production runs for repetitive manufacturing can be varied, ranging from prototypes and small-batch productions to production runs over one million units. In repetitive manufacturing, a particular tool is used for a particular shape. The tools may be adjusted or partitioned in such a way that portions of the tool form differing shapes. Additional manufacturing adjustments can be made through manufacturing speeds, manufacturing conditions, or changes in media.

In repetitive manufacturing, the production run lengths primarily depend on tooling costs. For example, because of the low capital costs to make a pattern, sand casting can be used for small batches. Conversely, plastic blow molding, which is used to make prescription pill bottles, is more appropriate for high-volume production. Often the product's production run offsets the production costs, so that high production runs are necessary for processes that have high capital 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.

CAM AND CRM

CNC equipment has affected architecture design and construction, and can be used directly or indirectly to fabricate building components. Directly, CNC equipment has fabricated many architectural components; examples include the panels and structural steel for Gehry's Experience Music Project, the structural members for Norman Foster's Great Court at the British Museum, and the copper screen for Herzog and deMeuron's DeYoung Museum. Indirectly, CNC equipment has fabricated individual molds to form unique architecture components. Examples of this approach include the BMW Bubble by Franken Architecture (1999) and the Nordpark Railway Stations in Innsbruck by Zaha Hadid Architects (2004-2007). In these examples, there is little to no repeatability in the panel shapes and therefore most of the molds that formed each of the panels were disposed after a single use.

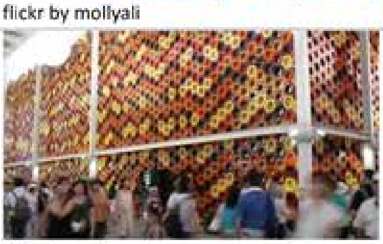
In contrast to indirectly using CNC equipment to make disposable molds for unique components, CRM requires that its tools produce multiple units from a single tool. Tools are made out of durable materials, which allow multiple units to be made, and therefore produce less waste during manufacturing. Today, many repetitive manufacturers use tools made by CNC equipment. Contact fiberglass molders and plastic thermoformers use CNC-milled, high-density foam for their tooling. CNC routers, CNC millers, and EDM wire and spark machines fabricate hardened-steel molds for injection, compression, and transfer moldings, and dies for extrusion and pultrusion. New developments in rapid tooling (RT) have been promoting the use of RP equipment to create tooling. For example, sand-casters can use FDM and SLA printed patterns for small production runs[2], and new production researchers are investigating the use metal laser sintering to make molds for injection molding plastic[3].

CNC equipment has reduced labor costs for tool fabrication. Since tooling costs are amortized over the number of units a tool produces, reduced tooling costs reduces the length of the production run necessary to offset those costs. This means that CNC technologies have allowed smaller production runs to be achievable with repetitive manufacturing. Smaller production runs allow for the possibility of architects customizing repetitive manufacturing on a per project basis. The number of prominent recent architecture projects that use of CRM in their designs demonstrates the popularity of this approach.

Table 1 lists of buildings, architects, manufacturing processes, and components that have been made using CRM. I have only included case studies from the past 10 years, when CAM has been available as an alternate option. The case studies demonstrate a wide range of projects, architecture practices, applications, locations, materials, and manufacturing processes. Some of the projects use repetitive manufacturing processes that are not highly mechanized and may be labor intensive. Those include slumping clay, contact molding fiberglass, and casting concrete. Some of the manufacturing processes are highly mechanized—such as extruding metals, clays, and plastics and stamping metal—and require larger production runs. In all of Table 1's case studies, the highlighted component is custom for that particular project and is not available to the mass market. The case studies include a mix of architecture practices, including high profile firms such as Foster and Partners, Herzog and deMeuron, and REX; local and experimental practices such as LMN, Carlos Jimenez Studio, and houminn practice; and student-led, design-build prototypes.

Since CRM is defined by a customized and yet repetitive manufacturing process, the manufacturing processes included in CRM must make repeated use of the tools in a building component's production. In other words, a component must be designed to be used in multiples. Customized repetitive manufacturing balances the value of repetitive manufacturing with the ability of the designer to customize a repeated building component. The case studies include projects that have a range of production runs. There are approximately 14 panels for the Rice University Data Service Building; over 360 contact-molded ceiling coffers for the North Carolina Museum of Art; 7,786 wood-molded, blown-glass spheres used on the Hesiodo; and over 300,000 bricks produced for the Yale University Health Services Building.

