Satisfying Customer Preferences via Mass Customization and Mass Production

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Abstract

Two operational formats — mass customization and mass production — can be implemented to satisfy customer preference-based demand. The mass customization system consists of two stages — the initial build-to-stock phase and the final customize-to-order phase. The mass production system has a single stage, building products with pre-determined specifications to stock. In each case, the company makes decisions on the number of initial product variants, product specifications, and product pricing. Under uniform customer preference distribution, the optimal number of base product variants has the form of the famous EOQ solution, and the optimal product specifications are equally spaced. We characterize the decisions and benefits of the mass customization system versus the mass production system.

1 Introduction

When contrasting the operational formats of mass production and mass customization, we note some pronounced differences. Mass production, with Henry Ford's Model T as its culmination, has the virtue of economy of scale. Specialized machines run at high levels of utilization in a make-to-stock environment and provide for an overall low manufacturing cost. While mass production can still be successful today in many traditional industries, advancement in manufacturing and information technology as well as rapid shifts in consumer behavior have led to the adoption of a new, value-based manufacturing philosophy: today, mass customization is becoming a more and more viable model for a broad range of different industries (Gilmore and Pine 1997, The Economist 2001, Business Week 2002b, Time 2002). Based on sophisticated consumer interfaces, modular product architectures, agile manufacturing processes, and speedy distribution, mass customization fundamentally caters to customer individualism.

Within the last decade, many companies have ventured on the road to mass customization. From lipsticks to cars, from M&M's to chinos, a growing number of products can be customized to customer's individual taste. Hewlett-Packard has effectively used postponement to realize mass customization in their printer and PC businesses (Feitzinger and Lee 1997). Levi Strauss launched the mass customization initiative to tailor women's jeans individually, based on a body scan, for a mass consumer group (Bailey 2000). The mass customization project at adidas-Salomon AG, "mi adidas", has gone through its successful pilot phase involving well over 100 retailers across Europe (Seifert 2002). The phenomena of mass customization is also becoming more prevalent in service industries, and individually customized financial, insurance and utility services are proliferating (Victor and Boynton 1998).

The trend of customization becomes increasingly important to U.S. companies as more and more basic manufacturing and services functions are outsourced to overseas. The biggest advantage of U.S. companies is that they are close to the customers and their ability to cater to customers' individual needs.

However, the promise of mass customization comes with potential pitfalls. A mismatch between technology and market demand can pull the firm exactly into what mass production has been trying to avoid, namely, high cost (Zipkin 2001). In addition, mass production system itself has evolved into one that can offer many varieties. The 180 different colors of Mazda 323 in 1991 (Fisher and Ittner 1999) is a clear contrast to Ford's single black Model T in 1913. For many firms today, which strategy to pursue remains unclear. Indeed, the relationship between market and operational conditions demands careful assessment in each case before conclusive decisions may be made.

When GE, for example, decided to redesign the family of Spectra RMS industrial circuit breakers (a $80 million business in 1995), they had come to offer 650,000 model permutations due to little standardization in their product structure. Replacing all of them by one model obviously would not satisfy dispersed customer preferences and needs. How could GE gain customization flexibility in its products while maintaining the low manufacturing costs of mass production?

This paper considers both mass production and mass customization as possible operational formats that can be employed to satisfy preference-based customer demands. For each operational format, we address the following questions: (1) What is the optimal number of product variants to offer? (2) What are the optimal or close-to-optimal product specifications? (3) What prices should the company charge? (4) How do these two operational formats — mass customization and mass production — compare to each other?

The paper is organized as follows. In Section 2, we review the relevant literature. In Section 3, we detail our general modelling framework for customer demand and the two operational formats: mass customization and mass production. In Section 4, we analyze operational issues in the mass customization model in detail. In Section 5, we analyze the corresponding mass production model and compare the two systems. In Section 6, we summarize managerial insights and provide directions for future research.

2 Literature Review

Specific aspects of the problem at hand have been studied in the economics, marketing, operations and information technology literature. Product differentiation problems have a long history in the economics literature. Horizontal or spatial differentiation, where each customer has her own taste, can be traced back to Hotelling's linear city model (Hotelling 1929). There is a rich literature in vertical differentiation, where quality is preferred by everybody. Tirole (1988) reviewed all these models in very fine details.

Economists focus on the optimal degree of product variety and whether monopoly or free-entry market under or over provide product variety. Lancaster (1990) gives an excellent review of product variety problems regarding the individual consumer, individual firm, market equilibrium and social optimum. Our research takes the profit maximization perspective of an individual firm and we consider more operational details.

