Making Visible: Creating an Architect's Guide to Customized Repetitive Manufacturing

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ABSTRACT: With the use of computer numerical controlled (CNC) equipment, architects and manufacturers have been working together to customize the molds, jigs, or patterns used in repetitive manufacturing for specific project design's building components. I am proposing the term 'customized repetitive manufacturing', or CRM, to reference this type of work. CRM is a necessary alternative to mass customization for the manufacturing of architectural components. CRM includes those repetitive manufacturing processes with relatively low capital costs and that can support low- to mid-volume production runs of repeatable objects. CRM allows for customization from the designer, while balancing the need for repetition in order to remain cost effective. This balance makes CRM easily applicable for the custom design of architectural components.

This paper will make visible architects and building designers that have used CRM for their building designs. Through my research, I have selected twelve recently completed case studies; each of the case studies customized a different repetitive manufacturing process. Unfortunately, through my research I have found a lack of resources that are available to educate architects about customizable repetitive manufacturing processes. This paper will demonstrate that there is a need for a resource that illustrates the possibilities of customized repetitive manufacturing to architectural design.

KEYWORDS: architecture, building components, customization, repetitive manufacturing

INTRODUCTION

In recent years, mass customization and computer-aided manufacturing (CAM) technologies have transformed design and off-site building component fabrication. Simultaneously, traditional repetitive manufacturing still dominates the majority of the production for architectural components. The benefits of repetitive manufacturing are that it produces objects quicker and often at a lower cost than CAM. At the same time, CAM's computer numerical controlled (CNC) machines have also made the fabrication of molds for repetitive manufacturing easier. CNC milling machines, electrical discharge machining (EDM), and hot-wire foam cutters are used to create molds for repetitive manufacturing. With the use of CNC equipment, architects and manufacturers have been working together to customize the molds, jigs, or patterns used in repetitive manufacturing for building components used in a specific project's design. I am proposing the term 'customized repetitive manufacturing', or CRM, to reference this type of work.

CRM is a necessary alternative to mass customization for the manufacturing of architectural components. Since CRM is defined by a customized and yet repetitive manufacturing process, the manufacturing processes included in CRM must make repeated use of the mold, patter, or jig in the production of the component. In other words, components must be designed to be used in multiples. At the same time the production runs of CRM are relatively small, as they may only be used to create components of a particular building's design. CRM includes those repetitive manufacturing processes with relatively low capital costs and that can support low- to mid- volume production runs of repeatable objects. CRM allows for customization from the designer, while balancing the need for repetition in order to remain cost effective. This balance makes CRM easily applicable for the custom design of architectural components. Through my research, I have selected twelve recently completed case studies, with each of the case studies having customized a different repetitive manufacturing process. The case studies are located around the world and demonstrate a global application of this approach. To demonstrate the relevance of CRM to today's architectural practice, I have limited the case studies to buildings that have been completed in the past 15 years. The wide range of case studies demonstrates that architects are interested in customizable repetitive manufacturing for building design.

This paper will make visible architects and building designers that have used CRM for their building designs. Unfortunately, through my research I have found a lack of resources that are available to educate architects about customizable repetitive manufacturing processes. This paper will demonstrate that there is a need for a resource that illustrates the possibilities of customized repetitive manufacturing. This paper will make visible existing case studies of this work, establish parameters for these processes, and show sample architectural applications. The long-range goal of this project is to demonstrate to designers and architects that there are numerous repetitive manufacturing processes available for customization.

1.0 CUSTOMIZED REPETITIVE MANUFACTURING

1.1. Overview

Manufacturing is "to make from raw materials by hand or by machinery… especially when carried on systematically with division of labor" (*Webster's Dictionary* 1988). Repetitive manufacturing is the "continuous production of similar products on relatively fixed production lines" (Steiner 1981, 35). Repetitive manufacturing reuses its jigs, molds, and patterns to create similar products. Although repetitive manufacturing often uses computers to run the machinery, it is distinct from CAM. In CAM, CNC equipment uses a computer controlled tooling to shape directly the manufactured item. Once programmed into the computer, alternative shapes do not necessary slow down a CNC machine or alter its operation. For CRM, I am excluding those manufacturing processes that use CNC equipment to manufacturer repetitive objects.

The production runs for repetitive manufacturing is varied and it can range from prototypes and small batch productions to over high volume productions that produce over 1 million units. The production run length is dependent on the process, the material, the labor, and most often the cost of the mold. 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.

