Beyond buildings [but] inside architecture

Dana K. Gulling

North Carolina State University, Raleigh, North Carolina

ABSTRACT: In recent years, mass customization and computer aided manufacturing (CAM) technologies have transformed off-site building component fabrication. At the same time, traditional repetitive manufacturing still dominates building component production. Bricks, bathroom fixtures, window mullions, and door hardware are all repetitively manufactured. Ironically, CAM's computer numerical controlled (CNC) machines have made the fabrication of custom molds for repetitive manufacturing easier. This allows architects to customize repetitively manufactured architecture components. I am using the term customized repetitive manufacturing (CRM) to refer to this type of work. Through my ongoing research, I have identified a wide range of historic and contemporary examples of CRM for architecture components.

Designs for repetitive manufacturing architecture components involve coordination between the architect and the manufacturer. Both must balance capital costs with production runs, mold complexity with manufacturing parameters, and size restrictions with manufacturer's abilities. How these issues are balanced depends on the application of the architectural component. I have identified three categories of custom designed architecture components based on application—custom components, architecture prototypes, and architecture products. This paper presents the three categories of application in reference to CRM. I define each category, provide multiple examples, and analyse particular case studies. Analysis of the case studies provides the architectural and manufacturing impacts on CRM within each category.

KEYWORDS: architecture, components, customization, manufacturing, and product design

INTRODUCTION

In recent years, mass customization and computer aided manufacturing (CAM) technologies have transformed off-site building component fabrication. At the same time, traditional repetitive manufacturing still dominates of building component production. Bricks, bathroom fixtures, window mullions, and door hardware are all repetitively manufactured. Ironically, CAM's computer numerical controlled (CNC) machines have made the fabrication of custom tools for repetitive manufacturing easier and thus have reduced costs. CNC milling machines, electrical discharge machines (EDM), and hot-wire foam cutters are used to creating tools for repetitive manufacturing. Reduced tooling costs therefore require smaller production runs to offset those costs. Architecture benefits from smaller production runs, as architects can now consider customizing repetitively manufactured products for architecture components. I will use the term customized repetitive manufacturing (CRM) to refer to this type of work.

Through my ongoing research, I have identified a wide range of historic and contemporary examples of CRM in producing architecture components and have presented in-depth investigations into selected case studies. The case studies of CRM in architecture are located around the world and use a variety of manufacturing processes. Using those examples, I have identified three categories of customized architecture components. The categories are custom components, architecture prototypes, and architecture products and they are based on the architects' design, intention, and application of their components. Custom components are designed by the architect to be custom manufactured for a particular building. Examples include Renzo Piano's sand-casted, ductile iron truss members for the Menil Collection (1987) and Tom Phifer's contact-molded, fiberglass reinforced plastic (FRP) ceiling coffers for the North Carolina Museum of Art (2010). Architecture prototypes are full-scale, mock-ups used to test and architectural idea. Examples include R. Buckminster Fuller's Prefabricated Bathroom for the Dymaxion House (1940) and houminn practice's Drape Wall (2008). Finally, architecture products are architecture components available for mass consumption. Examples

include Zaha Hadid's ZH Duemilacinque doorknobs for Valli&Valli and Robert A.M. Stern's Rhythm light fixtures for Lightolier.
Although building component design is outside of standard architecture practice, architecture components are simultaneously part of architecture. Components are attached to the building and it is the aggregation of components that physically makes a building. In order to use CRM for architecture component design, the architect must decide that the available building components products do not meet the needs of the design. Additionally, because the CRM component is repetitively manufactured, the architect must believe that a new component's design is strong enough to warrant multiples. Designs for CRM components require coordination between the architect and the repetitive manufacturer. Both must balance capital costs with production runs, mold complexity with manufacturing parameters, and size restrictions with manufacturer's abilities. How the architect and the manufacturer balance these parameters depends on the component's application.