Lancaster (1966) first modeled customer preferences by their utilities over each characteristic of the product. Goods are perceived as bundles of characteristics, a concept similar to "attributes" in the marketing literature and "specifications" in the operations literature. Our model also takes the product characteristic approach.

In the marketing literature, studies of product variety have focused on the product line selection problem to maximize revenue or market share of a company (Green and Krieger 1985, Dobson and Kalish 1988, 1993, Chen and Hausman 2000). These works do not consider the cost of supply the product variety.

In the operations literature, postponement has long been proposed as a strategy to mitigate the high cost of offering large product variety (Lee 1996, Lee and Tang 1997, Swaminathan and Tayur 1998, Swaminathan and Lee 2003). Our mass customization is based on delayed product differentiation and we explicitly include customer preferences, which is not considered in the postponement literature.

Krishnan and Ulrich (2001) reviewed the product development literature, which includes product design and variety problems. Chen et al. (1998) study a product line design problem with one physical attribute defined on a line segment. Joint inventory and product selection problems have been studied by Van Ryzin and Mahajan (1999) and Smith and Agrawal (2000).

The marketing and manufacturing coordination problem under flexible manufacturing system was first considered by de Groote (1994). The focus is on the flexibility of the manufacturing system and the breath of the product line; customization is not considered.

Research in design for variety provides practical methodologies using index-based measures to quantify a wide range of costs of offering variety. The goal is to reduce those costs early in the design phase of the product life cycle (Ishii et al. 1995, Martin and Ishii 2000).

Also in the operations literature, a series of empirical studies in the bicycle industry and the automotive industry provide valuable insights on the relationship between product variety and manufacturing and supply chain costs (Fisher and Ittner 1999, MacDuffie et al. 1996, Randall and Ulrich 2001, Ulrich et al. 1998). Randall and Ulrich (2001) note that the effectiveness of high variety strategies of mass customization or variety postponement depends not only on a supply chain's ability to deliver variety, but also on the ability to successfully reach its target market. Our model of mass customization coincides with this notion.

Mass customization has been considered with price discrimination in the recent literature of economics of information technology. Ulph and Vulkan (2001) demonstrate that mass customization and price discrimination are complementary. Our mass customization model indeed allows price discrimination.

3 Generic Model Framework

In this section, we provide an overview of the generic model framework that underlines our analysis. In Subsection 3.1, we outline the general market demand and customer preference model as used. In Subsections 3.2 and 3.3, we introduce our representation of the mass customization and mass production systems.

3.1 Market Demand and Customer Preference Model

Hotelling (1929) considers buyers of a commodity uniformly distributed along a line segment of length l, in order to analyze competition among a small number of firms. Because one cannot appear in two places at the same time, each individual customer buys only a single product in the product group. Companies can place their business anywhere on the line segment. Each buyer transports her purchase home at a certain cost per unit distance. In general, the transportation cost can represent other causes leading to customer preference behaviors.

Lancaster (1966, 1979) expands this locational idea into a linear virtual space in product characteristics to study the product variety problem. It is much in the spirit of the "Hotelling spatial location" model that we develop our market demand and customer preference model.

Let D denote the overall market demand for all products that belong to a certain product category, which could be stochastic. Another uncertainty in the model is the relative mix of different customer types along with their individual preferences. Since the focus of the study is on how mass customization and mass production cope with the different preferences of customers, we assume the aggregate demand D is deterministic.

Product specification θ belongs to a line segment $\Theta = [0, 1]$ normalized to length 1. The implicit assumption here is that the specification is continuously quantifiable. Customer types are indexed by variable $x \in \Theta$, i.e., each customer has a most preferred product represented by its specification. Each customer purchases either one unit of a product or nothing.

We decompose customer x's evaluation of product θ into two parts. First, we denote $p_0(x)$ as the reservation price for customer x's most preferred product, which is the price customer x is willing to pay for her ideal product. Customers who cannot get their ideal products may buy somewhat less-desirable ones, if they can pay much less than they would have paid for their most-preferred. This leads to the second part of the utility function — how customer x devaluates an arbitrary product θ that is different from her ideal. We denote $u(x, \theta)$ as the disutility function. Therefore, payoff for customer x purchasing product θ at price $p(\theta)$ is: $p_0(x) - u(x, \theta) - p(\theta)$.

