TECHNOLOGY REVIEW OF MASS CUSTOMIZATION

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Abstract: This paper provides a comprehensive review of how technology has and is still aiding the development of product customization to achieve mass production costs while being responsive. With the technological advances of manufacturing, information technology, communication, and product design, higher levels of mass customization can be realized. Industry examples are used in categorization of mass customization and corresponding technology is presented. In addition, key technological advances that is enabling mass customization are provided. The overall technology assessment is performed.

Significance: The technological innovation involved in (10) Productivity and Business Strategies.

Keywords: Mass Customization, Modularity, Configurators, Flexible Automation, Supply Chain Management.

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1. INTRODUCTION

Just as mass production was crucial to manufacturing in the 20th century, mass customization (MC) will be the key to economic growth in the 21st century. MC is the ability to design and manufacture customized products tailored to meet a customers needs at mass production costs and speed (see Figure 1). While organizations continue to outsource for economical reasons, managing the interfaces between suppliers has become expensive and inefficient. By dispersing engineering and production geographically, manufacturers have increased the number of places their knowledge interfaces and multi-tier supply chains can breakdown. This amasses hidden costs, increases lead times, and reduces control. This is especially true for customized products that have tight deadlines.

Significant reduction in inventory costs and lower obsolescence will also occur in a manufacture-to-order environment. The survival and growth of all companies, small to large alike will then be dictated by their ability to cater to this emerging market trend. Companies such as Dell, 80/20 Inc., and Lutron have clearly proven that customers prefer this type of sales model. This model requires manufacturers to be market-driven and customer-responsive, which means offering more product variation and allowing customization. However, adopting this model poses some serious challenges for traditional manufacturing environments. It dramatically complicates the manufacturing system design if the same design procedures that have been developed for standard products are used. In the MC model, value is created by people designing the product, combining the supplier competencies, establishing supplier networks, and ensuring customer satisfaction.

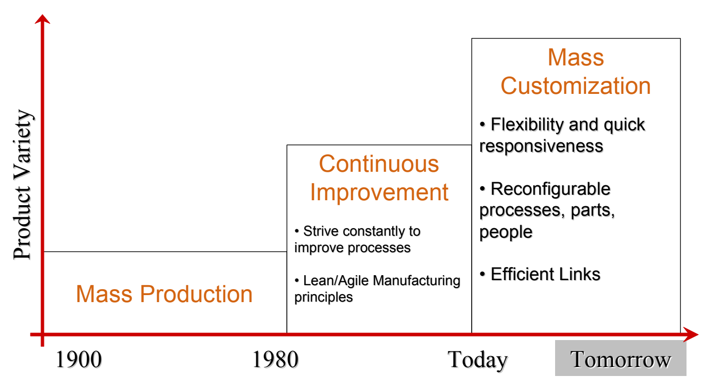

Figure 1. From Mass Production to Mass Customization

Among the many challenges for MC, the following are important: (i) keeping costs low to match those of standardized items, (ii) achieve high quality production of high variety of products, (iii) making these products available in a timely fashion to customers. A series of industrial shifts enable MC: (a) Modularization of products and processes has enabled management of product variety: and (b) The ability of "knowledge-based" software to configure products and (c) Flexible automation for manufacturing has been enabled because of improved low cost technologies. Hence, today's manufacturing systems have the potential to build a large variety of end products at costs comparable to mass-produced items. However,

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this potential is just the beginning to be realized based on the complexity of the product, manufacturing, and supply chain. Therefore, different manufacturing sectors have different business drivers and are at varying degrees of readiness to adopt MC methodologies.
With these trends, many issues arise in the product development and production cycle. These issues are being addressed by capabilities in computational, communicational, and informational areas creating innovations in flexible automation, networks, and electronic product design. An increasing number of companies are adopting mass customization strategies at different levels in their product development cycles (see Figure 2). In this review paper we seek to address some of technological innovations that aid in implementing MC. A case study is also presented for demonstrating a knowledge-based product configurator.