Customized repetitive manufacturing balances the value of repetitive manufacturing with the ability of the designer to customize a repeated building component. Customized repetitive manufacturing can make best use of those processes that require low-to-mid volume production runs. Since architects are most likely to use customized repetitive manufacturing on a building-by-building basis, I focused on those repetitive processes that have production runs under 10,000 units. 10,000 units may seem high, but if we consider exterior facing materials such as brick, terra cotta tiles, or metal panels, 10,000 units is easily achieved. For one of the included case studies, Hierve Diseneria used 7,723 CRM wood-molded, blown glass spheres on the Hesiodo, a 27,000 square foot apartment building in Mexico City.

Customized repetitive manufacturing has a number of valuable benefits. First, this process reuses its jigs, molds, or patterns during production. Depending upon the mold, the process, and the medium a mold can produce up to 500,000 units. Secondly, repetitive manufacturing typically only use as much materials as the mold, pattern, or jig needs. By reusing tools and reducing raw material requirements, customized 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. Fourth, because each unit uses the same design, the soft cost most likely will be lower than CAM (Pillar 2004). Next, because of typically low capital costs, designers can customize the molds, patterns, or jigs, with limited additional costs. Finally, there is a range of materials and processes that are available in repetitive manufacturing for customizing.

1.2. CAM and CRM

The use of CNC equipment has made it much easier to fabricate molds for customized repetitive manufacturing. Machines such as electronic discharge machines (EDM), water-jet cutters, and CNC routers allow for a faster and therefore less-costly way of manufacturing molds. This causes a tension between CAM and CRM. CRM is dependent on the technology of CAM in order to bring mold costs down, while at the same time it is an alternative to CAM. CRM relies on the balance between a particular production run that will distribute the molds' costs over a particular number of units while at the same time keeping the costs of the molds down so that each mold can be customized to a particular project. Because of the tension caused between CAM and CRM, this paper will use as its case studies only those projects that have been completed in the past 15 years. This ensures that the designers had the option of choosing CAM for their building component fabrication needs, but still choose CRM as the alternative.

1.3. Outcomes

There are a number of historic examples of the use of customized repetitive manufacturing. Examples include Frank Lloyd Wright's textile concrete blocks (c. 1923), R. Buckminster Fuller's thermoformed metal or plastic prefabricated bathroom for the Dymaxion House (1940)[1], Harrison & Abramovitz's stamped metal aluminium panels for the Alcoa Building (1951), or Gio Ponti's pressed glass tiles for the Denver Art Museum (1971). At the time these projects were completed, the molds most likely would have been fabricated by hand and would have been very costly to produce. A large production run would have been necessary to offset the mold's costs. In search for high production runs to offset mold costs, Wright and Fuller designed their architectural component with the possibility for mass-production. Similarly, DAM uses a large number of the custom tiles on both on its interior and exterior walls and the Alcoa Building is a high-rise; therefore both buildings are making use of a high-volume of produced units.

2.0 CASE STUDIES_12

This is a selected list of case studies of architects and building designers who have used CRM in their buildings. The selected case studies are of components that are neither intended for mass production nor available for mass consumption. There are of course numerous examples of architects who have gone into product design (e.g. Michael Graves) and of architects that have designed building products (e.g. Zaha Hadid's lever doorknobs and Robert A.M. Stern's light fixtures) for mass consumption. Both mass production and conception requires that the designs be speculative; they are for products that are either available for retail and are intended to be placed in buildings not yet designed. All of these case studies are examples in which the architect customized a component for a specific architectural design. The architects and building designers have customized the building components for a particular project.

The case studies are organized in reverse chronological order with the most recent examples first and the oldest examples last. Each case study was selected to represent one particular repetitive manufacturing process. There are many more examples of CRM in architecture, but I focused on the best examples of an architectural application of a particular repetitive manufacturing process.

2.1. Villa Nurbs

by Cloud9 (under construction) Empuriabrava, Spain

This house used humped ceramic tile to form the South wall's exterior rainscreen. The manufacturer, Ceramica Cumella (located just outside of Barcelona, Spain) worked with Cloud 9 to manufacture the clay tile. Over 325 tiles and 8 different tile shapes were manufactured. The manufacturing process included extruding the clay into a slab, using a template to hand cut the clay slab, laying the cut clay onto a CNC-milled polystyrene mold, and pressing the clay onto the mold. A mixture of the clay's weight and handwork shaped the clay into the 2-directional curve of the mold—in a process called humping.