There are advantages to CRM. First, there is a wide range of forms, materials, and finishes available in CRM. Processes such as precision slumping glass and clay, blowing glass, and contact molded fiber-reinforced plastic (FRP) are done with a mold. Repetitive manufacturing typically only use as much materials as the mold, pattern, or jig needs. By reusing tools and reducing raw material requirements,

Image	Year	*Repetitive Process,* Component	Project Name	Architect	Location
 flickr by InfoMofo	2003	*Slumped Glass,* Windows	Prada Store	Herzog and de Meuron	Tokyo, Japan
 flickr by Diorama Sky	2003	*Cast Metal,* Skylights	Nasher Sculpture Museum	Renzo Piano	Dallas, Texas
	2003	*Cast Metal*, Screen	Apartment Building	Rudinger Lainer and Partner Architectekten	Vienna, Austria
	2003	*Cast Metal*, Panels	Business and Fitness Center Addition	Rudinger Lainer and Partner Architectekten	Vienna, Austria
	2003	*Wood Molded, Blown Glass*, Screen	Hesiodo	Hierve Diseneria	Mexico City, Mexico
 flickr by mollyali	2004	*Rubber Molds,* Concrete Panels	Utrecht University Library	Wiel Arets Architects	Utrecht, Netherlands
 flickr by salisasaki	2005	*Pressed Clay,* Tiles	World Exposition, Spanish Pavilion	FOA	Aichi, Japan
	2005	*Precast Concrete,* Exterior Walls	Rice University Library Service Building	Carlos Jimenez	Houston, Texas

1

Table 1: Case Studies of Customize Repetitive Manufacturing in Architecture since 2003.

Image	Year	*Repetitive Process*, Component	Project Name	Architect	Location
	2005	*Explosive Forming*, Panels	Theater Castellum	Kraaijvanger Urbis	Alphen, Holland
 flickr by Carrie Sloan	2005	*Stamped Metal*, Panels	Walker Art Center Addition	Herzog + deMeuron	Minneapolis, Minnesota
	2007	*Fiberglass-molded Precast Concrete*, Walls	Rice University Data Center	Carlos Jimenez Studio	Houston, Texas
 flickr by Inhabitat	2008	*Extruding Clay*, Column Cladding	Spanish Expo-Pavilion	Francisco Mangado	Zaragoza, Spain
	2008	*Steel Mold Precast Concrete*, Screen	Argos Electrical Generator Building	MGP Arquitectura y Urbanismo	Yumbo Valle, Columbia
 flickr by joevare 15 April 2011	2008	*Extruding Metal*, Screen	Dee and Charles Wyly Theater	REX	Dallas, TX
 flickr by jeffreylcohen 6 September 2008	2008	*Rotational Molding Concrete*, Columns	Raleigh Convention Center	O'Brien/ Atkins Associates	Raleigh, NC
	2008	*Thermoformed Plastic*, Bricks	Drape Wall	houminn practice	Prototype
	2009	*Fiberglass Molded Concrete*, Panels	3.1 Phillip Lim Store	Leong Leong Architects	Seoul, South Korea

Table 1: (contd) Case Studies of Customize Repetitive Manufacturing in Architecture since 2003.

Image	Year	***Repetitive Process*, Component**	Project Name	Architect	Location
	2010	*Extruding Stiff Mud*, Bricks	Yale University Health Services Building	Mack Scogin Merrill Elam Architects	New Haven, Connecticut
	2010	*Extruding Stiff Mud*, Bricks	The Concave House	Tao Lei Architect Studio	Benxi, China
 flickr by Myxi 26 September 2008	2010	*Contact Molding*, Exterior Louvers	Walbrook Office Building	Foster and Partners	London, England
	2010	*Contact Molding*, Ceiling Coffers	North Carolina Museum of Art	Thomas Phifer	Raleigh, North Carolina
 flickr by joevare 4 October 2008	2010	*Rubber-Molded Composite Precast Concrete*, Panels	290 Mulberry Street	SHoP Architects	New York, New York
	2010	*Contact Molding*, Shell	Nature Boardwalk Pavilion at Lincoln Park Zoo	Studio Gang	Chicago, IL
	2010	*Pressing Glu-Lam*, Structure	Nature Boardwalk Pavilion at Lincoln Park Zoo	Studio Gang	Chicago, IL
	2010	*Thermoformed Metal*, Panels	Busta Line	Rentsch et al, University of California	Prototype

Table 1: (contd) Case Studies of Customize Repetitive Manufacturing in Architecture since 2003.