This paper highlights architects' design work beyond the profession's standard definition of architecture design. For this research, I use contemporary and historic case studies to define the three categories, study the lessons learned by the case studies, and draw conclusions. The three categories—custom components, architecture prototypes, and architecture products—provides particular constraints on CRM that the architect should consider. By grouping the examples together, I am able to draw out common themes, challenges, and constraints that should be considered in each category. For example, by examining the custom components together, I discovered the challenges for architects in educating themselves about potentially unknown manufacturing processes. This paper is part of my investigation to understand the overall conclusions that my collection of CRM case studies provides.

1.0 CRM AND ARCHITECTURE COMPONENTS

Repetitive manufacturing reuses its tools (e.g. jigs, molds, and patterns) to produce runs of similar products. Production runs for repetitive manufacturing can be varied, ranging from small-batch productions to production runs over one million units. Product run lengths depend on the production media, the tooling media, and manufacturing processes. Typically, the product's production run length is directly dependent on the cost of the tools; high production runs are necessary for manufacturing processes that have high tooling 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. CNC machines have made it more affordable to fabricate manufacturing tools and therefore have reduced production run lengths. This means that CNC technologies have allowed smaller production runs and therefore more customization in repetitive manufacturing.

CRM balances the value of repetitive manufacturing with the ability of the designer to customize a building component. There are forms, materials, and finishes available in CRM that are not available in CAM. Processes such as precision slumping glass and clay, blowing glass, and contact molded fiber-reinforced plastic (FRP) are available in CRM but not CAM. In comparison to subtractive CAM processes, repetitive manufacturing typically uses only as much materials as the mold, pattern, or jig needs[1]. By reusing tools and reducing raw material requirements, customized repetitive manufacturing can have little to no production waste. Manufacturing tolerances for most of these processes are high and have the potential to rival the tolerances of CNC equipment.

In comparison to CAM, architect need to consider more variables in CRM. In CRM, one must consider desired materials, shapes, allowable production runs, capital costs, and finishes in order to select a manufacturing process. For example, if a production run is small and costs are required to be low, then a designer may want to consider thermoforming for plastic rather than injection molding. Additionally, the mold media affects the manufacturing process. In thermoforming plastic, changing the mold from wood to aluminum (with imbedded cooling lines) increases the cycle time, tolerances, mold costs and production run lengths. Conversely, there are fewer variables in CAM than CRM. A CNC router is consistent in its operation regardless of the media, shapes, production runs, and finishes. Media and finishes may affect production speed, but the operation of the machine, tolerances, and production run lengths remain the same.

The three categories of architectural components—Custom Components, Architecture Prototypes, and Architecture Products—affect the variables of CRM production. Therefore, in order to design for manufacturability, the designer should consider the category in which their design is. For example, if an architect-designed component is a product to be made of metal and available for mass consumption, lost wax casting with injection-molded patterns could be considered. If a component is custom for a particular building application, then it may have a smaller production run and could be sand casted. The capital costs and finishes with the lost wax casting with injection-molded patterns are substantially higher than those of sand casting metal are.

1.1. Custom components

In many ways, custom components are the most interesting category of architectural components. Custom components are components that the architect has custom designed to be unique to a particular building design. (See Table 1.) Custom components are typically pursued by architects and building designers that are concerned with building details. Examples include Renzo Piano's custom sand-casted ductile iron truss members for the Menil Collection (1987) in Houston, TX and Herzog and de Meuron's slumped glass windows for the Prada Store (2003) in Tokyo, Japan. With those examples, the custom components complete the vision of the project. The truss members of the Menil Collection are part of the building's high-tech structural expressionism. The curved windows of the Prada Store are and extension of the building's consumer nature, as they create a convex lens in keeping with the store's consumerist program. (herzogdemeuron.com)

Table 1: Table listing selective case studies of CRM custom components. The listed case studies have been limited to examples from the past 10 years.