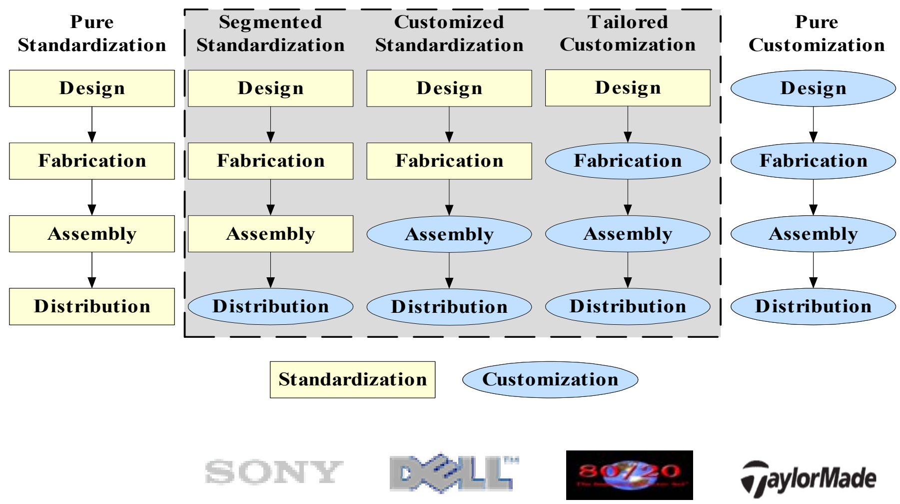

Figure 2. Levels of Customization (adapted from [Lampel96])

2. PRODUCT DESIGN AND DEVELOPMENT

2.1 Modularity and Flexibility

One of the difficulties with mass customization is that product variety increases drastically with just a few product options. This will likely stretch a company's own infrastructure, especially with regard to variety of tooling and fixtures needed to manufacture a wide range of product variants. Also, part numbers rise, adding complexity to logistics and manufacturing processes. As a result, there is increased outsourcing of significant portions of complex products such as automotives which allows more product derivatives to be built in their own facility without having to invest in expansion of their own plants. However, outsourcing alone may not solve the high part count problem unless the product and interface definitions are standardized across the supply chain. In other words, companies need tools to manage the product rather than product data.

One of the solutions to managing the complex variety is the product platform which is often defined by means of the product architecture. The product platform has been defined by McGrath [McGrath95, Halman03] as a set of subsystems and interfaces that form a common structure from which a stream of related products can be developed and produced efficiently. Baldwin and Clark [Baldwin97] define three aspects of the underlying logic of a product platform: (1) its modular architecture; (2) the interfaces (the scheme by which the modules interact and communicate); and (3) the standards (the design rules to which the modules conform).

Standardization and flexibility of products and processes is an important part of any mass customization initiative. This is achieved primarily through modularization of products, processes, and the supply chain. Modularization demands standardization of product interfaces and allows higher variety and customization. Trends towards modularization of products and increased use of product-platform approach are being observed in many manufacturing firms such as Sony, Siemens, and Lutron. An increasing number of automotive OEMs are consolidating and updating their assembly plants so that each of their remaining production facilities can produce a higher annual output and a wider variety of body styles built upon modular underbody structures. This is, in part, due to the increasing market pressure on OEMs to produce more niche vehicles. This in turn demands a wider introduction of flexible manufacturing systems into their body shops capable of building multiple body styles through the same production facility.

Another important aspect of today's product development process is the convergence of multiple disciplines and technologies in providing products with higher efficiency, better safety, and more customization. The automotive industry has had one of the biggest impacts due to this trend. It is estimated that almost 25% of the base cost of an automobile is due to the electronics and software. For the first time, technology has reached a point where it can be expected to provide consistently, reliably, and cost-efficiently the systems and software that will allow a level of cohesive, networked communication throughout a vehicle. This benefits safety, performance, emissions reduction, and comfort [ref] for the automobile. A convergence of various technologies in different disciplines such as electronics, mechatronics, materials and manufacturing systems has lead to improved products and better customer satisfaction.

Interesting issues arise while developing modular components and assemblies, especially with regard to interfaces between components. The relationships between the various modules will change dynamically whenever the product, process, or distribution changes. This warrants a different organization of the communication and information infrastructure. These include both the physical interfaces between modules such as geometric interference and tolerances, as well as software interfaces. In addition, for products driven by electronics the communication and information interfaces between the different modules will need to be standardized and well-defined. From a product design perspective, Computer Aided Design (CAD) and Computer Aided Manufacturing systems have become mature and allow third-party interfacing and applications. Several standards for information communication, such as XML and STEP, have emerged in the past decade without significant impact in the manufactured products domain. Several software solutions in the area of Product Lifecycle Management (PLM) and Product Data Management (PDM) have emerged in the past decade. PDM/PLM systems are being used by various manufacturers to provide workflow and store/manage product-process data. PLM/PDM systems (1) offer no significant value addition to the core product, (2) do not spot design errors, and (3) are not product-centric (but data-centric). PDM/PLM systems merely manage the data through functions once done by other slow modes of interaction across distances. They do not add inherent value to the product itself.

