

CRM Manufacturers in Architecture

Dana K. Gulling

North Carolina State University

Abstract

Computer-aided manufacturing (CAM) has revolutionized architecture. Proponents argue that CAM's computer numeric controlled (CNC) machines make individual architecture components that are not prohibitively expensive, reconnects designers directly to making, and transforms architectural form.¹ Despite these accolades, there is a distinction between CNC equipment directly and indirectly fabricating architecture components. Directly, CNC equipment punched the holes in the copper screen for Herzog and deMeuron's DeYoung Museum and the steel skin and structure for SHoP's Barclay Center. Indirectly, makers use CNC equipment to fabricate tooling (e.g. molds, patterns, and dies) to repetitively manufacture components that have been customized on a per-project basis. Examples include the pressed ceramic tiles on Machado Silvetti's Center for Asian Art at the Ringling Museum and the precast concrete panels for COOKFOX Architects' 260 Kent Street in Brooklyn.² The term 'customized repetitive manufacturing' or CRM refers to this process.

Through research, we have collected over 200 examples of CRM in architecture. Our CRM examples are located around the world and demonstrate a global application of CRM in architecture. See *figure 1*. A wide range of

architecture practices use CRM in their building design; this includes high profile firms such as Foster and Partners, Herzog and deMeuron, and REX; as well as local and experimental practices such as LMN Architects, 5468796 architecture, and Assemble. Some firms, such as Kengo Kuma and Associates and Neutelings Riedijk Architects, are 'repeat offenders' and have many projects on our list of examples (four and six, respectively). Some firms, such as Gramazio Kohler Architects and Herzog & deMeuron are well-known for experimenting with CNC technology but have used CRM for several of their award-winning projects.

In architecture, CRM's production runs are smaller and manufacturing more flexible than those typically associated with repetitively manufactured, mass-produced components. CRM manufacturers need to respond to orders as they are placed, tooling changes must be quick, and machine set-up times short. There are specific types of manufacturers and manufacturing facilities that can take on CRM work. This paper defines manufacturing terms and provides broad overviews of manufacturers, while focusing on those elements that relate to CRM in architecture. We concentrate on manufacturers that are able to take on custom work via contracts, while demonstrating that the types of manufacturers for CRM in architecture is broad. Using

¹ Kolarevic, Branko and Kevin Klingner. *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. Routledge, 2013

² Machado Silvetti. Center for Asian Art at the Ringling Museum of Art. 2016, Sarasota, FL plaster molds were fabricated with a

CNC mill. COOKFOX. 260 Kent. In-progress, Brooklyn NY used large-scale, 3D printed molds that were CNC milled to their final shape and finish.

the case studies, this paper explores, categorizes and qualitatively identifies different types of CRM manufacturers of architecture components.

Defining Manufacturing Methods

We define ‘**manufacturing**’ as to make from raw or unformed materials by hand or by machinery, especially when done systematically.



Figure 1 | World Map of CRM in Architecture – locations of built case studies

With this definition, manufacturing refers to the forming of raw or unformed materials into a component’s final form. The term ‘manufacturing’ can include the rotary cutting of a log to make wood veneers, the laminating of those veneers into plywood sheets, or the hydraulic pressing of thin, flat plywood sheets in a mold to make a bent plywood component. For the last example, manufacturing includes the deformation of the unformed plywood into its bent, final

form. This is analogous to stamping a metal blank or extruding an aluminum billet. The cut metal sheet (i.e. blank) or cylindrical aluminum billets are not complete on their own; instead those merely formed for the manufacturing ease of the subsequent processes of stamping or extruding, respectively.³ The definition of manufacturing does not necessitate a production quantity or size limitation. Manufacturing can include the making of

³ In context beyond this paper, manufacturing can include the making of non-discrete items such as chemicals, textiles, foodstuff, or energy. It can also refer to postproduction

processes—such as cutting, joining, and finishing, or product assembly.