Year	***Repetitive Process,* Component**	**Project Name**	**Location**	**Designer**
2003	*Slumped Glass,* Windows	Prada Store	Tokyo, Japan	Herzog and de Meuron
2003	*Wood Molded, Blown Glass*, Screen	Hesiodo	Hierve Diseneria	Mexico City, Mexico
2003	*Cast Metal,* Skylights	Nasher Sculpture Museum	Dallas, Texas	Renzo Piano
2004	*Rubber Molds,* Concrete Panels	Utrecht University Library	Utrecht, Netherlands	Wiel Arets Architects
2005	*Explosive Forming*, Panels	Theater Castellum	Alphen, Holland	Kraaijvange r Urbis
2005	*Stamped Metal*, Panels	Walker Art Center Addition	Minneapolis, Minnesota	Herzog + deMeuron
2007	*Fiberglass-molded Precast Concrete*, Walls	Rice University Data Center	Houston, Texas	Carlos Jimenez Studio
2008	*Extruding Clay,* Column Cladding	Spanish Expo-Pavilion	Zaragoza, Spain	Francisco Mangado
2008	*Extruding Aluminum,* Screen	Dee and Charles Wyly Theater	Dallas, TX	REX
2010	*Slumped Glass,* Windows	VAKKO Fashion Center	Istanbul, Turkey	REX
2010	*Extruding Stiff Mud*, Bricks	Yale University Health Services Building	New Haven, Connecticut	Mack Scogin Merrill Elam Architects
2010	*Contact Molding FRP*, Exterior Louvers	Walbrook Office Building	London, England	Foster and Partners
2010	*Contact Molding FRP,* Ceiling Coffers	North Carolina Museum of Art	Raleigh, North Carolina	Thomas Phifer
2013	*Rubber Molded Precast Concrete*, Panels	Cleveland Medical Mart and Convention Center	Cleveland, Ohio	LMN & URS
2013	*Contact Molding GFRC,* Panels	Contemporary Art Center	Cordoba, Spain	Nieto Sobejano Arquitectos

Figure 1: Selected Images of custom components. From left to right: Prada Store by Herzog and de Meuron, flickr: (InfoMofo, 2006); 290 Mulberry St. by SHoP, flickr: (joevare, 2008); Walbrook Office Building by Foster and Partners, flickr: (Myxi, 2009).

Custom manufactured custom components allow for customization from the designer while balancing the need for repetition in order to remain cost effective. Since customization is done on a per-project basis, the architect has to pay particular attention to the production run length of the custom component. Required production runs for custom components can vary between designs, applications, and production methods. Prior to the use of CNC equipment to fabricate tooling, tools were fabricated by hand and were thus labor intensive and costly. Therefore, historically an architect would be required to consider tooling costs for the designs of their custom components.

Historic examples of custom components include Frank Lloyd Wright's cast textile blocks for his California concrete block houses (c. 1920) and the stamped aluminum panels for the Harrison & Abramovitz's Alcoa Building (1953) in Pittsburgh, PA. Both examples used different methods to offset the additional tooling costs. Wright's textile blocks were manufactured on site, by hand, in a multipart mold. The mold was similar to a springform pan—its sides unhinged so that they could be separated from the mold's face. Tooling costs were reduced by breaking the mold into parts. The mold's sides were used for every block and two different faces were used to create the flat and textile block faces. The mold was made from aluminum, and by reusing the sides for all block production, less fabrication work was required to make the tools. The Alcoa building used a different approach for offsetting tooling costs. A thirty-story, high-rise building, the Alcoa has a custom, stamped aluminum panel under each window. Because the Alcoa Building is a high-rise, additional costs for the custom component is offset by the number of panels required to clad the high-rise.[2]

Today, because of the availability of CNC equipment to make tools, custom components are easier to produce than they were historically. CNC equipment fabricated the tools for the Utrecht Library, Walbrook Office Building, NC Museum of Art, 290 Mulberry St. and Cleveland Medical Mart. The case studies listed in Table 1 demonstrate the advantages of CRM over CAM. Sometimes CRM is less costly than CAM. For example, Foster and Partners had investigated using CNC equipment to make the louvers on the Walbrook Building, but then learned that repetitively manufacturing them with a mold was more cost effective. Oftentimes CRM produces less waste than CAM; such was the case for the Cleveland Medical Mart. Here the design team used a CNC-milled pattern multiple times to produce rubber molds and then used the rubber molds multiple times to create the precast panels. If the tools, were not used repeatedly for production, more manufacturing waste would have been created to make the panels