Image	Year	***Repetitive Process,*** **Component**	Project Name	Architect	Location
 flickr by hakaco 1 September 2012	2010	*Slumped Glass,* Windows	VAKKO Fashion Center	REX	Istanbul, Turkey
	2010	*Thermoformed Metal,* Panels	Busta Line	Rentsch et al, University of California	Prototype
 flickr: Paola Todesco 28 July 2010	2010	*Pultruded,* Exterior Skin Panels	Sheraton Milan Malpensa Airport Hotel and Conference Center	King Roselli Architetti	Milan, Italy
	2011	*Extruding Plastic,* Screen	Auditorium	Selgas Cano	Cartagena, Spain
	2011	*Vibration Casting CMU,* Screen	The Brick Loft	FARM	Joo Chiat Ln, Singapore
	2012	*Pressing Plywood,* Scales	Dragon Skin Pavilion	Emmi Keskisarja, Pekka Tynkkynen, Kristoff Crolla, and Sebastien Delagrange	Hong Kong & Shenzhen Bi-City Biennale of Urbanism/ Architecture
	2013	*Slumped Clay,* Tiles	Villa Nurbs	Cloud 9	Empuriabrava, Spain
	2013	*Contact Molded, glass-fiber reinforced concrete (GFRC)* Exterior Panels	Contemporary Art Center	Nieto Sobejano Arquitectos	Cordoba, Spain
 flickr by tedeytan 22 August 2013	2013	*Rubber Molded Precast Concrete,* Panels	Cleveland Medical Mart and Convention Center	LMN & URS	Cleveland, Ohio

Table 1: (contd) Case Studies of Customize Repetitive Manufacturing in Architecture since 2003.

repetitive manufacturing can have little to no production waste. Next, manufacturing tolerances for most of these processes are high and have the potential to rival the tolerances of CNC equipment. Finally, because of typically low tool costs, designers can customize the molds, patterns, or jigs, with limited additional costs. Conversely, there are some advantages that CAM has over CRM. These include direct-to-production from digital design files, the ability to make free forms and unique components, and speed to prototyping. Additionally, for additive CNC equipment, no tooling is required, which reduces the necessary materials for the production processes.

CASE STUDIES OF CNC FOR CRM

Several of the case studies from Table 1 demonstrate two potential approaches of using CNC equipment for CRM. For the first approach, CNC equipment directly makes the tooling for CRM. CNC equipment can be used directly to make soft tools, such as CNC-milled foam, or can be used to shape harder tools, such as steel, that are more durable. The type of tool fabricated by CNC equipment depends upon the manufacturing medium, process, and production run length. Second, CNC equipment can make the CRM tool, indirectly. This is when the CNC machine fabricates a master and then the tool is formed from the master. Typically, this is done when a larger production run is required and soft tools, such as CNC milled foam, are not durable enough to support the necessary production run lengths. In order to offset CRM tooling costs, some of the case studies creatively use their molds to form unrepeated components. Additionally, this paper highlights specific projects in which architects purposely selected CRM instead of CAM for their component manufacturing.

CRM sometimes uses soft tools that are made from low- or high-density foams and that CNC equipment can fabricate easily. These tools are inexpensive, as material costs are low. Additionally, the materials are relatively soft and can easily and quickly be cut by most CNC equipment, including CNC millers, routers, lathes, and hot-wire foam cutters. Drape Wall by houminn Practice, Rice University Library Service Building by Carlos Jimenez Studio, and the Villa Nurbs by Cloud 9 use soft tools from CNC-milled foam. Drape Wall thermoformed plastic bricks over a CNC-milled, high-density foam; The Library Service Building used CNC-milled Styrofoam molds as a casting bed for the precast, tilt-up concrete walls; and the Villa Nurbs used CNC-milled Styrofoam molds to slump the clay tiles for its rainscreen.

The benefit of using soft tools is that tooling costs are low; however, the tools are not durable. Depending on the manufacturing process and media, these tools can only be used for small productions runs. Drape Wall's production run for the thermoformed bricks was only 15 units. The Styrofoam forms for the Library Service Building were intended to be reused, but were so delicate that many of them were damaged when removing the concrete from the forms. In the end, the construction workers had to spend time removing broken Styrofoam pieces that had stuck to the precast concrete.[4] This means that most of the molds were disposed of after a single use. Using soft tools, with little to no repetition, can generate more manufacturing waste than more durable tooling. Additionally, the material used for soft tools—expanded plastic foams—are petroleum-based and have a high embodied energy. This results in added environmental impact with their disposal.

