CRM in Architecture: Data Collection of Customized Repetitive Manufacturing Case Studies Analyzed

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In architecture, computer-aided manufacturing (CAM) and computer numerical controlled (CNC) equipment has revolutionized the relationship between design and fabrication. Directly, CNC equipment can cut, carve, and shape materials to fabricate architecture components; indirectly, CNC equipment can cut, carve, and shape custom tools (e.g. molds, patterns, and jigs) to manufacture architecture components. With its indirect use, CNC equipment has made it affordable and practical to customize repetitive manufacturing (CRM) on a per-building basis. For many processes and projects, CRM offers a wider range of component materials, with less manufacturing waste, in less time, and for less money than directly manufacturing with CAM.

We have collected over 340 examples of CRM in architecture. Our examples are located around the world and demonstrate a global application of CRM in architecture. Our CRM example data includes project year completed; architect; building location, size, type, and budget; and categorizes the CRM component types, manufacturing processes, materials, production runs, and the number of produced variants. Using the data visualization software Tableau, this paper presents and analyzes our CRM data.

INTRODUCTION

In architecture, computer-aided manufacturing (CAM) has revolutionized the relationship between design and fabrication. Proponents argue that CAM's computer numeric controlled (CNC) machines can make individual and unique architecture components that are not prohibitively expensive.[1] Simultaneously, architects should recognize differences between directly and indirectly using CNC equipment to produce architecture components. Directly, CNC equipment can cut, carve, and shape materials to fabricate architecture components; indirectly, CNC equipment can cut, carve, and shape custom tools (e.g. molds, patterns, and jigs) to manufacture architecture components. An example of indirect CNC use is Snohetta's San Francisco Museum of Modern Art, for which a five-axis CNC mill fabricated the single-use Styrofoam molds for the façade's glass fiber reinforced plastic (GFRP) panels. Instead of fabricating a single-use mold that then is either disposed or recycled, this paper investigates custom components that are manufactured with reusable tools—otherwise known as customized repetitive manufacturing (CRM).

Today, repetitive manufacturers use tools made by CNC equipment. Contact fiberglass molders and plastic thermoformers use CNC-milled, high-density foam to fabricate their tools. 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 rapid prototyping (RP) equipment to create tools. For example, sand-casters can use FDM and SLA printed patterns for small production runs[2] and manufacturing production researchers are investigating the use of metal laser sintering to make molds for injection molding plastic.[3] Architectural examples of this include COOKFOX Architects' 260 Kent (2018) that used three-dimensional printed, carbon-fiber reinforced plastic mold inserts to form its exterior precast concrete panels; and 6a Architects' Paul Smith Store Expansion (2013) that used a CNC-milled, high density foam pattern for its sand-casted iron panels. With its indirect use, CNC equipment has made it affordable and practical to customize repetitive manufacturing (CRM) on a per-building basis, making CRM an option in producing custom architecture components.

There are advantages that CRM has over CNC equipment in the making of custom architecture components. 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 and cannot be replicated with CNC equipment. Second, CRM typically only uses as much materials as the mold, pattern, or jig needs. By reusing tools and reducing raw material requirements, repetitive manufacturing can have little to no production waste. For many manufacturing processes, the process waste can be recycled directly onsite. For example, excess clay from extruding bricks is sent directly back into the extruder to be re-extruded. Third, manufacturing tolerances for most of these processes are high and have the potential to rival the tolerances of CNC equipment. Fourth, because of typically low tool costs, designers can customize the molds, patterns, or jigs, with limited additional costs; and the cost for the tools is amortized over the number of units