a single, or bespoke, item, such as a man's suit or custom nameplates; the making of large products, including manufactured buildings or the making of ships; or the assembly of other standardized pre-manufactured components, such as the making of custom floating docks from standard aluminum extrusions.⁴

Like the making of a bespoke suit, manufacturing does not necessarily favor mechanized or industrialized processes and can include hand-crafted and labor-intensive processes. Generally, manufacturing by hand is viable where labor costs are low and where financial capital, necessary to purchase large equipment, is difficult to acquire. CRM examples of these labor-intensive manufacturing processes include the wood-molded, blown-glass spheres manufactured by craftsmen in Guadalajara, Mexico, for the Hesiodo in Mexico City by Hierva Diseneria and new concrete masonry units (CMU) manufactured on a concrete block hand press for MR 299 also in Mexico City by HGR Architects with Ariel Rojo.

Repetitive manufacturing makes repeated use of tooling (e.g. jigs, patterns, molds, or dies) for the production of similar units. Production runs for repetitive manufacturing can be varied, ranging from small-batch productions to production runs over one million units. The production run lengths primarily depend on tooling costs, because the tool's costs are amortized over the number of units produced. If a tool is inexpensive, then few units need to be produced to cover the tool's cost; whereas large production runs are necessary to offset high tool costs. 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. Different tools, and thus tooling costs, can be used in the same manufacturing processes. For example, metal

casting can use wood patterns and sand molds for low-volume productions, or hardened tool steel molds for high-volume productions.



Figure 2 | SHoP Architects. 290 Mulberry Street. 2010 New York City. joevare. Flickr. October 4, 2008.

In repetitive manufacturing a particular tool is used for a particular shape; however, the manufacturing processes can be customized or adjusted to introduce differences in the produced components. For example, tools may be partitioned so that portions of the tool form different shapes. An architectural example is the CNC-milled master molds for SHoP Architect's 290 Mulberry Street that were partitioned into smaller shapes to cast multiple, differently-shaped rubber molds for the building's precast, brick and concrete panels. Additional manufacturing adjustments can be made through manufacturing speeds, conditions, or changes in media. This allows for some variation while still making repeated use of the tooling. An example is the dimpled surface of Herzog and deMeuron's DeYoung Museum in which a CNC-controlled, metal stamper used a steel-hardened, static-shaped, custom tool to strike the

⁴ Wahoo Docks is a dock manufacturer in Georgia that manufactures docks from components made at from a local aluminum extruder. Gulling, Dana K. "Manufacturing Architecture: Case Studies of Collaborations between Designers and Makers" *Made: Design Education & the Art of Making*

copper skin at different forces, causing the dimples to appear irregularly shaped.

Manufacturers operate with either 'push' or 'pull' models of production. A push model of production is when a manufacturer starts producing units before orders are placed, essentially pushing the manufactured units onto consumers. A pull model of production is when manufacturer waits for orders before manufacturing units, essentially allowing the demand of the customer to pull units from production. Generally, push models require more capital than pull models as manufacturing costs are spent before the manufactured items are purchased, requiring a financial risk. Pull models of production have less financial risk than push models, but the manufactured items are not immediately available and require time to be produced after orders are placed. Manufacturers operate within both a push and pull model, depending on available capital, capacity, storage space, and predictability of sales.

Customized repetitive manufacturing (CRM) is repetitive manufacturing processes that have been customized on a per-project basis. In recent years, CNC technology has reduced tooling costs for repetitive manufacturing. Today, many repetitive manufacturers use tools fabricated by CNC equipment. Contact fiberglass molders and plastic thermoformers use CNC-milled, high-density foam for their molds. CNC routers, CNC millers, and EDM wire and spark machines fabricate hardened-steel molds for transfer moldings and dies for extrusion. New developments in rapid tooling (RT) have been using this

equipment to make tools. For example, sand-casters can use FDM and SLA printed patterns for small production runs, researchers are investigating using metal laser sintering to make injection molds for plastic⁵, and precast concrete manufacturers are using large-scale, carbon-fiber, 3D-printed mold plugs for casting precast concrete. Since tooling costs are amortized over the number of units a tool produces, reduced tooling costs reduces the production run necessary to offset those costs. This means that CNC technology has enabled smaller production runs for repetitive manufacturing and therefore has increased opportunities for customizing.