Consider the linear market case, in which a customer's reservation price is linear to her type (Chen et al. 1998), i.e., $p_0(x) = p_0 + ax$. The special case of $a = 0$ is the common horizontal product differentiation model. When $a > 0$, higher types of customers are willing to pay more for their ideal products. The model thus represents a more general horizontal differentiation in a sense that each customer still has her own taste. This is quite different from vertical differentiation under which everyone prefers more to less.

Also consider a linear disutility function: $u(x, \theta) = \lambda|\theta - x|$. Here, $\lambda \geq 0$ represents customers' preference sensitivity. Higher values of λ mean customers are more particular about their ideal products, while smaller values of λ mean customers are less sensitive. Suppose customers are only willing to sacrifice their desires for products with higher attributes than their ideal but regard products with lower specifications as nonfunctional. Thus, $u(x, \theta) = \lambda(\theta - x)$ if $\theta \geq x$; $= p_0(x)$ if $\theta < x$.

The GE's Spectra RMS circuit breaker example is exactly such a case of upside disutility. The circuit breakers are designed to provide overload and overcurrent protection to electrical distribution and utilization equipment. The breaker body is in the shape of a square molded case with different frame sizes, each of which accepts a range of rating plugs that determine the electric current rating of the breaker. For example, one frame can handle rating plugs of 7, 30, 60, 100 and maximum 150 amperes. The bigger the frame size, the bigger is the maximum rating plug that can fit in the frame. A customer is almost indifferent to frame size as long as their maximum current protection can be satisfied. Smaller frame size that cannot handle the required maximum current is not useful to the customer.

The distribution of individual customer preferences x is modelled by a beta distribution with probability density function $f(x)$ and cumulative density function $F(x)$. Two shape parameters ν and ω characterize a beta distribution (See Johnson and Kotz 1969). When $\nu = \omega = 1$, the beta distribution degenerates to the uniform distribution. A beta distribution can have very general shape and is constrained to the interval $[0, 1]$ without need for truncation. It has been widely used in the literature to model consumer preference distribution.

3.2 Mass Production System

Mass production systems are prominently characterized by producing finished goods to stock. Thus, the number of product variants, their specifications and production quantity must be committed before the market demand information is revealed. In addition, mass production is commonly linked to conventional sales channel with physical stores, where each variant of product is displayed and sold at a uniform price to different customers. Each customer picks the product that serves her best.

There can be other reasons for producing pre-made products as opposed to custom-made products, such as impatient customers who need a product right away. That aspect is not the emphasis of the current study.

Economies of scale in mass production are captured through the fixed cost K of introducing each new product variant, which could include redesign, tooling and set up costs. Furthermore, if we assume constant unit production cost, the cost of producing s units of product θ is $c(\theta, s) = c(\theta)s$, where $c(\theta)$ is the unit production cost of product θ. We then define the derivative $c'(\theta)$ as the marginal cost of product differentiation. When higher θ requires more materials as in productions of frames, steel bars and clothes, the cost for product θ can be linear in θ, i.e. $c(\theta) = c_0 + c_1\theta$. Hence, $c'(\theta) = c_1$. It is reasonable to assume that $a \geq c_1$, which means the marginal cost of product differentiation does not exceed the first-best marginal revenue.

3.3 Mass Customization System

As an ideal, mass customization should provide customers with anything they want at anytime. In reality, companies providing symbolic product variants with one-dimensional specifications might come closest to this goal. We see such examples in soap stamped with customers' names, cookies glazed with customers' pictures, and web sites with personal greetings on the front page. Products with easy customization processes are second in reaching the ideal. Mixing a variety of color pigments with a generic paint (Feitzinger and Lee 1997), adding unique ingredients to base formulas of cosmetics (Time 2002), inserting plug-and-play parts into the standard expansion slots of a computer, cutting longer steel bars, or grinding mechanical parts to meet lower dimensional specifications fall into this category.

In both of the above two cases, some form of initial base products (the soap or the generic paint) already exist in stock waiting to be customized for individual orders. Building a customized personal computer doesn't mean that the manufacturer has to start from raw wafer in meeting each order. In fact, IBM had a strategy of first making semi-finished computers (vanilla box) to stock and later customizing them to specific orders (Swaminathan and Tayur 1998). After the redesign of their product, GE also used the modular concept for the Spectra RMS product line. The rating plugs are interchangeable and easy to install on different sizes of frames. Generic inventories for a limited number of base product specifications are first mass produced, then the company observes the individual customer's order specification, and customizes a certain base product to satisfy that particular customer request. This is essentially a postponement strategy to enable mass customization (Feitzinger and Lee 1997).