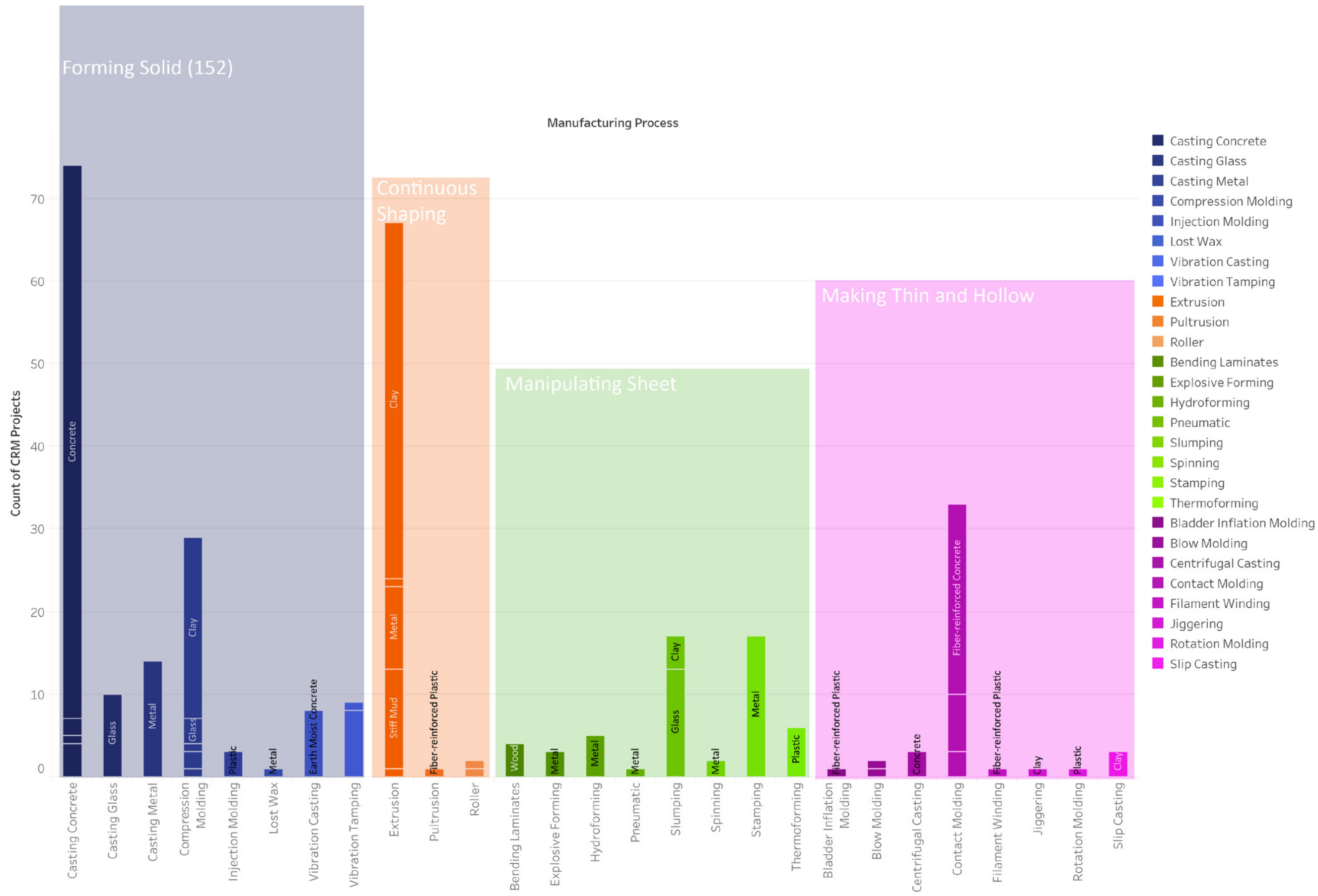

Figure 1. CRM Projects by Manufacturing Processes, including component materials. By Author.

produced. Fifth, CNC equipment can have longer production times and thus higher fabrication costs than CRM. For Foster and Partners' Walbrook Office Building (2010), Gramazio and Kohler's Switzerland Federal Criminal Courthouse (2013), and HOK's Basra Sports Complex (2014), the firms investigated using CNC equipment to fabricate custom building components, but instead chose CRM to meet project deadlines and costs.[4] Finally, soft costs associated with design fees and construction labor may be lower with CRM than CAM. For example, Gehry and Partners have pioneered CAM processes and have streamlined communication between designer and fabricator, but their projects' costs can greatly exceed the industry standard.[5]

Through our research, we have collected 340 examples of CRM in architecture. Most examples have been completed in the past 15 years, with just under half having been completed in the past 5 years. Our examples are located around the world and demonstrate a global application of this approach. See Figure 2. A wide range of architecture practices use CRM for their buildings, including Foster and Partners, REX, LMN Architects, and Frida Escobedo. Some firms, such as Herzog and deMeuron, Neutelings Riedijk Architects, and OMA are 'repeat offenders' and have multiple projects on our list. Our CRM data includes information about the project and components. Using the data visualization software Tableau, we present analysis of our CRM data to better understand how CRM is being used in architecture.