CRM is not specific to architecture; however, architecture easily employs the benefits of CRM for the manufacturing of building components. Like the manufacturing of ships or airplanes, buildings are made from several highly repetitive, discrete elements.⁶ These elements may include extruded, aluminum mullions; extruded, stiff-mud bricks; spun, metal hardware; and cast metal fixtures. It is these repetitively-manufactured elements that hold the opportunity for customization. In addition, buildings have the potential to be bigger than ships or airplanes; therefore, the production runs of building components can be large with plentiful opportunities for potential customization. Additionally, the project scope of a building's construction is defined, containing the customization of the repetitively manufactured component within a project's building or a collection of buildings.⁷

⁵ Lan, Hongbo. "Web-based Rapid Prototyping and Manufacturing Systems: A Review". *Computers in Industry*. June 2009. Combrink, J. et al. "Limited Run Production Using Alumide Tooling for the Plastic Injection Moulding Processes" *South African Journal of Industrial Engineering*. Online.

⁶ Both Le Corbusier in *Towards an Architecture* and Stephen Kiernan and James Timberlake in *Refabricating Architecture* have made the analogy of ships and airplanes to buildings.

⁷ There are some CRM components that were custom manufactured for a particular building or project that after that product was completed, the components were then available commercially. This includes the custom brick Peter Zumthor's Kolumba Museum now available through Petersen <<https://en.petersen-tegl.dk/kolumba/>> Accessed 18 February 2019; and custom blow-molded polli-brick Miniwiz's EcoARK. These are included because they were commercially available after they were first customized their corresponding projects.

Defining Manufacturers

Defining manufacturer terms can be ambiguous, as the terms often change depending on manufacturing sectors. In this section, we define the different types of manufacturers that produce discrete components that would be most often associated with architecture.

Original Equipment Manufacturers (OEM) are the final manufacturers of a product before it is purchased. Examples include pre-hung doors, light fixtures, airplanes, and cars. For simple products like drinking glasses—where only one manufacturing process (i.e. pressing glass) is used—the component manufacturer is the same as the OEM. For complex products like a car, the OEM assembles the final product and often subcontracts some of the car's component manufacturing to other manufacturers. This is typically done for the making of small components that may require specialized manufacturing skills—such as the extruding of polymers for tubes and belts—or when manufacturing of components can be done elsewhere at a lower cost.

There is ambiguity in the term 'OEM', as there is not consistency as to what define an OEM manufacturer. Some OEMs can manufacture some of the product's components, sub-contract other parts, and assemble all the parts together. Some OEMs only assemble components that have all been manufactured by other subcontract manufacturers. Generally, OEM products are available for commercial purchase; however, they can be sold under another company's name (i.e. Foxconn, a

Taiwanese electronics company produces the products for Apple). Some OEMs can also be an end-product producer while other OEMs produce parts that end up in another product. Examples of this include Goodyear tires that come with a new car, or a Trane air-handling unit that comes with a Butler manufactured building. Both products are part of the final OEM, as well as being commercially-available for retail purchase as products themselves from another OEM (i.e. Goodyear and Trane). The term OEM is then further complicated as it can also refer to the manufacturer of aftermarket parts, such as using a Carrier HVAC unit to replace the Trane HVAC unit that came with the Butler building. In architecture, the term 'OEM' is analogous to the construction of the building, regardless of the building's components.⁸

Product manufacturers are manufacturers that produce only their own products. In architecture, this could include Valli&Valli door hardware and clay brick by General Shale. Generally, product manufacturers are not able to fulfill custom orders, as they are designed and optimized to efficiently manufacture their own products. General Shale offers a pre-described list of 'custom' shapes—such as bell coping, bullnose stretchers, and concave radial—which are prescribed special shapes and not actually custom designed.⁹ Product manufacturers may operate on a push model of production, particularly if their product market is predictable.