Analyzing the custom component case studies offers lessons for designer considering CRM for production. First, in order to reduce production costs and waste, the designer should consider creative uses for the production tools. Similar to Wright's multipart, textile-block molds, some of the case studies have considered molds that can be broken down or subdivided. At 290 Mulberry St., SHoP designed the building's precast concrete and brick composite panels so that they could be manufactured using one large rubber mold that was sub-divided. At the Cleveland Medical Mart, the toolmaker used dams to make different rubber molds from a single CNC-milled pattern. Both examples allowed for multiple variations using a single tool, thus reducing cost and waste. Second, a designer must consider both the production run and the manufacturing processes. For some manufacturing processes, high tooling costs cannot be reduced and the only way of balancing those additional costs is through high production runs. These processes typically use steel tools and include extruding clays, metals, and plastics. There are over 27,000 extruded clay pieces on the Spanish Expo-Pavilion and over 300,000 custom bricks for the Yale Health Services Building. Alternatively, some manufacturing processes have low tooling costs and therefore can support small production runs. This includes the explosive formed panels for the Theater Castellum, the precision slumped glass for the VAKKO Center, and the contact molded FRP coffers for the NC Museum of Art. Finally, since custom components are done on a building-by-building basis, architects may not have prior experience with their selected repetitive manufacturing processes. This often requires architects to find manufactures who are willing to collaborate for a particular design. Such was the case with FiberTech who worked with Phifer's office for the NC Museum of Art, and Ceramica Cumella and Ceramica Decorative who worked with Mangado for the Spanish Expo-Pavilion.

1.2. Architecture prototypes

I am defining architecture prototypes as explorations of architectural ideas, using full-scale, physical, mock-ups. Architecture prototypes are often not full buildings, but are pieces or ideas that can be applied to future buildings. Examples of prototypes include Dunescape by SHoP (2000) which explored CNC fabrication and unskilled assemblage and the Cellophane House by KieranTimberlake (2008), which was a vehicle for the firm to further develop applications for SmartWrap.[3] Architecture prototypes can include investigations into new materials, exterior enclosure systems, wall types, fabrication systems, or methods of construction. Architecture prototypes may be sited, but since they are built investigations of a larger architectural idea, they are often site-less. An historic example of an architecture prototype is R. Buckminster Fuller's prefabricated bathroom for the Dymaxion house (1940).

Innovative architectural practices, architecture researchers, and studio courses tend to explore design ideas through architectural prototypes. Today, CNC equipment and robots fabricate most prototypes. This may be because of the accessibility of CNC equipment in architecture academia, because CNC equipment can be programmed directly by the designer, or because CAM equipment has little-to-no capital costs. Despite those advantages, there are a handful of architecture prototypes that have made use of CRM for their component production. See Table 2. In these examples, CRM was selected because it offered something the CAM did not. For example, thermoforming metal was a cost-effective method to get 3-dimensionally formed tiles out of metal for the Busta Line project, and for the Dragon Pavilion CRM was more beneficial than CAM because the students could fabricate their own molds rather than gain access to CNC roller equipment.

Table 2: Table listing current, selective case studies of CRM in architecture prototypes

Year	***Repetitive Process,*** **Component**	**Project Name**	**Designer**
c 2008	*Ram Pressed Ceramic,* Structural Tiles	EcoCeramic Envelope System	Jason Vollen, Center for Architecture Science and Ecology (CASE)
2008	*Thermoformed Plastic,* Bricks	Drape Wall	houminn practice
2010	*Thermoformed Metal,* Panels	Busta Line	Rentsch et al, University of California
2010	*Thermoformed Plastic,* Bricks	OS Wall 2.0	houminn practice
2012	*Bending Plywood*, Scales	Dragon Skin Pavilion	Keskisarja et al
2013	*Electroforming,* Copper	Electroform(alism)	Akoaki