2.2. 290 Mulberry Street

by SHoP ARCHITECTS (2010) New York, NY

Figure 1: Photograph of 290 Mulberry Street under construction. flickr (Creative Commons): (joevare 2008)

This apartment building has a precast concrete and brick veneer composite panel on its exterior façade. The master for the panels was fabricated using a CNC router and then a rubber mold was made from the master. Brick were hand laid onto the rubber mold and concrete poured directly onto the back of the brick surfaces. The concrete filled the spaces between the brick to give the appearance of mortar joints. A large mold was created and was subdivided with dams to create smaller composite panels as per the design. The mold was used repeatedly throughout the manufacturing of the panels.

2.3. North Carolina Museum of Art
by Thomas Phifer and Partners (2010) Raleigh, NC

Figure 2: Photograph of the NCMA ceiling coffers. flickr (Creative Commons): (Chirag D. Shah 2008)

The NCMA's West gallery building has custom designed ceiling coffers. The oculus at the center of the coffer has a diffuser and skylight at the top. The coffer distributes the natural light emitted from the oculus throughout the gallery. The coffers are manufactured using traditional, contact molded, fiber-reinforced plastic (FRP). Because the coffers are FRP, they are lightweight and weigh just over 400 pounds each. The coffers are demountable, which allows building maintenance to access the diffusers and building systems when necessary.

2.4. Walbrook
by Foster and Partners (2010) London, England

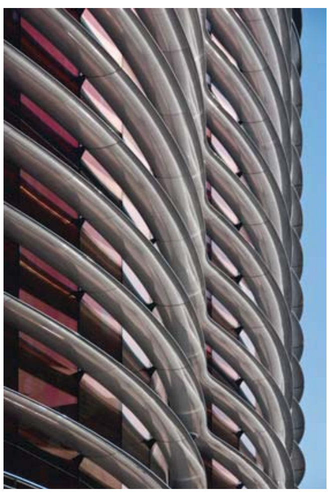

Figure 3: Photograph of the Walbrook's exterior fiberglass louvers. flickr (Creative Commons): (Myxi 2009)

Foster and Partners designed custom exterior, free-spanning louvers for this office building in Walbrook. The louvers are hollow and were manufactured by inflating the interior of a fiberglass and resin layup against a hollow mold. The louvers are lightweight, stiff, and weather well. The louvers' shape is a complex curve, curving in both cross section and in plan. According to *Detail*, serial production was the most cost efficient way to make the louvers. The mold was designed to create repetitive cross section and plan curvatures, while allowing for varied lengths (Gabler 2008).

2.5. 3.1 Phillip Lim
by Leong Leong Architecture (2009) Cheongdam-Dong, Seoul, South Korea

The architect designed fiberglass-molded, precast concrete tiles as the building's rainscreen. The tiles are double convex curves, creating a pillowed effect for each tile. This gives a quilt-like feeling to the façade. There are seven square tiles with seven different values of convexity, ranging from pillowed to flat in profile.

An eighth L-shaped, pillowed tile was used to allow for windows. Fiberglass molds are inexpensive to make and can produce more units than Styrofoam or rubber molds. The fiberglass mold gives the precast concrete a smooth and slightly glossy finish.

2.6. Argos Cement Electrical Generator Building
by MGP Arquitectura y Urbanismo (2008) Yumbo Valle, Colombia

This project uses steel-molded, precast concrete panels to create an exterior screen for the electrical generator building of this cement factory. The building uses low-density concrete for the screen. MGP designed two different panels for the screen. By reducing the variety of different panels, the cost per panel is reduced, as not a many molds are needed.

2.7. Spanish Expo-Pavilion
by Francisco Mangado (2008) Zaragoza, Spain

Figure 4: Photograph of Spanish Expo-Pavilion. Wikipedia Commons: (Sergio 2008)

Mangado designed a custom, half-round, extruded clay tile that clad the pavilion's round steel columns. The project uses 28,000 terracotta pieces to clad the 750 columns. Metal angles that were attached in the factory to the columns support the terracotta pieces. Two manufacturers worked together with Mangado to design and manufacture the pieces.[2] The manufacturers extruded the ceramic pieces with a temporary support structure that would be broken away prior to firing.