METHOD

In 2013, we started our collection of CRM architecture case studies and in 2017 we moved the collection to Excel and began actively managing their data. Each example has used CRM on a per-project basis, meaning that the custom architecture component was manufactured for a particular project and was not available to the mass market at the time of conceptualization and manufacturing. All included CRM data points enclose space; they do not include art installations, assembly studies of building parts, or architectural product design (e.g. doorknobs, light fixtures). Most of our CRM examples are of permanent structures with only a handful being of temporary pavilions.

Our CRM data has been mined from publicly accessed architecture and design databases (e.g. ArchDaily, Architizer, DesignBoom, etc.), architecture firm websites, manufacturer websites, manufacturing association websites (e.g.

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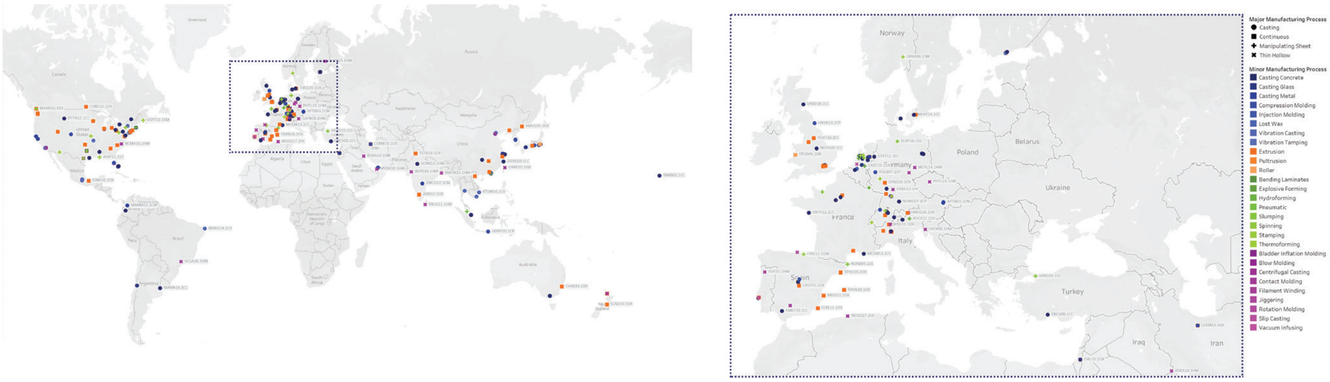

Figure 2. CRM Project Locations with Manufacturing Process. Image by Author.

Precast/ Prestressed Concrete Institute (PCI) and Tiles of Spain Awards) and architecture publications (e.g. *Architect Magazine*, *Architectural Record*, *The Architect's Newspaper*). The data points include building name; year completed; design architect, and architect of record, when appropriate; building location (exact longitude and latitude when possible), size, type, and budget; and categorizes the CRM component types, manufacturing processes, materials, production runs, and the number of produced variants. The mined sources must state that the CRM component was custom for the particular project. The source, either through photographs or written descriptions, must indicate that there are multiples of the custom component or that a tool was used to manufacture the component. Some of the information gathered of a particular data point may have been gathered through contact with the project architect.[6]

We assigned each CRM example a unique identification (ID) code that references the building name, year completed, component number, and manufacturing process. Names and grouping of manufacturing processes are based on the names and organization found in *Manufacturing Architecture: An Architect's Guide to Custom Processes, Materials, and Applications*.[7] For all the CRM examples, we sought confirmation of the manufacturing process. For a few cases, when we were not able to find a record of the component's manufacturing process, we extrapolated by reviewing project detailed photographs and drawings. This educated deduction was noted in the data collection spreadsheet and accounts for only 1.5% (5 out of 340) of the total entries.