In contrast, a transition to mass customization needs a "product centric" model that has the following:
1. Flexible product family and supply chain modularity,
2. Faster design tools,
3. Quality designed into the part,
4. Optimization of engineering decisions, and
5. Immediate part procurement (reuse).

2.2 Design and Product Configuration

Design tools have been aided by the technological innovations. Some of the most widely used design tools are Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), and Computer Aided Engineering (CAE). CAD is used as a means to link a part model with analysis software (CAE), quickly create machining code and visual simulation information (CAM), and provide a form of communication (usually visual) for the product.

The major CAD innovation that provides an enabling step to mass customization is parametric modeling techniques. Parametric modeling essentially creates flexible product models that can easily be modified geometrically. This geometric modification can also be linked to the analysis software packages such as finite element analysis (FEA), computational fluid dynamics (CFD), user defined analysis programs, and more.

The general direction of industry is to perform engineering analysis earlier in the design and to create robust, flexible models. This allows designers to more easily vary designs and see what will happen to a product and its performance if different aspects should be varied, and what could cause failure. To get such answers, [designers] need to put the engineering back into design and turn to CAE [Ell04].

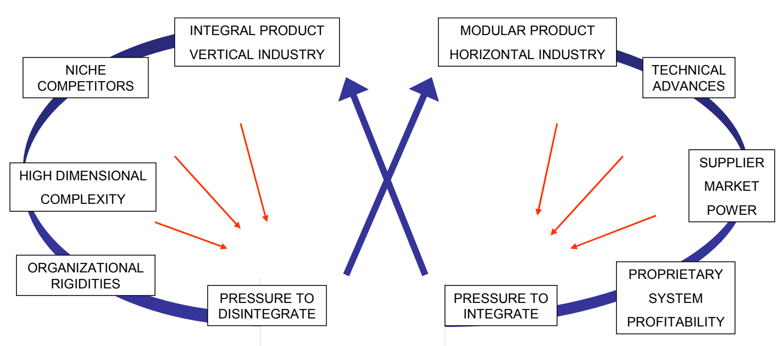

Figure 3 Modularity Integration loop for the cycle of product evolution

Other companies such as Engineous Software, Inc. link analysis and CAD software with their optimization software, iSight™. This dynamic link is made possible by flexible models and Open APIs. Open application programming interface (API) allows CAD users to create highly flexible models in programming code. It also permits analysis developers to build tools into CAD software. This in turn promotes a cyclical product evolution from technological innovation (see figure 3).

Since CAD software is now generally needed for product development, trillions of 3D CAD models have been created.

In fact, CAD model libraries have been formed as parts catalogs. The designer can now easily insert a CAD model of a part that will be used in the product from the supplier instead of having to create the part model from scratch. The latest version of Pro/Engineer Wildfire ™ CAD program incorporates a direct link with CADregister™, a CAD parts catalog run by ThomasRegister™. The user can drag and drop parts directly into the CAD software environment for analysis and representation. Other CAD software companies such as SolidWorks™ and Unigraphics™ are doing the same while also allowing user defined parts libraries. This saves the designer a significant amount of time in terms of procurement, modeling, and analysis.

In order to manage and keep track of the parts and products within a company, further software suites were developed. Product Lifecycle Management (PLM) software is intended to aid the process of design to production by managing the information attached to products, suppliers, processes, and resources. Enterprise Resource Management (ERP) software aids upper management in getting an overall view of operations regarding the product.

Recently, a new set of design solutions, called Product Configurators (PC), have become significant in addressing many of the design issues related to mass customization. Design is the most important piece of information that describes and defines a product. Product Configurators focus on the product design itself, and attach other process and product information to the design, thereby taking an integrated (product-centric) approach to product representation.

Configuration is "*... the construction of a physical system according to specifications by selecting, parameterizing, positioning and assembling instances of suitable existing component types from a given catalog"* [Gunter 99].

Product Configurators enable: (1) Rapid product development (2) Design reuse, (3) Reduced design time, (4) Collocation of parts in viable design, (5) Engineering rules-based design, and (6) Enhanced product reliability. In summary, product configurators in conjunction with CAD/CAM systems and flexible automation (e-Factories of the future) have the potential to achieve the goals of data management systems with regards to rapid product development. These product configurators have emerged as the newest design tools for 21st century product development and will play a key role in realizing the goals of mass customization. In addition, new systems for managing product information enable reuse of past designs, and thus reduce product development time [Iyer03, Lou04].