2.8. Castellum Theater
by Kraaijvanger Urbis (2005) Alphen, Holland

The Castellum Theater is clad in customized corrugated aluminum panels. The corrugations are small and form a wave-like pattern, referencing the nearby river. The panels are manufactured using explosive forming. Explosive forming uses the force of an explosive charge in a medium (often water) to form a metal sheet against a mold. This process has relatively low capital costs and is good for small to mid-volume production runs. It has very high tolerances and can produce large curved panels (similar to car hoods) or small details such as those on the Castellum Theater.

2.9. World Exposition, Spanish Pavilion
by Foreign Office Architects (2005) Aichi, Japan

Figure 5: Photograph of Spanish Pavilion at the 2005 World Exposition. flickr (Creative Commons): (Keemz 2005)

This pavilion uses custom pressed clay to form the screen tiles of the Spanish Pavilion. The tiles are an irregular hexagon shape. There are six different hexagons and each hexagon either is formed solid or with an opening. Each hexagon is formed with a separate front and back pieces that conceal and are supported by interior metal supports. This process has relatively low capital costs and is good for small to mid-sized production runs. Ceramica Cumella (Barcelona, Spain) was the manufacturer for the tiles.

2.10. Hesiodo
by Hierve Diseneria (2003) in Mexico City, Mexico

This apartment building uses wood-molded, blown glass spheres as a screen between the city and the exterior apartment corridors. There are 7,723 spheres on the building. The spheres were hand-blown inside of a wood mold so that the spheres would be consistent in size and shape. Craftsmen in a Guadalajara workshop manufactured them.

2.11. Prada Store
by Herzog & de Meuron (2003) in Tokyo, Japan

A portion of the windows in the exterior glazed curtain wall of the Prada store was manufactured as a complex curve. To achieve the double curve, flat float glass was slumped against a custom mold (Schittich 2006). To slumped glass, a manufacturer slowly heats a flat glass sheet. The sheet will begin to sag and deform from its own weight. Using a mold for this process precisely controls the curvature of the glass. Reheating the glass to create the curvature also achieved a partial pre-tension on the glass (Shittich 2006) and thus increased its strength compared to annealed glass.

2.12. Nasher Sculpture Center
Renzo Piano Building Workshop (2003) Dallas, TX

Figure 6: Photograph of the Nasher's custom sunshade devices. Photo taken from building interior. Spanish Expo-Pavilion. flickr (Creative Commons): (Diorama Sky 2008)

This project uses custom designed sunscreen to control natural light into the building. The monitors are shaped to eliminate direct light and to maximize the amount of indirect light. The monitors' shapes are specific to this building in this location with this shape of roof (patent pending)[3]. The sunscreen is made of cast aluminium and is manufactured in 4 feet by 4 feet units. 912 units cover the building's roof and each unit weighs 150 lbs. La Societa Sider s.r.l. (Bologna, Italy) manufactured the units.

3.0. AVAILABLE LITERATURE
There are a number of books that focus on repetitive manufacturing, and they tend to fall within two categories—technical or designer oriented. The technical oriented books may be directed towards either industrial or manufacturing engineers and engineering students. These books are often production-oriented, giving information about the production speeds, material flows, mold design, etc. They are specific for an engineer to manufacture a particular product. Often these texts are not accessible enough to a designer; information is often buried in text and there often are a number of calculations for production speeds, mold pressures, and material flows. The texts do not highlight the critical information in which a designer is interested—such as typical size restrictions, tolerances, draw angles, typical production runs, finishes, typical materials, and sample products manufactured by a particular process.

The alternate category of books is those that are designer-oriented. The design-oriented books tend to use visuals and graphics to describe the process. They include images of products that already manufactured with a particular process and they often include images of the manufacturing processes. The goal of these books is to give the designer an overview to the processes and to provide some design guidelines for each process. They most often are intended to engage the industrial designer or other visual disciplines (Lesko 2008). These texts are often enough to give a designer an overview to a particular process, but because of the lack of technical information they necessitate the designer to work closely with a manufacturer to actually develop a product for manufacturing.