Every CRM component gets its own line in Excel and must have a different CRM manufacturing processes, a secondary process for select components, or building component type. For example, Studio Gang's Nature Boardwalk Pavilion (2010) has curved wood laminates for its building structure and contact-molded fiberglass shells for weather protection. This project has two entries, one for each component.[8] Another example is Hariri Pontarini Architects' Bahá'í Temple of South America (2016); the building has nine sails that form its massing and the sails' skin is made from panels of kiln-cast glass. After all the panels were cast, a small percentage of them were shipped to another manufacturer for slumping. For the Bahá'í Temple, the components with the secondary slumping process were assigned their own line. A final example is Elenberg Fraser's 33 Mackenzie (2013), which gets two entries, one for a screen and one for the building envelope. The building has a feather-like motif for all of the custom precast concrete panels; however, some of the panels are open and form a screen for the building's parking deck while other panels are closed and form the exterior envelope for the building's apartment tower. At the same time, the parking deck screen has two variations, and the apartment tower envelope has several variations, depending on the panel length. The variations were not included as separate entries.

For data visualization, we used the sofware Tableau. This software live links to the Excel spreadsheet and created the paper's figures. Any *null* entries, or when a field was left blank, were excluded from the visualization. Tableau has calculation functions that are like Excel; we used Tableau's function COUNT to count the number of entries per field. Our Excel spreadsheet has drop down menus for some fields (e.g. manufacturing process, building type, component material, etc.) to ensure a common word choice. Tableau does have capability to identify longitude and latitude coordinates, based on address; however, we gathered longitude and latitude coordinates through Google Maps. This allowed us to verify the project's location with Google street view, which was particularly important in countries such as South Korea and China, because the English spelling of street names can be inconsistent. In 4.4% of the data points (15 of 340), we could not find the project's specific location and associated the data point with the nearest city.[9]

ANALYSIS

Our visual analysis of the CRM data includes five visualizations: 1) CRM Manufacturing Processes and Materials 2) Map of CRM Projects 3) Timeline of Completed CRM Projects 4)

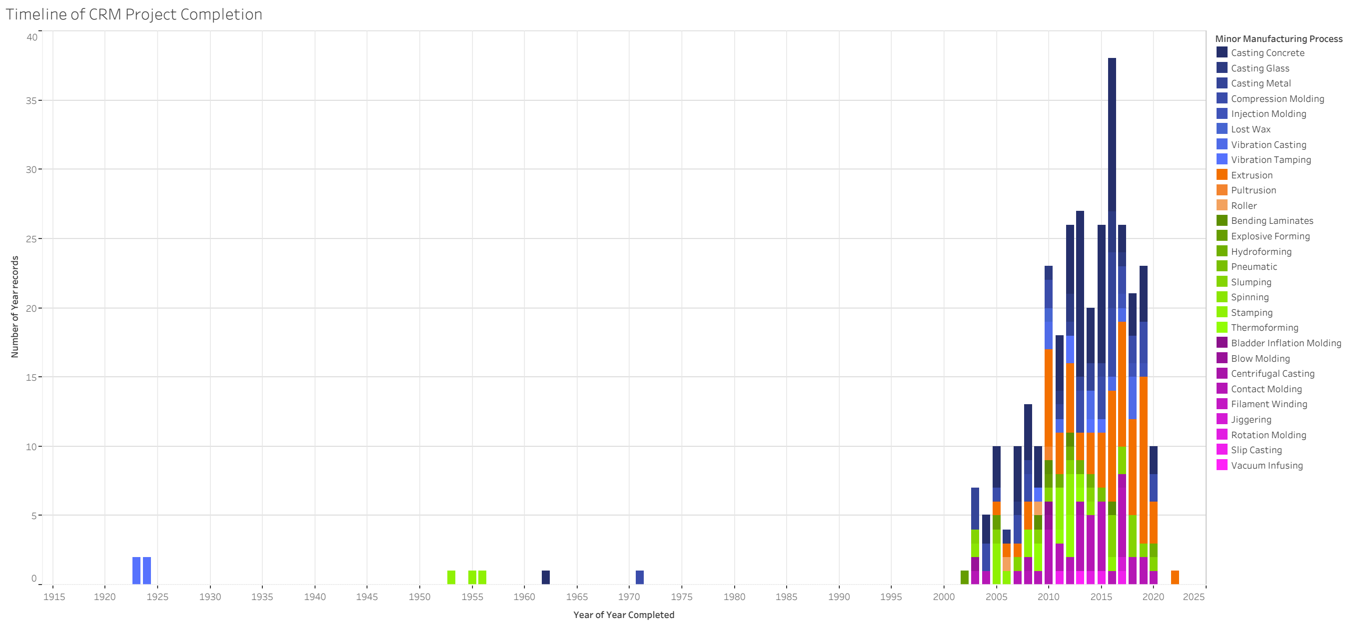

Figure 3. Timeline of CRM Completed Projects with Manufacturing Processes. Image by Author.