Since CAD is essentially the design portal for products, software that directly translates customer requirements into design concepts in the CAD system is necessary. Product configurators fill this need to link the customer to the design stage. Designers or end customers use product configurators to create a product from a set of predefined options or variables. The level of configuration depends in part to the level of product modularity and maturity. Configurators range from simple tools with limited options to complex rules based systems that bring together all of the parts, products, and processes to meet the customer specifications. We present an industry example of a rules based configurator that demonstrates the customer-to-design bridge.

Case Study from Imaginestics, LLC

The Barker Company designs a product line of merchandiser (display cases) for stores to showcase their products. It was decided that the order-entry process currently performed in MRP, which is Symix, was to be integrated to capture the job number and customer directly. Barker elected to use the BMD series product line for the initial implementation, this happened to be one of their more complex configurations. In addition, it was a high volume product line so any cycle time improvements would be realized substantially. The BMD Series is a full-service merchandiser standard with flat or curved front lift glass and optional mezzanine shelving. This flexible merchandiser allows customers to display their product on one or two rows of easily removable painted metal shelves, or to create a product design on a full single deck (see Fig. 4).

Imaginestics, LLC, developed a customizable rules matrix that allows a company to define their unique environment and special allowable customer configurations. The rules matrix forms the basis for their configuration engine called the i-config engine. These rules are established in Microsoft Access, since most companies are familiar with it. The matrix also gives companies the greatest amount of flexibility as their business and manufacturing environment changes. However, the i-config data repository can be either Oracle or MS SQL. At Barker, three rules matrices were designed to define the product and unique customer configurations, namely, the Parameter Rules matrix, Assembly Rules matrix, and a Material Rules matrix.

Figure 4 Barker Company Merchandiser configuration (Courtesy: Imaginestics, LLC)

Parameter Rules Matrix - Parameter rules are broken into control (global) and local variables. Control variables are parameters such as length, depth, height, which are global in nature and affect the overall dimension of the product. Local variables are more specific to a component, such as a type of finish, which defines the thickness variable. Any allowable size configurations or limitations were established for each assembly and component options in this matrix. All available assemblies and their respective component and feature options were defined in this matrix.

Assembly/Component Relationship Rules Matrix - The assembly and component rules were established in this matrix. The assembly and the available components were entered in an indented bill-of-material type of a chart. Each assembly configuration contains all available subassemblies and their respective components.

Material Rules Matrix - The properties for all available materials and the type of finish were established in this matrix, along with the component or feature that the user had options to select. Local variables such as thickness of the finish and material density were assigned in this matrix.

Parallel to the definition of the rules matrix, solid models were created in CAD for the BMD series. The CAD solid parts were designed using sketches and the sketch entities defining the control (global) variables and local variables were given unique variable names and linked throughout the assembly-component design, using the rules matrix definitions. All available components and their related drafting files were modeled using Solid Edge. Meta-data information was also linked to title block and revision block fields in drafting files, such as job number, designer, customer & build date.

Prior to the rules-based configurator, the solid modeling process at Barker was performed only by the engineering design group and was one step removed from the entire manufacturing information flow. Following the use of the product configurator, not only has the task of creating solid models of product variants been simplified and automated, but has also helped manage the process of converting diverse customer requirements into deliverable final products. This enhanced process has the capability to seamlessly integrate the engineering and design function into the entire product life cycle - customer service to final manufacturing and assembly.

3. FLEXIBLE AUTOMATION

In a similar way that CAD allows for flexible parts and products, software tools have been used to design flexible factories. Also, simulation and analysis can be performed in order to optimize the processes involved in product fabrication and delivery. This software has been generally named virtual factory software. It could also fall under the umbrella of manufacturing process management.