For both of these groups of texts, I have only selected those texts that I have found the most useful in my teaching and research in CRM. The selected books focus on the limitations of the process and provide information that would be critical to any designer. Most of the books include the processes that may work for a prototype or small batch production, or they may be good for high volume productions (up to 1 million or more units). Most sources include CAM manufacturing as well as repetitive manufacturing. Most of these books are geared to product or industrial designers. They do not highlight some of the issues that an architect may be interested, such as maximum size of products produced or typical production run sizes. The books explore materials that are typical to product design, but may not include materials typical to architecture. For example in architecture, the manufacturing process of extrusion typically includes plastic, metal, and clay; however most of the texts found primarily focus on plastics. The books also do not cover some of the manufacturing processes (e.g. precast concrete with a rubber mold) that may only be applicable to architecture.

The list of books is organized alphabetically by author.

3.1. Allen, Edward. *Fundamentals of Building Construction: Materials and Methods*. 2009. John Wiley & Sons: Hoboken, NJ.

Although this book primarily focuses on standard manufactured architectural materials (e.g. brick, concrete, dimensional wood, steel, etc.) and construction methods, there is an introduction into the manufacturing processes of clay and precast concrete. This is one of the few identified sources that includes the manufacturing process for architectural materials (e.g. concrete and clay). Unfortunately, Allen is limited in his description. He describes the manufacturing process for structural precast on steel casting beds, but does not include information about architectural precast concrete cast on coated MDF, fiberglass, or rubber molds. In addition, Allen illustrates brick manufacturing and discusses some of the custom shapes that brick can take, but does not describe the design parameters for a designer to engage with extruding clay.

3.2. Guidot, Raymond. *Industrial Design Techniques and Materials*. 2006. Editions Flammarion: Paris.

Guidot's book offers a strong historic and current perspective on industrial design techniques and materials. The book is organized by manufacturing materials. Guidot offers a brief introduction and history to the material and introduces the reader to the manufacturing and fabrication processes available for that material. The processes are described verbally with about half of the processes illustrated with either diagrams, photographs, or a mixture of the two. The book does a thorough job of describing ceramic, glass, and metal manufacturing—all of which are applicable to architecture. Guidot organized the book as if it is to be read from cover to cover, rather than as an encyclopaedic resource for the designer.

3.3. Hudson, Jennifer. *Process: 50 Product Designs from Concept to Manufacture*. 2008. Thames & Hudson: London.

Hudson's book investigates both the design and manufacturing processes of 50 case studies. It demonstrates the design process, philosophy, design iterations, and collaborations of a designer working with the manufacturer in order to get a design to production. The case studies often offer information as to how a designer may have customized a particular manufacturing process, or worked with a manufacturer to develop a new process. Outside of the case study, Hudson's book does not offer further information about a manufacturing process or technique. This book is a reference about the design process for CRM rather than a resource for an architect to learn about repetitive manufacturing.

3.4. Lefteri, Chris. *Making It: Manufacturing Techniques for Product Design*. 2007. Laurence King Publishing: London.

Lefteri's book is an encyclopaedic reference book that provides an overview to all of the currently available manufacturing processes. Lefteri focuses on those manufacturing processes that form goods, and organizes the processes according to categories. Processes are grouped within category headings and are located in the book next to similar alternative processes. For example, pultrusion and extrusion are included under

“Continuous”. This allows the reader to understand better the differences between the two, and when one may be more applicable to a particular design. Lefteri also includes a number of specialized manufacturing techniques (e.g. inflating metal and Pulshaping) that may be trademarked or available through limited manufacturers. Lefteri included many high-design examples of products that use a particular manufacturing process.

3.5. Lesko, Jim. *Industrial Design: Materials and Manufacturing Guide*. 2008. John Wiley & Sons: Hoboken, NJ.

This is an introductory text geared toward second-year industrial design students. Lesko gives an overview of the manufacturing processes and materials so that designers are aware of the possibilities available to them. It is also presented visually, so that designers more easily access the information. The book is organized according to material types with metal and plastic being the primary focus. Unlike Lefteri and Hudson, Lesko includes very few high-design examples and instead focuses on the everyday manufactured items (e.g. cast gears, rolled I-beams, and faucets).

3.6. Schrader, George F. and Almad K. Elshennawy. *Manufacturing Processes & Materials*. 2000. Society of Manufacturing Engineers: Dearborn, MI.