Contract manufacturers (CM) do not produce any of their own products and instead manufacture items to

⁸ Kieran, Stephen and James Timberlake. *Refabricating Architecture: How Manufacturing Methodologies are Poised to Transform Building Construction*. McGraw-Hill Education, 2003.

⁹ On the company's website, the shapes are listed as 'custom' under a specific tab but then are full specified and dimension in a downloadable brochure titled "Special Shapes". General

Shale. "Products/ Custom Brick Shapes". General Shale, Inc. 2015. <https://generalshale.com/products/custom-brick-shapes/> Accessed 18 February 2019. General Shale. "Special Shapes". General Shale, Inc. 2018. <https://generalshale.com/resources/file/612aecc0-01b4-4736-99b5-cf19eedd2061.pdf> Accessed 18 February 2019

the specifications of the contract. CMs manufacture components or products as orders are placed. They operate on the pull model of production, waiting to produce after the order is placed. Examples of contract manufacturing is casting of architectural precast panels and injection molding, plastic car bumpers. Other terms for contract manufacturers might be 'job shops' or 'work shops', in which the facility does the manufacturing as per the job or work requires. Contract manufacturers may have contracts to manufacture a single production of units in a limited amount of time or they may have a contract to produce a certain number of units, for each given cycle, over a long period of time. This second option allows the CM to continually supply the product manufacturer or OEM. For example, each month, a plastic, injection molding CM sends 100 bumpers to an OEM to install on their new cars.

The benefits of using a CM for manufacturing is flexibility and increased specialty. CMs can handle the uneven demands for units and small production runs by balancing its workload through multiple contracts. In contrast, a product manufacturer not using a CM would need to sell enough product run to operate its facility year-around. Unlike OEMs that make complex products assembled from different parts, CMs focus on a limited number of manufacturing processes such as Penn Compression Molding that does compression, transfer, and injection molding with thermoset, reinforced plastics.

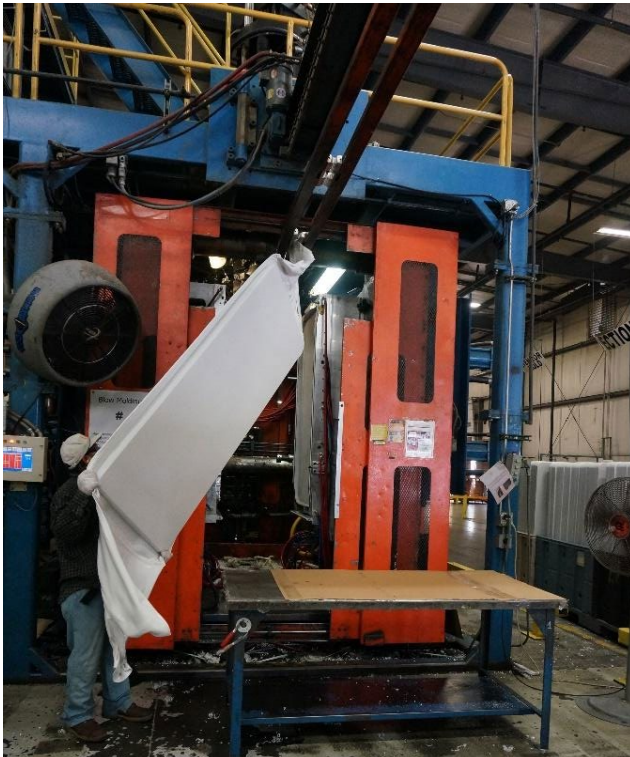


Figure 3 | Large press for compression molding thermoset plastics. Penn Compression Molding is a CM and focused on manufacturing with thermoset plastics.