CNC equipment can directly create harder, more durable tooling. CNC equipment such as routers, millers, water-jet cutters, and electronic discharge machines (EDM) make tools from wood, aluminum, plastic, and metals. For example, Superior Tooling in Raleigh, NC uses wire and spark EDM, and CNC-milling machines to make molds from tooling steel for injection molding plastic. CNC routers and millers fabricate wood tools for pressing plywood. CNC water-jet and plasma cutters can be used to fabricate steel dies for extruding plastic, metal, and clay. CNC fabricated tools can produce architectural component similar to the pressed clay tiles for the Spanish Pavilion for the World Exposition by FOA, the stamped metal panels of the Walker Art Center Addition by Herzog + deMeuron, the extruded clay column cladding for the Spanish Expo-Pavilion by Francisco

Mandgado, the extruded aluminum screen of the Dee and Charles Wyly Theater by REX, and the extruding stiff mud bricks for the Yale University Health Service Building by Mack Scogin and Merrill Elam Architects.

Because durable tooling materials are more expensive than foam and the required CNC fabrication time is slower, hard tools are more expensive than soft tools. On the other hand, durable tooling materials can support larger production runs than less durable materials. For example, depending on the materials, sand-casting patterns can support different production run lengths. A plastic pattern can support a run of 50 units, a mahogany wood pattern can support a run of 1000 units, and a metal pattern can support high production runs over 10,000 units. Depending on the architectural design, a building using CRM components can have production runs over 10,000 units. For example, in the Spanish Expo-Pavilion, there were over 27,000 extruded clay pieces manufactured and over 300,000 bricks manufactured for the Yale Health Service Building.

CNC equipment can also be used indirectly to produce tooling. This is when CNC equipment fabricates a master, and then the tool is fabricated from that master. For example, in contact-molded fiberglass plugs are typically made from CNC-milled, high-density foam; then a fiberglass mold is made from the plug. The fiberglass mold is used for manufacturing the units, and supports a higher production run than the high-density foam. In the example of contact molding, high-density foam can typically only support the production of 1-10 units, whereas a fiberglass mold can produce 50-100 units. Manufacturers do this when they want the fabrication ease that come with soft tooling, but need a more durable tool to support higher production runs.

Architecture examples of this approach include the exterior louvers of the Walbrook Office Building by Foster and Partners, the ceiling coffers of the North Carolina Museum of Art (NCMA) by Thomas Phifer, the composite precast panels of 290 Mulberry Street Apartments by SHoP Architects, and the precast concrete panels of the Cleveland Medical Mart and Convention Center by LMN and URS. For the Walbrook Building and the NCMA, a CNC mill milled a foam plug that was then used to fabricate a fiberglass mold. The Walbrook's plug was used twice to form each side of the louvers' closed mold. For the NCMA, the contact molder (Fibertech) created three fiberglass molds from the plug so that the multiple molds would speed up production time. At 290 Mulberry Street, a rubber mold was cast against a CNC-milled foam master and at the Cleveland Medical Mart, multiple rubber molds were cast from the same CNC-milled master. Rubber molds are much more durable and flexible than other precast concrete mold materials and can be used up to 50 pours without damage.

To offset the tool costs associated with this additional step, manufacturers and architects may consider how to use a tool repeatedly, but to form different shapes. For the Walbrook Building, the cross section and plan curves of the mold remained consistent throughout all of the louvers, but the manufacturer was able to customize the louvers' lengths. The lengths were adjusted, depending on where they were installed on the building. Similarly, 290 Mulberry St. used a large, rubber mold for its composite brick and precast concrete panels. The precast manufacturer subdivided the mold into smaller panels of different shapes, which allowed for variety between the manufactured panels while using a single mold. At the Cleveland Medical Mart, the manufacturers placed dams on the CNC-milled master to create rubber molds of different heights. These examples demonstrate that although a single CNC-fabricated mold is used, manufacturers can use the molds creatively to produce design variations typically associated with mass customization.