Since each customer x gets a different product, price discrimination can be effectively applied by the company. The fixed cost of introducing an initial base product variant is K. As in the mass production system, the unit cost of making a base product θ is $c(\theta) = c_0 + c_1\theta$. Corresponding to the upside disutility function, base products can only be downward customized. The unit cost of customizing base product θ to satisfy customer x's ideal preference is $c_2 + c_3(\theta - x)$ if $\theta \geq x$, and $+\infty$ if $\theta < x$, where c_2 is the fixed customization cost and c_3 is the marginal customization cost. Such downward customization can represent disabling certain functions of hardwares and software or cutting or shrinking physical sizes of a product. The mass customization costs can be categorized into four areas: information elicitation, manufacturing, distribution, and customer service (Zipkin 2001).

Mass customization for more complex products is often performed through modularity and standardization. With modular product design, several key modules and a stock of varieties for each module are provided, so that customers can mix and match to customize their own products. Dell computer is a prime example of this model. Some key auto manufacturers are also exploring this direction. Known as the "3DayCar" project, such car makers as Volkswagen, Ford, General Motors, Nissan, Honda and Peugeot set out to see if the Dell model can be applied to car making (The Economist 2001). With modular process, production is broken down into subprocesses to provide flexibility.

As the study of product modularity and assembly introduces additional complexity into the problem, we focus on the one-dimensional customization observed in many industries to compare the mass customization system with the mass production system. A multi-dimensional problem can be decomposed into multiple one-dimensional problems if the different attributes are independent in demand and production.

4 Operational Issues in Mass Customization

Since orders are individually fulfilled according to customers' specified requirements, the company can charge each customer her reservation price $p_0(x)$ for her ideal product. We start with the first-degree price discrimination, then later discuss the second-best, where the company only charges different prices to different groups of customers.

The company collects a non-negative profit on sales to every customer. A sufficient condition for this to happen is $c_0 + c_1 + c_2 + c_3 \leq p_0$ when only one initial base product variant is offered. Even though this particular condition may not always be satisfied, any increase in the number of base product variants can relax the sufficient condition. If production has increasing returns to scale, i.e., the average cost of producing one unit of product θ is actually smaller when the production volume s is bigger, the sufficient condition can be further relaxed.

In fact, Jiang and Lee (2002) conclude that it is always optimal to place the initial base product at the top of the product space if a single base product variant is provided to customers with non-decreasing preference distribution, even when the company only chooses to sell to a portion of the whole market. Using that result, we can see that the company will cluster those unprofitable customers at the bottom of the customer space $[0, \underline{\theta}_e]$, where $\underline{\theta}_e < \theta_1$. All customers above $\underline{\theta}_e$ can get their ideal products from the company. The following study then focuses on the case of $\underline{\theta}_e \leq 0$, i.e., the company sells to the whole market.

4.1 Optimal Product Offering Policy

The company makes three decisions concerning its product offering: the number of base product variants n to produce initially, the corresponding product specifications θ_i, and their production quantities s_i, $i = 1, 2, .., n$. When the annual demand is stable and big (250K units per year for Spectra RMS industrial circuit breaker), the production quantity for each product variant is $s_i = D[F(\theta_i) - F(\theta_{i-1})]$, where $\theta_0 = 0$. The manufacturer's profit function is

$\sum_{i=1}^{n} \int_{x=\theta_{i-1}}^{\theta_i} [(p_0 + ax) - (c_0 + c_1\theta_i) - c_2 - c_3(\theta_i - x)]\, Df(x)dx - Kn$

$= \{\int_{x=0}^{\theta_n}(p_0 - c_0' + a'x)f(x)dx - \sum_{i=1}^{n} c_1'\theta_i[F(\theta_i) - F(\theta_{i-1})]\}D - Kn$, where $a' = a + c_3$, $c_0' = c_0 + c_2$ and $c_1' = c_1 + c_3$. Because the revenue term is dependent on θ_n, we first locate the product with the highest specification.

Lemma 1 *If customer preference follows a beta distribution with parameters ν and ω, the optimal product specification of the highest-specification product θ_n is*

i) $\theta_n = 1$ if $\nu \geq \omega = 1$;

ii) $M < \theta_n < 1$ if ν, $\omega > 1$, where M is the mode of the probability density function f.