Drawbacks of manufacturing with a CM may include capacity limits, scheduling, and oversight. CM manufacturers fulfill multiple contracts and therefore may not have the capacity to schedule jobs that will dominate their facilities. CMs schedule their productions to keep their workforce and machinery busy, and incoming jobs may not be able to be started until after a preceding contract has completed. CMs have their own methods of operations that may be different than the contracting company. This may include employee hiring practices, shift hours, and safety measures. Unless the contracting company specifies how the CM should operate, the CM's operation may conflict with the goals of the contracting company. This is particularly a concern when the CM is located far from and in a different culture than the contracting company. Recently, this has been particularly problematic for clothing and shoe manufacturers, when it comes to issues of worker safety and child labor.

Some manufacturers are not easily categorized as solely product manufacturers or contract manufacturers. Some manufacturers will produce their own product lines, while

simultaneously fulfilling manufacturing contracts for other companies. An example is Penguin LLC in Sturgis, Michigan that does plastic injection and blow molding contract manufacturing. In the same manufacturing facility is the OEM for their proprietary line of folding office tables.¹⁰ Both the contract and OEM manufacturers are in the same space with dedicated blow-molding and pipe-bending stations, and powder-coating lines for their office products. Manufacturers may choose to do both product and contract manufacturing if their products are seasonal or are sensitive to economic downcycles. Generally, for these manufacturers particular manufacturing lines or stations are dedicated to fulfilling contracts, while others are pushing out products.



¹⁰ Iceberg Enterprises is Penguin LLC's sister company with its own web presences and distribution systems. Although separate companies, manufacturing for both takes place in the same facility.

Figure 4 | Large plastic blow molding machine that make tabletops for Penguin LLC own line of folding tables.

The ability for a product manufacturer to customize depends on the manufacturer's size and flexibility. Generally, large companies that have high production runs of their standard building products, are not able to easily customize. Manufacturers such as General Shale have invested a lot of capital to optimize their assembly lines and equipment. This allows them to produce their standard products quickly; however, this investment may mean that their lines and equipment are not flexible enough to accommodate custom shapes. Contrasted with General Shale is Taylor Clay Products, Inc. located in Salisbury, North Carolina. Taylor Clay survived the economic downturn in 2010-2015 by taking their assembly line robots off-line and increasing their ability to manufacture custom brick shapes.¹¹

Shops and Studios: Alternative Contract Manufacturers



Figure 3 | Jeff Goodman Studio website. 2019 <
<http://www.jeffgoodmanstudio.com/>> Accessed 19 February 2019.

¹¹ In contrast to General Shale, Taylor Clay Products' website list their custom brick shapes under "Special Shapes" but states clearly "Charles Taylor does not recognize the work 'no' when it comes to ceramic brick." 2014 Taylor Clay Products, Inc. <http://taylorclaybrick.com/wp/special-shapes/> Accessed 18 February 2019.

The term 'contract manufacturer' is an umbrella term that refers to the relationship between the manufacturer and the contracting company. **A subset of 'contract manufacturer' includes small manufacturing facilities such as fabrication or machine shops, craft production, or artisan workshop or studio.** These shop facilities are smaller than typical contract manufacturers, have fewer employees, and are not automated. Generally, fabrication shops, and machine shops are dedicated to custom work. They are set up to produce one-offs and prototype, but may be able to manufacture small, batch productions. Craft production and artisan workshops or studios often produce some of their own products for sale but can usually accommodate small-to-medium-sized production runs.

Since these alternative manufacturing shops and studios produce short production runs, their scheduling is more flexible, offering shorter lead times than traditional contract manufacturers. Workers are highly skilled and can produce high-quality items. Generally, shops and studios may experiment outside of a CM's production parameters to produce unique units. In addition, shops and studios are more adept at collaboration between designers and makers. An example is Jeff Goodman Studio's collaboration with Hariri Pontarini Architects for their kiln-cast, custom glass panels used for the Baha'l Temple of South America (2016) in Santiago, Chile. Jeff Goodman Studio is a Toronto-based glass studio that does primarily glass blowing, with some glass casting and slumping. Goodman Studio produces their own commercial and fine-arts work, and collaborates with architects, interior designers, and others for commissioned, custom-designed projects. The Temple's glass panels resulted from a four-year research project

between the Studio and the architects, in which 200 samples were made to achieve the desired design.¹²