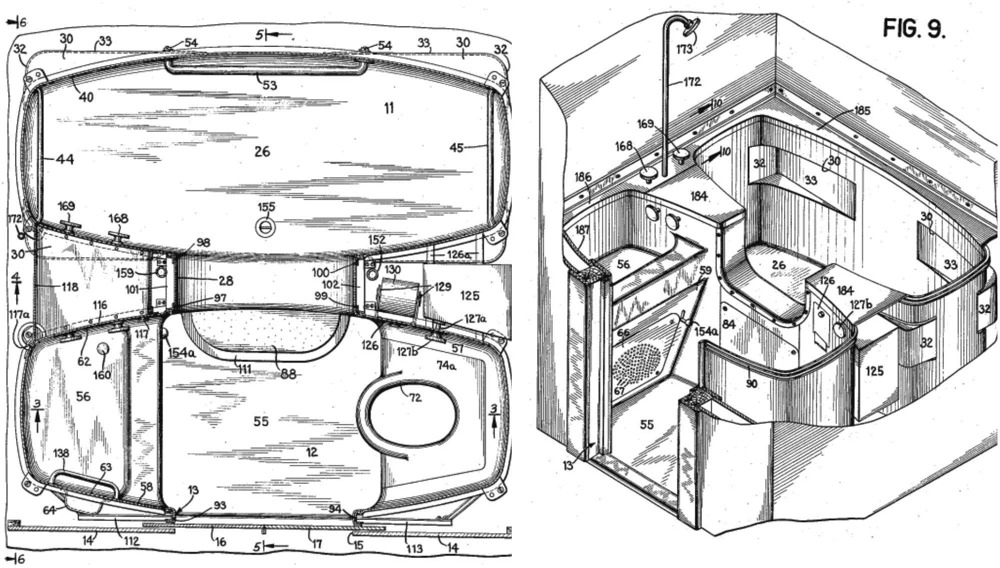

Figure 2: Patent drawings of R. Buckminster Fuller's Prefabricated Bathroom. United States Patent Office. "Prefabricated Bathroom". No. 2,220,482.

For some architecture prototypes, the design team manufactures the CRM architecture components, directly. This was the case for Drape Wall, EcoCeramic Envelope System, and the Dragon Skin Pavilion. By working directly with the manufacturing process to build the architecture prototype, designers had freedom to experiment with the process. For example, the Drape Wall design and fabrication team purchased vacuum-forming equipment to make the prototype. According to an interview with Mark Swackhamer, the team researched the thermoforming industry's manufacturing parameters before experimenting with the process themselves to make the prototype. Although the manufacturing parameters were stated as a given, the team discovered that some parameters could be altered. Their investigations with Drape Wall have led the team in two directions. First, they continued to develop their architectural ideas into subsequent prototypes.[4] Second, lessons learned about vacuum forming plastic have led to research into manufacturing and they have been investigating the possibility of using a dynamic mold for thermoforming plastic.[5]

If architects intend to use CRM for their architecture prototypes, then there are specific issues that they should consider. First, in order to reduce costs, the architects themselves or other, less-skilled laborers often make the architecture prototype. For examples, Emmi Kerskisarja et al made the plywood scales of the Dragon-Skin Pavilion, houminn practice's team manufactured all Drape Wall's thermoformed plastic bricks, and Jason Vollen (with CASE) ram pressed the structural tiles for EcoCeramic. Second, CRM processes that use little or no complicated equipment are most often selected. For example, Drape Wall's plastic bricks and the scales of the Dragon-Skin Pavilion were both made in university fabrication shops. Third, to reduce capital costs, architects may fabricate the CRM tooling themselves. This happened in all of the case studies listed in Table 2. Finally, for prototypes, the architect will want to consider manufacturing processes with low capital costs, and thus will allow the small production runs associated with prototypes. All of the CRM processes listed with the case studies have low capital costs and thus small production runs.