The case of $\nu > \omega = 1$ characterizes an monotonically increasing density function $f(\cdot)$, while ν, $\omega > 1$ describes an unimodal $f(\cdot)$. If the company has to cover the whole market due to reasons such as maintaining long-term customer relationship, the highest-specification product θ_n would be 1. This is particularly proper when the customer preference distribution function $f(\cdot)$ does not have a long and light right tail. In such a case, since the revenue term is independent of n and θ_i $(i = 1, ..., n)$, the manufacturer can focus on the following cost minimization problem:

$$C = \min_{n,\theta_i,1\leq i\leq n-1} \sum_{i=1}^{n} c_1'\theta_i[F(\theta_i) - F(\theta_{i-1})]D + Kn.$$

We first solve the subproblem for optimal product specifications θ_i given the number of base products n:

$c = \min_{\theta_i,1\leq i\leq n-1} \sum_{i=1}^{n} c_1'\theta_i[F(\theta_i) - F(\theta_{i-1})]$. It is obvious that this cost function is monotonically decreasing in the number of initial base product variants n. In the following Proposition 1-3, we characterize the optimal product specifications.

Proposition 1 *For uniform customer preference distribution* ($\nu = \omega = 1$)*, the optimal product offering solution is* $\theta_i = F(\theta_i) = i/n$*,* $i = 1, ..., n$*, and the minimum cost is* $c = (1 + 1/n)c_1'/2$.

For the product specification decision, $\theta_i = i/n$ denotes an equal space policy and $F(\theta_i) = i/n$ denotes an equal fractile policy. Define c_{es} and c_{ef} as the manufacturer's cost in the subproblem from the equal space policy and the equal fractile policy, respectively. Proposition 1 shows that under uniform distribution the equal space policy is equivalent to the equal fractile policy and is optimal. The complete product specifications can also be characterized for an increasing $f(\cdot)$.

Proposition 2 *If customer preference follows a beta distribution with* $\nu > \omega = 1$*, the optimal product specifications are:* $\theta_i = k_i\theta_{i+1}$*, where* $k_1 = \nu/(\nu+1)$*,* $k_i = \nu/(\nu+1-k_{i-1}^{\nu})$*,* $i = 2, ...n-1$*, and* $\theta_n = 1$.

By substitution and iteration, we can find the final solutions of the optimal product specifications. In order to characterize the distance between adjacent products in the product space, we define the space spectrum $\Delta_i = \theta_i - \theta_{i-1}$ and the fractile spectrum $\Delta F_i = F(\theta_i) - F(\theta_{i-1})$. We have the following monotonicity property.

Proposition 3 *For a general distribution of customer preference, the optimal space spectrum* Δ_i *(the optimal fractile spectrum* ΔF_i*) is decreasing (increasing) in* i *when* $f(\cdot)$ *is increasing. The opposite is true when* $f(\cdot)$ *is decreasing.*

The two optimal spectrums Δ_i and ΔF_i together control the optimal distance between adjacent products. When $f(\cdot)$ is increasing ($\nu > \omega = 1$), equal space policy ($\Delta_i = 1/n$) underestimates the space spectrum for low-specification products and overestimates the space spectrum for high-specification products, while equal fractile policy ($\Delta F_i = 1/n$) does the exact opposite.

4.2 Performance of the Equal Policies

Product variants are often equally spaced due to its simplicity of implementation. It is therefore important to see how the equal space policy and the equal fractile policy perform in comparison with each other and with the optimal solution. As discussed before, the two equal policies are both optimal for uniformly distributed customer preference. For general customer preference distribution, the cost of the two equal policies has the following properties.

Proposition 4 *For beta distributions of customer preference with parameters ν, $\omega \geq 1$,*

i) $c_{es} > c_{ef}$ *for* $\upsilon > \omega = 1$ *and* $n = 2$*;*

ii) $c_{es} = c_{ef} = (1 + 1/n)c_1'/2$ *for* $\upsilon = \omega \geq 1$*;*

iii) Given the reflected beta distribution with parameters $\nu' = \omega$, $\omega' = \nu$, $c_{es} > c_{ef}$ *if and only if* $c_{es}^{'} < c_{ef}^{'}$.

When the probability density function $f(\cdot)$ is monotonically increasing ($\upsilon > \omega = 1$), the equal fractile policy outperforms the equal space policy if two initial base product variants are offered. Numerical study suggests $c_{es} > c_{ef}$ for any $n \geq 2$. Figure 1 shows the performance of the equal

Table 1: Cost Performance of the Equal Policies when v =w and n=5

$\nu = \omega$	1	2	3	4	5	5.5	6	7
$(c_{ef} - c)/c$	0%	1.0%	2.4%	3.5%	4.5%	4.9%	5.3%	5.9%

policies in comparison to the optimal for a wide variety of increasing density functions. For the cases tested ($n = 2, ..., 50,\ \nu = 2, ..., 20$), the cost increase of equal fractile policy from the optimal is bounded by 0.404%, while the equal space policy can have up to 5.5% cost increase from the optimal. It shows that the equal fractile policy dominates the equal space policy and it is a very good heuristic when $f(\cdot)$ is increasing.