Architecture Firm Names with CRM Projects Completed and 5) CRM Projects by Building Type. We focused our analysis on visualizations that represent almost all the CRM data points with at least 95% of the data points included in each visualization. Due to low representation, we excluded noted metrics, such as building costs per square foot that could only be calculated for 7.5% (25 of 340) of the data points.[10]

When prudent, we created our visualizations to include multiple layers of understanding. For example, our Map of CRM Projects includes a key of which manufacturing processes were used, and our Architecture Firm Names include project ID codes and manufacturing process.

1 | CRM Manufacturing Processes with Materials

Figure 1 represents 96.9% (326 of 340) of the data points. In descending order, 148 of the CRM process categories are Forming Solid, 70 are Continuous Shaping, 54 are Manipulating Sheet, and 44 are Making Thin or Hollow. In Forming Solid, 74 of those components are made from casting concrete. Casting concrete typically uses a standard concrete mix of water, cement, large and small aggregate, and admixtures that is placed as a wet mixture into a mold. Seven of the included projects use non-standard concrete mixtures, such as wet-cast fiber-reinforced mixtures or the making of composite panels, which use brick as a facing material. In Forming Solid, second most prevalent process is pressing (29), sometimes known as compression molding.[11] In pressing, the manufacturing media is placed into a mold and the mold is compressed until the media fills all the mold. For architectural applications, most pressing is done with clay or stiff mud, and can be done by mechanical press or by hand.

Given the value of architectural precast concrete as an exterior building facing material and that architectural precast concrete manufacturers are equipped to produce custom architectural components, it is not a surprise that casting concrete dominates Forming Solid. We did not anticipate the relative frequency of other processes and materials such as casting metal (14); casting glass (10); vibration tamping (9), used to make cast stone; and vibration press-casting (8) used to make concrete masonry units (CMU)

Continuous Shaping are processes that produce a continuous cross section along the length of the manufactured component. In Continuous Shaping, extrusion represents 95.7% (67 out of 70) of the manufacturing processes and extruding clay represents 64.2% (43 of 67) of the extruded examples. Stiff mud (12) and metal (10) are a distant second and third, respectively.[12] We have gathered only 1 example of pultrusion, a manufacturing process for fiber reinforced materials, and 2 examples of rolling, in which a material is passed under a continuous roller that imprints onto the material surface.

Manipulating Sheet is when a preformed, flat sheet material is deformed into its final shape. This category most often uses metal sheets, but can include wood laminates or veneers, sheets of glass or plastic, or clay slabs. Slumping (14) and Stamping (14) each account for 31.5% of Manipulating Sheet. Slumping is when gravity slowly deforms a material over a mold and for architectural applications, it is done with glass sheets heated in a kiln or clay slabs draped over molds. Metal stamping is when a metal sheet is placed between two matched dies. The dies then strike each other, often repeatedly, deforming the metal between the dies. In metal stamping, dies are made from harden tool steel, are expensive to produce, and require