There are disadvantages for selecting shops or studios as the contract manufacturer. Because of their small size and less-automated equipment, lead times may be longer than traditional contract manufacturers. Shops and studios may have limited manufacturing equipment, restricting their capacity to manufacture to certain specifications. Because they are less automated, costs for manufacturing in shops and studios is often higher than manufacturing with traditional contract manufacturers. Although quality of production is high, depending on the process and the materials, consistency between the manufactured units may be difficult. For certain architectural projects, consistency between units may not be a desired trait. Examples of this include the hand-thrown, black quartz grains for the cast stone panels for Duvall Decker Architect's Mississippi Library Commission Headquarters (2010); the artist-applied glaze for the slumped clay tiles of Cloud 9's Villa Nurbs (2009); and the glass panels for Hariri Pontarini's Baha'l Temple.

Manufacturer Selection

Generally, manufacturing processes and manufacturer types are local or regionally-based. A manufacturer's location is based on the availability of and access to raw materials, human resources, available transportation, and proximately to markets. This may mean understanding a region's history to know of its manufacturing capabilities. First, in North Carolina, because of the state's nature clay deposits, has ten brick and tile manufacturers in the state. Second, because of North Carolina's history with boat-building, the state has a high number of contact-molders that work with

¹² Justin Ford. Hariri Pontarini Architects. Personal Interview. 2 November 2015.

fiberglass reinforced plastics (FRP). These include Piedmont Fiberglass that does spray-on FRP; Windsor Fiberglass that does hand-layup, specialty items; and a small two-person workshop, called Custom Fiberglass International that does highly specialized work and boat repair. Third, western North Carolina has many artists and craftspeople, educated at Black Mountain College or Penland School of Craft, that settled in the Blue Ridge Mountains, near Asheville. There, we find many artist studios that make blown-glass and are able to do custom productions.

When considering a CRM manufacturer, architects should look toward contract manufacturers and may be able to approach small-scaled, more unknown product manufacturers. Small product manufacturers are less well-known than high-volume product manufacturers and may be flexible enough to accommodate custom productions. In North Carolina, Taylor Clay is more adept at producing custom shapes for brick than General Shale, although both manufacture their own brick lines.

To search for manufacturers in the United States, Thomasnet.com is the leading to find manufacturers, and can restrict searches to geographic areas. Thomasnet is not exhaustive and is best for traditional contract manufacturers and product manufacturers that meet certification specifications (e.g. ISO). We have had some ability to find some small, one-person fabrication shops listed on Thomasnet; however, we have yet to find a sourcing platform that can be used for consistently identifying workshops or studios.¹³ Currently, we rely on simple web-based searches.

As an architect new to understanding manufacturing processes that can be customized, one should consider

selecting a manufacturer who can collaborate during early design phases. This may restrict you to smaller workshops and studios, as many contract manufacturers competitively bid prospective projects without accounting for collaboration costs, unless specified in the bid. Some CMs will work with designers during design development with the hope that they may be awarded the bid contract. This involves financial risk that many conservative CMs are unwilling to do. An alternative to this is to include a manufacturing design consultant for a small fee.

Conclusion

CNC technology has made the fabrication of custom molds cost effective for small-volume productions that have been customized on a per-project basis. We have collected over 200 examples of CRM in architecture that are located around the world and have been designed by a wide range of architecture firms. For architectural application, the production runs for customized repetitive manufacturing are smaller than those typically associated with commercially-available components. CRM manufacturers must be flexible; respond to orders as they are placed, with quick tooling changes and short machine set-up times short. Generally, CRM manufacturers are contract manufactures with all or part of the facility work on a pull model of production. The definition for contract manufacturing is broad, with small workshops or artisan studios also able to do CRM.

¹³ This included Bill Ganz & Company, a one-man fabrication shop in Midvale, Utah, which makes spun metal components for light fixture and aerospace companies.