When the customer preference distribution is symmetric ($\nu = \omega$), c_{es} and c_{ef} are equal and independent of ν and ω. Since c_{es} and c_{ef} stay at the optimal cost value c for the uniform distribution, the optimal cost for non-uniform symmetric distributions is smaller than that for the uniform distribution. Table 1 shows that the cost difference between the equal policies and the optimal becomes larger when v and ω increases. This means that the two equal policies perform better when customers are more heterogeneous, i.e., $f(\cdot)$ is flatter.

For general customer preference distributions, the cost of either policy can be lower than that of the other policy depending on the shape of the distribution. Recall that it is optimal to place the highest-specification product θ_n at the top of the product space only if $f(\cdot)$ is non-decreasing. When the customer preference distribution has a long and light right tail, forcing $\theta_n = 1$ is much more detrimental to the equal fractile policy than to the equal space policy, because the cost for satisfying the last $1/n$ fractile of the customers is too high. The search of the optimal θ_n is then critical if the equal fractile policy is to be implemented. Alternatively, we can just cut off the long and light right tail of the distribution and place the last product at θ_n such that $f(\theta_n) = \varepsilon$, where $\varepsilon > 0$ is a small threshold.

4.3 The Optimal Number of Initial Base Product Variants

Proposition 5 *For uniform customer preference distribution* ($\nu = \omega = 1$)*, the optimal number of initial product variants* $n = \sqrt{c_1' D/(2K)}$ *and the corresponding profit is* $[p_0 - c_0' + (a - c_1)/2]D - \sqrt{2c_1' DK}$.

Since n is an integer, the true optimal n^* could be either one of the two consecutive integers between which $\sqrt{c_1' D/(2K)}$ lies. Higher marginal cost of product differentiation (c_1) and customization (c_3) and lower fixed cost K result in more initial product variants. The result resembles the well-known economic order quantity (EOQ) solution, which models the trade-off between the fixed cost K per product variant and the cost of delayed customization. The number of initial product variants n corresponds to the order frequency in the EOQ model. The production quantity for each variant $s = D/n = \sqrt{2KD/c_1'}$ corresponds to the economic order quantity.

Note that $p_0 - c_0' + (a - c_1)/2$ can be regarded as the unit profit from the average customer at $x = 1/2$. And $c_1' D/(2n)$ is the cost adjustment for the final customization. Similar to the EOQ model, the optimal cost adjustment $c_1' D/(2n) = \sqrt{c_1' DK/2}$ equals the optimal fixed cost, which is an increasing concave function of the parameters. The optimal number of product variants is robust in a sense that if n is off the optimal, say by 50%, the resulting cost is only about 8% higher than the optimal. Thus this result has significant managerial implications: large errors in the number of initial product variants lead to relatively small cost penalties as long as the optimal product specification is used, which is the equal space policy in this case.

4.4 Incremental Pricing Scheme

Many companies use an incremental pricing scheme instead of complete first-degree price discrimination for ease of implementation. Customers are segmented into different groups. Prices for the customized products are the same within one group but are different across groups.

A natural way of segmenting the customers is to group customers according to the initial base product. Recall that all customers $x \in (\theta_{i-1}, \theta_i]$ are satisfied based on the same initial product θ_i. The prices for customer $x \in (\theta_{i-1}, \theta_i]$ would simply be $p_0(\theta_{i-1}) = p_0 + a\theta_{i-1}$. Since the disutility function is one directional, the pricing scheme is incentive compatible (no arbitrage) to all customers.

For uniform customer preference distribution, the equal space and equal fractile policy is still optimal. The optimal number of initial products variants is $n = \sqrt{(a + c_1')D/(2K)}$ and the optimal profit is $[p_0 - c_0' - (a + c_1)/2]D - \sqrt{2(a + c_1')DK}$. Comparing with Proposition 5, we can see that the number of initial product variants increases and the total profit is reduced due to the lost profit of first-degree price discrimination.