Interestingly, for select case studies, architects used CRM as a means of manufacturing because it was a better alternative to CAM. For example, Carlos Jimenez Studio designed the Rice University Data Service Building after the Library Service Building was completed. The Library Service Building used CNC milled Styrofoam molds for the production for the building's precast, concrete, tilt-up walls. Jimenez was dissatisfied with using the Styrofoam as the mold material because its insulation properties affected the concrete's curing process and the molds were often damaged when the concrete panels were removed. For the Data Service Building, Jimenez and the contractor decided not to duplicate their mistakes on the Library Service Building and instead decided to fabricate fiberglass molds for that building's precast panels. The fiberglass molds themselves did cost more than the Styrofoam molds, but reduced overall construction labor costs and materials waste. In the cases of both the Walbrook Building and the Cleveland Medical Mart, CRM was selected as a method of production over CAM as a means to reduce costs.[5]

IMPLICATIONS FOR ARCHITECTURE

It seems that as digital technology has changed building form, it has also changed building surfaces. Ornamentation, surface articulation, and pattern making have had resurgence in architecture. As Antoine Picon writes, "The widespread return of ornament that can be observed today is actually inseparable from the massive diffusion of the computer in the architectural profession".[6]   In practice, we are seeing more of this type of work. Practices such as SHoP, Herzog and de Meuron, NADAA, Neil Denari, and Michael Maltzan are recognized for their surface manipulation. Books about these practices have been recently published, including *Digital Fabrications* by Lisa Iwamoto, *The Articulate Surface* by Ben Pell, and *Material Strategies in Digital Fabrication* by Christopher Beorkrem. This case studies of CRM are a smaller subset of this larger movement. Specifically, projects such as Wiel Arets' Utrecht Library, Kraaijvanger Urbis' Theater Castellum, Herzog and deMeuron's Walker Art Center, Carlos Jimenez's Rice University buildings, Leong Leong's 3.1 Phillip Lim Store, Mack Scogin and Merrill Elam's Yale Health Services, and LMN & URS's Cleveland Medical Mart are all examples of a surface-applied building ornament.

I will admit that CRM may not offer the same freedom of form making as the direct application of CAM to surface fabrication. Additionally, CRM may require more coordination between the manufacturer and the architect in order to educate the architect about what is possible in the manufacturing processes. At the same time, there is design restraint and rigor to the case studies that is apparent. This restraint and rigor differentiate the architectural ornament made by CRM from that of CAM.

CONCLUSION

My research into CRM is ongoing. Currently, I am working on a manuscript that will go into greater depth into the case studies. The goal of this paper was to highlight the unintended and indirect application of CAM in architecture design and construction and how that has impacted CRM. As architectural educators, we might promote CRM as an alternative to CAM to our students. Selected case studies, in Table 1, demonstrated how CNC equipment is being used in architecture to facilitate customization of repetitive manufacturing. The case studies illustrate that architectural practices are using CRM to make their components. The case studies present projects that have been completed in the past ten years, when CAM was a viable alternative for component production. All of the case studies demonstrate the application of CRM on a per project basis; in other words, the architects and building designers designed the customized components for the particular building.

Through this research, we can see that the implications of CAM on architecture design and construction are wider than its direct impact on making unique building components. In repetitive manufacturing, CNC equipment is used directly to make both soft and hard tools, or can be used indirectly as a pattern to make tooling. CNC equipment has lowered tooling cost for repetitive manufacturing and therefore required production runs are shorter. Shorter production runs mean more opportunities for customization. Ironically, the efficiency of CNC technology to make tooling for CRM has resulted in CRM being an alternative to CAM for architecture component manufacturing.

ENDNOTES

1. Kolarevic, Branko. *Architecture in the Digital Age: Design and Manufacturing*. New York: Spon Press (2003).

2. Plastic patterns in sand-casting tend to wear-out faster than wood or cast aluminum patterns and can be used for production runs under 50 units.

3. Lan, Hongbo. "Web-based Rapid Prototyping and Manufacturing Systems: A Review". *Computers in Industry*. June 2009. Elsevier. Combrink, J. et al. "Limited Run Production Using Alumide Tooling for the Plastic Injection Moulding Processes" *South African Journal of Industrial Engineering* . http://sajie.journals.ac.za/pub. Accessed Jan. 20, 2014.

4. Interview with Carlos Jimenez, Principal of Carlos Jimenez Studio. Houston, TX. 2 Feb. 2010, via phone.

5. Foster and Partners had originally conceived of the louvers as being made by CAM, but had to look in to means of repetitive manufacturing the louvers in order to reduce costs. Gabler, Markus "The Walbrook London- Façade in Glass-fibre-reinforced polymer" *Detail.* June, 2008.

6. Picon, Antoine. Ornament: The Politics of Architecture and Subjectivity. West Sussex, UK: John Wile & Sons Ltd. (2013).