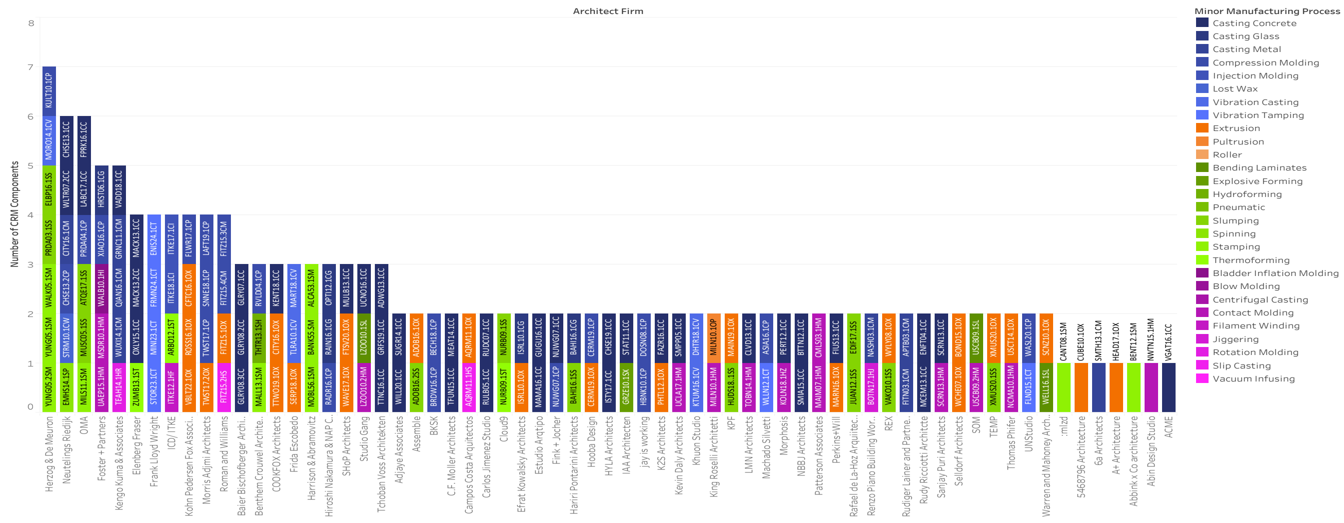

Figure 4. CRM Projects Completed by Architecture Firms with Manufacturing Process and ID. Image by Author.

large manufacturing equipment; generally, metal stamping requires large production runs to offset its high manufacturing costs. The other notable processes in this category are hydroforming metal (5) and thermoforming plastic (5); both have lower capital costs, longer cycle times, and are appropriate for smaller production compared to stamping.

Making Thin or Hollow is reserved for those manufacturing processes that make component shapes with relatively thin cross-sections. Contact molding accounts for 72.7% (32 of 44) of the manufacturing processes in this category. In contact molding, a thin media is applied onto an open mold, it cures, and then is demolded. For architectural applications, fiber reinforced concrete (FRC) accounts for 71.9% (23 of 32), fiber reinforced plastic (FRP) represents 18.8% (6 of 32), and fiber-reinforced gypsum plaster (FRG) represents 9.4% (3 of 32) of all contact molded materials. Other notable processes in Making Thin or Hollow include slip casting (3) and centrifugal casting (3), with all other manufacturing processes and materials in this category having only one example.

2 | Map of CRM Projects

Figure 2 maps 100% of all the identified CRM projects, with their building locations, manufacturing category, and manufacturing process for each component. Our collected CRM projects are located around the world, and are in North and South Americas, Europe, Asia, Australia, and Africa.[13] Most of the collected projects are located in the United States; Europe, including the United Kingdom, central Europe from The Netherlands through Germany to Northern Italy, and the Iberian Peninsula; and Southern Asia, including India, China, South Korea, and Japan. Overall, Europe has the highest density of CRM projects. There we find primarily extruded clay and cast concrete manufacturing processes, which may be due to the overall dominance of these CRM processes. In addition, we find a high concentration of manufacturing processes that manipulate sheet good (21) (e.g. stamping, hydroforming, explosive forming, or slumping) and contact molding (9). These processes use materials such as sheet metal, glass, FRP, FRC, or FRG, all of which are generally thin, light, and can be nested for ease of transport. The highest urban density of CRM projects is New York (34), London (9), Seoul (7), Los Angeles (6), Beijing (6), and Amsterdam (6).

3 | Timeline of CRM Project Completions

Figure 3 is a timeline of CRM project completions with 97.6% (332 of 340) of our CRM projects represented. Our CRM projects from 1923 to 2002 is limited and 95.9% (326 of 340) of our CRM projects have been completed since 2003. We anticipate that there are more projects completed prior to 2002 than our list indicates; however, the rise in 2003 is compelling as CAM manufacturing was a viable choice for component manufacturing and yet, CRM was selected. The increase since 2003, can also be contributed to CNC technology as CNC equipment lowers tool fabrication costs in CRM. Since 2003, the count of CRM projects rises, currently reaching a recording peak in 2016. We continue to add projects to the database as CRM projects are identified and we predict that 2016 will not remain as the peak year.