4.5 The EOQ and the Equal Fractile Policy Heuristic

For customer preference distribution with increasing density function f, the combination of the above EOQ-type solution n_{EOQ} and the equal fractile policy (termed EE for EOQ and equal fractile) can perform very close to the true optimal. Let C_{EE} be the cost of using the EE heuristic: $n_{EOQ} = \sqrt{c_1' D/(2K)}$ combined with the equal fractile policy. The cost difference with the optimal can then be written as $C_{EE} - C_{opt} = (C_{EE} - C_{opt}^{EOQ}) + (C_{opt}^{EOQ} - C_{opt}) = \epsilon_{ef} + \epsilon_{EOQ}$, where C_{opt}^{EOQ} is the cost of using the optimal product spacing policy for fixed n_{EOQ} number of initial base products. Therefore, ϵ_{ef} represents the deficiency of the equal policy and ϵ_{EOQ} represents the deficiency of the EOQ solution. We have seen that both ϵ_e and ϵ_{EOQ} are very small, thus the EE heuristic is close to the optimal solution.

5 Mass Customization vs. Mass Production

In this section, we first derive the optimal pricing and product design decisions for the mass production system in Subsection 5.1. In Subsection 5.2, we compare the two manufacturing systems — mass customization and mass production.

5.1 Pricing and Product Design Problems in Mass Production

Mass produced products are often mass distributed and sold in an open market. The sales price of a particular product must be the same to different customers. Essentially, the customer preference distribution is known, yet individual customer's type is unobservable to the manufacturer. Customization therefore is not an option. Each customer buys the product that maximizes her utility. In the following analysis, we assume uniform customer preference distribution ($\nu = \omega = 1$). The three decisions n, θ_i, and p_i for the manufacturer can be solved in reverse orders.

Lemma 2 *The optimal price for product i is $p_i = \max(p_0 + a\theta_{i-1} - \lambda\Delta_i, (p_0 + a\theta_i + c_0 + c_1\theta_i)/2)$, where $\Delta_i = \theta_i - \theta_{i-1}$, $\forall\ i = 1, ..., n$.*

Denote $\epsilon_i = (p_0 + a\theta_i + c_0 + c_1\theta_i)/2 - (p_0 + a\theta_{i-1} - \lambda\Delta_i)$. When the product margin is low enough ($\epsilon_i > 0$), only a fraction of the customer segment covered by product θ_i will make a purchase. The firm thus leverages monopoly pricing to rule out less profitable customers and only serves high margin customers within that segment. On the other hand, when the product margin is high ($\epsilon_i \leq 0$), the demand function is inelastic and every customer in the segment will make a purchase.

Jiang and Lee (2002) conclude that it is always optimal to place the initial base product at the top of the product space if a single base product variant is provided to customers with non-decreasing preference distribution, whether or not the whole market is covered. Therefore, it is easy to see that uncovered customers, if exist, will be clustered at the bottom of the customer space $[0, \underline{\theta}_R]$ where $\underline{\theta}_R < \theta_1$, and all customers above $\underline{\theta}_R$ will make a purchase ($\epsilon_i \leq 0$ for $i = 2, ..., n$). The following study then focus on the case of $\underline{\theta}_R \leq 0$, i.e., the whole market is covered. The manufacturer's profit function is

$$\left\{ \sum_{i=1}^{n} \int_{x=\theta_{i-1}}^{\theta_i} \left[p_0 + a\theta_{i-1} - \lambda\Delta_i - (c_0 + c_1\theta_i)\right] Df(x)dx \right\} - Kn$$

$= \left\{ \sum_{i=1}^{n} \int_{x=\theta_{i-1}}^{\theta_i} \left[(p_0 + a''x) - (c_0 + c_1''\theta_i) - a''(x - \theta_{i-1}) \right] Df(x)dx \right\} - Kn$, where $a'' = a + \lambda$ and $c_1'' = c_1 + \lambda$.

In comparison to the mass customization system profit function, the term $a''(x - \theta_{i-1})$ can be interpreted as an "information rent" the manufacturer must grant to customer x. The information rent decreases from the highest customer type to the lowest in each segment covered by product θ_i.

Proposition 6 *Under a uniform customer preference distribution, i) the equal space policy and the equal fractile policy are equivalent and optimal;*

ii) The optimal number of product variants is $n_p = \sqrt{(a'' + c_1'')D/(2K)}$ *and the corresponding profit is* $[p_0 - c_0 + (a - c_1)/2]D - \sqrt{2(a'' + c_1'')DK}$.

The form of the optimal number of product variants is the same as that of the mass customization case except that c_1' (or $a + c_1'$ under incremental pricing) is substituted with $(a'' + c_1'')$. Again, the true optimal n_p^* could be one of the two consecutive integers between which $\sqrt{(a'' + c_1'')D/(2K)}$ lies.