1.3. Architecture products

Architecture products are the most difficult to define and yet are probably the most ubiquitous architect-designed components.[6] Architecture products are architecture components designed by architects and available for mass consumption. Architecture products demonstrate a push model in both design and manufacturing. This is to say that the architecture product is pushed from the manufacturer to the consumer. Before the building has been designed, the architecture product has been designed; before the building construction starts, the product is manufactured. Architecture products offer the greatest breadth of examples, both historical and contemporary and they are the most difficult to substantially catalog. Table 3 represents a selected list of architecture products that are currently available on the market.

Table 3: Table listing current, selective case studies of repetitively manufactured architecture products. For brevity, the table offers only one sample product for each component type.

Component	Project Name	Designer
Door Lever	Valli&Valli Fusital Series	various designers
Faucet	Axor Starck Organic	Phillipe Starck
Bathroom Sink	Agape Nivis washbasin	Shiro Studio
Bathroom Pedestal Vanity	Duravit Starck 1	Phillipe Starck
Lighting	Lightolier Rhythm Collection	Robert A.M. Stern Architects
Doors	Lualdi L16	Lissoni Associati

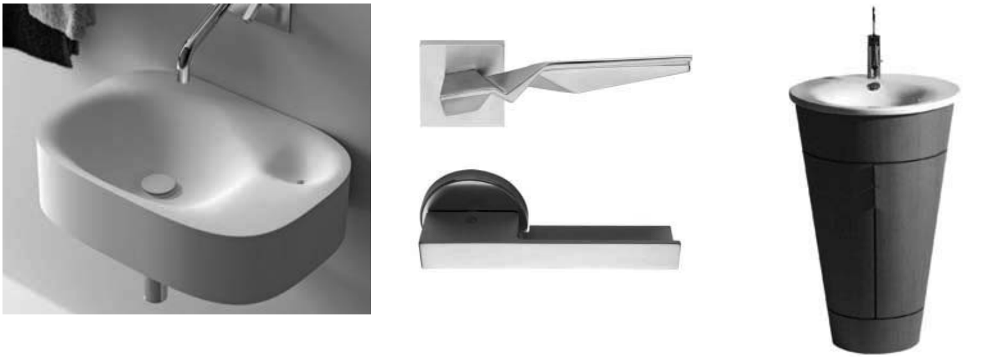

Figure 3: Selected Images of Architecture Products. From left to right: Agape Nivis washbasin by Shiro Studio, Valli&Valli Fusital door levers by Zaha Hadid (top) and Jean Nouvel (bottom), Duravit Starck 1 Pedestal Ceramic by Phillipe Starck.

Unlike custom components or architecture prototypes, which are developed by the architect for a particular application, the architecture product's success depends on the consumer. Customers must desire the product, and therefore companies must promote the products. Companies promote products through advertising and are facilitated by the companies' brand, the quality of the design, or the designer's name recognition. Such is the case with the Valli&Valli Fusital Series door levers, which include designs by Zaha Hadid, Robert A.M. Stern, Frank Gehry, Jean Nouvel, and Richard Meier.

The value of architecture products to the architectural community is perhaps a difficult one to access. On one hand, it is beneficial to the architectural profession to specify building components designed by other architects. Since architects have not been involved with the design of the majority of our building products, architecture products allow architects to promote the value of our profession throughout all aspects of the building. This in turn offers architects more design opportunities beyond that of building designer. On the other hand, since architecture products are available to the public, products may be seen either as a commodification of design or as a perverse extension of a designer's fame (Deamer). For example, the Valli&Valli door levers demonstrate the importance of the designer's fame to the product—as each image of the door lever includes a head shot of the designer.[7]

Architectural products affect the parameters for repetitive manufacturing. First, depending on the anticipated popularity of an architecture product, architecture products could use manufacturing processes with high capital costs that support large production runs. With high production runs, an architecture product may support injection molding instead of thermoforming. This would in turn affect the component's finish, design, detailing, and materials used. Second, unless specifically marketed to have a handcrafted feel, consumers purchasing architect-designed products have high expectations of quality. This may require manufacturing processes that can produce items with high tolerances and quality finishes—such as the smooth, high-gloss finishes are available in lost-wax casting but not sand casting metals. Third, architecture products may be required to be certified by third party agencies, such as the Underwriter's Laboratory (UL) certification for light fixtures and American Society of Testing and Materials (ASTM) certification for hardware. The product's designs must be compliant with the certifying agency.