This book gives a good overview of manufacturing and its place in the United States and the global economy. The book provided more technical information, such as describing the cellular structure of certain materials. The book primarily focuses on metals, both ferrous and nonferrous alloys, and discusses the forming, shaping, manipulation, and joining of metals together. Only one chapter in the book is dedicated to non-metallic materials (e.g. plastic, rubber, clay, and glass) and in that chapter only the manufacturing process typical to plastics (e.g. compression molding, transfer molding, pultrusion) are illustrated or discussed in any depth.

3.7. Thompson, Rob. *Manufacturing Processes for Design Professionals*. 2007. Thames & Hudson: London.

This large survey book offers information about all of the manufacturing processes readily available. It is organized by forming, cutting, joining, and finishing technologies and includes a separate part on standard materials. Thompson organized the section “Forming Technologies” by material and is further categorized by similar and possibly alternative processes. The book uses high quality photographs and diagrams to describe the manufacturing processes, but do not offer the designer many of the design parameters associated with a process. Most forming technologies include an in-depth case study of a particular manufactured product. Thompson’s case studies and materials covered are more alighted with product design rather than architectural design.

3.8. Thompson, Rob. *Prototyping and Low-Volume Production*. 2011. Thames & Hudson: London.

This book focuses specifically on those manufacturing technologies that are best suited for prototypes or small batch productions. Thompson divided the book according to forming, joining, and finishing technologies. The forming technologies are those manufacturing process that form objects. Thompson gives equal weight to repetitive manufacturing and CAM. Although this book excludes processes that have a mid-sized production runs, under each prototyping or low-volume production process, Thompson indicates what larger-volume production process would be similar. High quality photographs and diagrams are used to describe the processes, but very few design parameters are given to the reader.

CONCLUSION

This paper proposed the term CRM to refer to repetitive manufacturing processes that are customized to a particular architectural project. With the use of CNC equipment, architects and manufacturers have been working together to customize the molds, jigs, or patterns used in repetitive manufacturing for building components used in a specific project’s design. CRM included those repetitive manufacturing processes with relatively low capital costs and that can support low- to mid-volume production runs of repeatable objects. CRM allows for customization from the designer, while balancing the need for repetition in order to remain cost effective. This paper made visible architects and building designers that have used CRM for their building designs. I selected twelve recently completed case studies and presented a literature review of the existing resources for architects and building designers to understand better CRM.

The existing literature on repetitive manufacturing includes books for the designer that would allow them to design products for small to mid-volume production runs. The current literature educates anyone about available manufacturing processes, and illustrates how those processes work. Most of the available texts are geared to product or industrial designers, or to engineers. Most of the current literature does not illustrate the processes or materials primarily applicable to architects. As the CRM processes identified by the case studies, the associated manufacturing processes are not those typically used by industrial designers. The case studies included atypical processes such as extruded, humped, and pressed clay, slumped glass, wood-molded blown glass, and precast concrete—not all of which are addressed in the majority of literature on manufacturing processes.

REFERENCES

Gabler, Markus "The Walbrook London- Façade in Glass-fibre-reinforced polymer" *Detail.* June, 2008.

Giffen, James W. "Method of Manufacturing Nonporous Vitreous Building Tile". No. 3,528,791, 15 September 1970. United States Patent Office

Piller, Frank T. *et al.,* "Does Mass Customization Pay? An Economic Approach to Evaluate Customer Integration" *Production Planning & Control: The Management of Operations.* 2004. Taylor & Francis Ltd.: London.

Schittich, Christian, ed. *Building Skins*. 2006. Birkhauser: Basel

Steiner, Joseph C., "Requiem for the Manufacturing Order", *Repetitive Manufacturing Seminar Proceedings*, (Falls Church, VA: American Production and Inventory Control Society, 1981)

Webster's Ninth New Collegiate Dictionary. 1988. Merriam-Webster Inc.: Springfield, MA.

ENDNOTES

[1] In the patent filled with the United States Patent Office, Fuller states that his prefabricated bathroom can be made of metal or plastic. Fuller, Richard Buckminster. 5 November 1940. "Prefabricated Bathroom". No. 2,220,482, United States Patent Office.

[2] The two manufacturers were Ceramica Cumella (Barcelona), founded in 1880, and Ceramica Decorative (Valencia), founded in 1862.

[3] Campbell, Duncan, Alistair Gunthrie, Renzo Piano. 15 December 2004. "Light Transmission System and Method for Buildings" No. EP1485544 A1. United States Patent Office.