Since 2003, Making Solid, specifically casting concrete, dominates the CRM processes; however, we note that the timeline indicates a shift of CRM processes. Manipulating Sheet is introduced in 2002 with Asymptote Architecture's HydraPier Pavilion, peaked in 2012, and significantly dropped to fall in 2017. Within Manipulating Sheet, the CRM processes transition from stamping, explosive forming, and hydroforming metal toward slumping glass. There are a few early examples of extrusion, but the manufacturing process dominates CRM processes starting in 2009 and has remained consistently high to date. Making Thin and Hollow appears in the timeline in 2003 and becomes prevalent from 2009-2017, with contact molding as the primary manufacturing process of this category.

4 | CRM Firm Counts

99.7% (339 of 340) of the CRM data points are associated with an architecture firm name. A wide range of architecture practices use CRM for their buildings. This includes high profile firms such as Foster and Partners, Kohn Pedersen Fox Associates, and Machado Silvetti; local and experimental practices such as LMN Architects, 5468796 architecture, and Assemble; and university led design-build projects such as University of Arizona and University of Stuttgart. 74.6% (170 of 228) of firms have only one CRM component on our list, with 26.4% (58 of 228) of firms having two or more CRM components.

It is compelling when internationally recognized, architecture practices—such as Herzog and deMeuron, Neutelings Riedijk Architects, OMA, Kenga Kuma, and Morphosis—that are well known for CAM processes, appear with multiple CRM projects on our list. Simultaneously, our list includes small, award-winning, local practices with multiple CRM projects. These include Elenberg Fraser in Australia, Frida Escobedo in Mexico, Hiroshi Nakamura in Japan, and Kevin Daly Architects in California. These firms used more than one CRM processes for more than one architectural project. For example, Frida Escobedo's office used vibration press-casting to manufacture custom CMUs for La Tallera Siqueiros Museum (2010) and extruded concrete for their 2018 Serpentine Gallery Pavilion.

5 | CRM by Building Type

We assigned a building type to 100% (340 of 340) of the data points, based on the building's original program. We hypothesized that most of the CRM projects would be sizable, institutional projects, typically associated with large budgets; instead, we note that the highest count of CRM projects is single family residential (46) followed by commercial (43) space. We are surprised that Museums (40) are ranked third, followed by mixed-use (30) and multifamily (29). With institutional projects accounting for only one of the top five building types, it demonstrates that CRM components are appropriate for small projects and do not require institutional budgets or support to be realized.

CONCLUSION

CRM balances an architect's desire for custom building components, with the economics associated with repetitive manufacturing. With our gathered list of 340 CRM components in architecture, we used data visualization software Tableau to present five figures of CRM analysis: 1) CRM Manufacturing Processes and Materials, 2) CRM Project Location Map, 3) CRM Project Timeline with Manufacturing Processes, 4) CRM Project Count by Architecture Firm, and 5) CRM by Building Type. Some of the visualizations confirmed what we suspected of CRM, while others surprised us. First, we anticipated that casting concrete would be the most dominant manufacturing process, as the precast concrete industry works closely with architects to produce architectural precast concrete; however, other CRM processes such as extruding clay, stiff mud, and metal; compression molding; stamping metal; slumping glass and clay; and contact molding appeared frequently. Next, we knew that CRM projects were worldwide, but we found a high concentration of CRM projects in the United States, Europe, and South Asia. Third, our timeline indicates that CRM projects have rapidly increased since 2003. While Forming Solid appears consistent for CRM processes, we see a shift from Manipulating Sheets to extrusion. Fourth, we have noted several high-profile firms on our list, with about a quarter of firms being repeat offenders.[14] Finally, we noted that CRM is not limited to institutional projects, and most often can be found in residential, commercial, mixed-use, and multifamily projects.