Finally, architecture products can be fabricated from a variety of single-process manufactured components. That is to say that the product's manufacturer may contract out the sub-components. For example, Phillipe Starck's pedestal vanity for Duravit fixtures are made with molded wood products and an injection-molded ceramic sink. Those subcomponents would be manufactured by different subcontractors and assembled by the final Original Equipment Manufacturer (OEM), Duravit. This means companies, such as Duravit, that contract with architects to design their products inherently separate the architect from the sub-component manufacturers. This means that Starck would have little to no contact with either the wood product molder or the ceramic injection molder. This in turn reduces the possible collaboration of the architect with the subcomponent manufacturer.[8]

CONCLUSION

As the case studies demonstrate, CRM is rooted in both history and contemporary practice. There are many recent and global examples of architects using CRM for the design and production of architecture components. In comparison to CAM, CRM has more variables that an architect should consider for architecture component design and production. These variables include materials, shapes, required production runs, capital costs and finishes. From my collected case studies of CRM in architecture, I have identified three categories of architectural component applications. They are custom components, architecture prototypes, and architecture products.

This paper organizes these case studies into a larger discussion. My future goal for this research is to create a guide CRM for architects. The guide will include an introduction to different repetitive manufacturing processes, parameters for possible customization, and architectural case studies. By presenting this paper as an overview, my goal was to establish commonalities between the case studies within the category. Each of three categories provides particular constraints on the architect for the design and production of an architectural component using CRM. Custom components require the architect to consider production run lengths, creative use of molds to distribute costs, and collaborate with manufacturers. Architecture prototypes often use lower-skilled manufacturing processes, manufacturing processes that are accessible by designers, and allow for greater experimentation by the architect. Architecture products often use manufacturing processes with tight tolerances and high quality finishes, they are certified, and may allow for less collaboration between manufacturer and designer. Understanding the constraints on the designer at the beginning of the design process is important, as they influence the component's design.

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ENDNOTES

[1] Subtractive CNC machines are those machines that take material away in order to produce the unit. Subtractive equipment includes 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.

[2] Additionally, the building was a showcase for architectural uses of aluminum and so the client had a financial interest to offset the added cost of a custom component.

[3] The Cellophane House was designed and fabricated for a Museum of Modern Art exhibit in New York.

[4] Subsequent prototype iterations by houminn practice include Cloak Wall and OSWall.

[5] In a 2010 interview with Mark Swackhamer, we discussed the practice's research into using dynamic molds for thermoforming. According to the practice's website, they recently presented their variable vacuum forming research at ACADIA 2013.

[6] For architecture products, I am including only 3-dimensional architecture products, but not 2-dimensional components such as carpets and fabrics. This keeps the types of components listed in architecture products similar to those listed in the categories of custom components and architecture prototypes.

[7] Headshots of each designer or architect are presented with all of the door levers. For an example of Zaha Hadid's door lever and head shot, visit http://www.vallievalli.com/en/site/vallievallicom/ValliValli-USA/Products11/Fusital/Handles/H356/

[8] The distancing of an architect from the manufacturer may be even worse than this exampled provides. Based on a recent story broadcasted on National Public Radio (NPR) a companies are now licensing their brands to products that they may not manufacturer. This means that Black & Decker may not have made the toaster oven that bears its name. Bobkoff, Dan. "How Much is NPR's Brand Worth? $400 Million". Aired November 1, 2013. www.npr.org/blogs/money/2013/11/01/240285576/how-much-is-nprs-brand-worth-400-million. Accessed November 2, 2013.