Use of Automation for Cost Competitiveness

To cater to the demands of custom products, companies will require manufacturing systems that have a great deal of agility to respond to changing market needs [ABr97]. A "responsive" manufacturing system is one that can quickly reconfigure itself to allow flexibility not only in producing new products but also in changing the system itself. Such systems will necessitate the use of highly sophisticated automation systems that are flexible, extensible and re-usable. The elements of an Automation System include the following:

a) Manufacturing Systems (refers to actual machines, their flexibility,)
b) Software Support Systems
c) Industrial Communication Systems (refers to systems that enable supply chain integration)
d) Mechatronics
e) Production Control Systems (refers to use of JIT, Lean Manufacturing concepts, six-sigma)
f) E-Business

The maturity of a company in each of these elements determines its overall automation level. The Level of Automation (LOA) in any manufacturing facility plays a very important role in determining the manufacturing effort (i.e. the time required) required to produce a particular part. The LOA also decides the percentage of tasks that will be done using manual labor and the percentage of tasks that will be completed using machines. This breakup determines the net resource rates and consequently decides the cost structure for that company. Other important aspects that impact the automation-cost relationship are the following [AHW95]:

1) Reduced Labor content
2) Increased flexibility
3) Quality / Yield improvements
4) Capacity Increase (leading to quick response)
5) Reduced changeover and installation times
6) Reduced floor space requirements
7) Reduced downtimes
8) Improved Safety

In the past, the prohibitive costs of the automation systems presented a major obstacle for use of automation systems. However, the costs for automation systems have reduced and the above mentioned benefits provide major incentives for companies to adopt automation. With greatly reduced payback period on these sophisticated systems, use of automation is fast becoming a major competitive advantage especially in countries with high labor costs. World leaders in automation technologies like ABB, Siemens and Rockwell are pushing the envelope for the next generation of factories. Investments in vision systems, sensors, multi-axis and multi-function machines, cells, robotics, Radio Frequency Identification (RFID) tages, wireless systems, simulation, and other technologies are a testimony towards the vision. A "digital factory" which can be designed and simulated on the computer is the ultimate dream of every factory designer and automation specialist [Wuc03]. A "flexible factory" producing "flexible products" will enable increased productivity and competitiveness.

4. SUPPLY CHAIN MANAGEMENT

One of the biggest hurdles faced by companies trying to adopt mass customization has been the lack of flexibility and responsiveness in the supply chain. The supply-chain management research has generally focused on analyzing supply-chain configurations for satisfying the demand for standardized products. A traditional supply-chain configuration consists of a fixed network of raw material suppliers, manufacturers of finished products, distributors of finished products, and the end customer. Issues such as where the components should be procured from, where they should be assembled, how it is possible to minimize the procurement and assembly costs, and what are cost effective ways of distributing these finished products have been addressed for standardized products which are manufactured in high volume. However, increased product variety due to mass customization has led to additional challenges in managing this new dynamic demand chain. Fisher et al. [Fisher99] have shown that the increased product variety, although beneficial to consumers, is making it more difficult for manufacturers and retailers to predict which goods will sell and to plan production accordingly. Traditional production planning systems such as JIT, MRP, and quick response are not able to handle demand chains with customized products. The primary source of difficulty is that the supply chain is not responsive enough to changing demand environments. Even a flexible system, such as the one developed by Dell Computers, is constrained by component suppliers' long lead-times. Pine et al. [Pine93, Pine97] discuss the challenges associated with making mass customization work.

A number of recent studies explore the impact of increasing product variety on manufacturing efficiencies. For example, Fisher et al. show that day-to-day variability in option contents of an automobile assembly has a significant adverse impact on manufacturing efficiencies. However, if the process is optimally buffered, then product variety has an insignificant impact on direct assembly labor. Fisher et al. address issues related to component sharing to manage product variety. Randall and Taylor [Randall01] study the impact of product variety on the supply chain structure in the bicycle industry. Their analysis suggests that firms producing locally (in the U.S.) are more efficient in offering higher product variety than firms off shoring.

To cope with the pressures of competition and product customization, manufacturers have tried to mimic the mass customization ideal of "build-to-order" with "locate-to-order". Here, a product that is similar to the customer's order is located within the companies vast inventory and is shipped. This is a compromise for customers. New trends have emerged where the products are being customized as they are in the Supply chain. This is illustrated by Toyota's Scion where customization is carried out in the Port and at the dealer to achieve shorted order-to-delivery time. [SAE May article]

5. CONCLUSIONS

Therefore, the technological innovations in key areas of design, configuration, automation, and supply chain management are enabling mass customization in today's highly productive companies. The modularity of products coupled with flexible design systems such as CAD, configurators, and automation are creating customized products at mass production costs and high responsiveness. Individual innovations in these areas will lead to higher levels of mass customization. Incorporating these technologies is creating more customer-centric businesses that are able to meet the individual needs of its customers. The next innovations will bring tighter coupling of the customer to product design, supply, and delivery. Our research at PRECISE is focused on customer driven networks and product development. This review provides a foundation for further research.

6. ACKNOWLEDGEMENTS

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