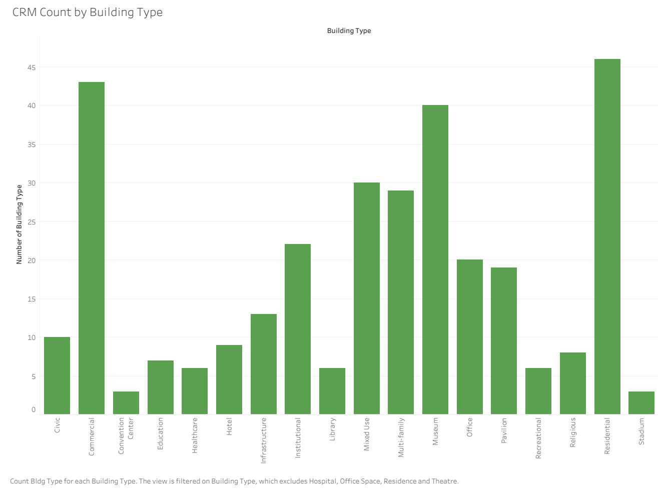

Figure 5. CRM Projects by Building Type. Image by Author.

We acknowledge that our data list of CRM examples does not contain every occurrence of CRM in architecture. We continue to update the list as new data points are added and are always seeking additional projects. We recognize that since our list is updated constantly, the analysis presented in this paper is not static. It does, however, correctly represent our analysis of our research to date and begins to give us an understanding of CRM and its role in producing custom building components. The future goal of this research is to survey additional information from the architecture firms, beyond what is publicly available, to better understand CRM in architecture.

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. Combrink, J. et al. "Limited Run Production Using Alumide Tooling for the Plastic Injection Moulding Processes" *South African Journal of Industrial Engineering*. Online.
4. Gulling, Dana K. *Manufacturing Architecture: An Architect's Guide to Custom Processes, Materials, and Applications* (London: Laurence King Publishing, 2018). Print. Minutillo, Josephine "Sculptural Skings: Digital Fabrication Comes into its Own for Creating Precisely Crafted, Complex Building Envelopes, Even on Large Projects" *Architectural Record*. September 2014. Print
5. According to Wired Magazine, Gehry and Partners' 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. Scanlon, Jessie, "Frank Gehry for the Rest of Us", Wired Magazine (November 2004), http://www.wired.com/wired/archive/12.11/gehry.html.
6. Some of the information about a data point was gathered through my research for *Manufacturing Architecture*.
7. *Manufacturing Architecture* has grouped categorized similar manufacturing processes together. These include 1) Manipulating Sheet with slumping, thermoforming, explosive forming, bending plies, stamping, hydroforming, and spinning; 2) Continuous Shaping with extrusion, pultrusion, and rolling; 3) Making Thin or Hollow with contact molding, bladder inflation molding, filament winding, centrifugal casting, and blow molding; and 4) Forming Solid with casting concrete, metal, and glass, vibration-press casting, vibration-tamping, and pressing or compression molding.
8. Note that the wood laminated components get only one entry, even though the wood laminated structures uses two different molds in their two-step manufacturing process, because all of the wood laminated pieces go through both manufacturing steps.
9. Any non-specific locations are noted in the Excel spreadsheet but not in the Tableau map
10. The term 'project costs' is inclusive of many things and is inconsistently defined. For some projects, 'constructure costs' would be listed, whereas for others 'project costs' would be listed. Without confirmation, we would have to assume that project costs would include design and management fees (i.e. soft costs) and construction costs (i.e. hard costs), but it may or may not include land costs. In addition, project costs vary over time (2002-2020) and are not always tied to inflation. Finally, many of the projects are international and variable exchange rates further manipulate the data.
11. Typically, the manufacturing industry using the term 'compression molding' to only refer to a type of plastic manufacturing; whereas clay and glass are pressed to fill their molds.
12. Clay and stiff mud are similar as they are both earthen products, they only vary in water content. Clay has more water than stiff mud, and can be formed with much less force, on smaller equipment. Extruded clay will be used for rainscreen components, whereas extruded stiff mud is to make brick. Through my research, manufacturers that work with clay (e.g. Boston Valley Terra Cotta and NBK Terracotta) are not the same as the brick manufacturers that work with stiff mud (e.g. General Shale, Lee Brick, etc.)
13. We believe it likely that there are more CRM examples in Africa, but due to our collection sources we acknowledge that this continent is underrepresented.
14. We hypothesize that the percentage of repeat offenders will continue to increase as we add additional projects to our list and will track this in future analysis.