5.2 Comparison of Mass Customization with Mass Production

Let Δ be the profit difference between the optimal mass customization system and the optimal mass production system, i.e., $\Delta = \sqrt{2DK}(\sqrt{c_1 + a + 2\lambda} - \sqrt{c_1 + c_3}) - c_2 D$.

Proposition 7 *The mass customization system outperforms the mass production system if and* *only if* $\sqrt{c_1 + a + 2\lambda} > c_2\sqrt{D/(2K)} + \sqrt{c_1 + c_3}$*; otherwise, mass production is better.*

When $c_2 = 0$, mass customization dominates mass production if and only if $a + 2\lambda > c_3$ (Figure 2). Notice that mass customization system could be beneficial even if the cost of customization is bigger than the cost of disutility, i.e., $c_3 > \lambda$. This implies that customization is indeed a strategy for a company to gain the surplus that previously belong to the customers.

Defining $c_2\sqrt{D/(2K)} + \sqrt{c_1 + c_3}$ as the effective cost of mass customization and $\sqrt{a + c_1 + 2\lambda}$ as the effective cost of mass production, we can see that the mass customization system improves in comparison to the mass production system when the fixed cost of each initial product variant K, or the customer reservation price slope a, or the slope of disutility function λ increases. Mass production is more attractive relative to mass customization when customization costs (c_2 and c_3) are high. As the overall market demand D increases, mass production eventually outperforms mass customization if $c_2 > 0$ (Figure 2).

Since the number of initial product variants is $n = \sqrt{(c_1 + c_3)D/(2K)}$ for the mass customization system and $n_p = \sqrt{(a + c_1 + 2\lambda)D/(2K)}$ for the mass production system, $n_p > n$ if and only if $a + 2\lambda > c_3$. As mass customization dominates mass production if and only if $a + 2\lambda > c_3$ (when $c_2 = 0$), it means that a superior mass customization system actually reduces the initial number of base product variants compared to a mass production system. Even though mass customization introduces tremendous amount of product variety in finished goods, an efficient customization system actually requires less initial base product variants than a mass production system. Standardization, therefore, could be an effective strategy to mitigate the negative effects of customization on supply chain operations. The recent trend on "crossover vehicles" and proliferation of car models indeed reward companies like Toyota, Volkswagen and Honda, who excel at incorporating shared components among different models (Business Week 2002a).

Replacing $\sqrt{c_1 + c_3}$ with $\sqrt{a + c_1 + c_3}$ in Proposition 7, we can conclude the comparisons under incremental pricing for the mass customization system. Particularly when $c_2 = 0$, mass customization is better than mass production if and only if $2\lambda > c_3$. Thus, companies can gain extra surplus from customization even first-degree price discrimination is not used.

6 Managerial Insight

A mass customization system can be decoupled into two stages. The mass stage originates from an initial mass produce-to-stock phase, followed by the customization stage at which an individual order is customized and delivered. We find that an equal space (equal product specification distance between two adjacent initial products) and equal fractile policy (each product covers equal amount of demand) for initial base product specifications are optimal under uniform customer preference distribution. The optimal product space and fractile spectrum have monotonic properties for general customer preference distributions. An EOQ type of solution for the number of initial base product variants is optimal under uniformly distributed customers. Consequently, a practical product offering strategy is to use an EOQ type of solution to decide the number of initial base product variants to offer and the equal fractile policy to decide product specifications. This easy-to-implement strategy performs very well for non-decreasing beta distribution of customer preferences.

Many companies are facing a strategic decision of whether and how to move from a mass production system to a mass customization system in face of increasingly more diversified customer preferences. Customization could be the advantage of U.S. manufacturers in competition with the low-cost overseas manufacturers, because the U.S. companies are close to the market and know customers' preferences better.

Under the upside-linear disutility function, we analyzed when mass customization outperforms mass production. We showed that mass customization is better than mass production if and only if the effective customization cost $c_2\sqrt{D/(2K)} + \sqrt{c_1 + c_3}$ (or $c_2\sqrt{D/(2K)} + \sqrt{a + c_1 + c_3}$ under incremental pricing) is smaller than the effective mass production cost $\sqrt{a + c_1 + 2\lambda}$. Under a superior mass customization system, the optimal number of initial product variants is actually reduced. This may partially explain why companies such as Toyota and Volkswagen are reducing their number of component modules while increasing final product variety to satisfy individual customer requirement.

GE's restructure of their Spectra RMS circuit breaker product family is another case of mass customization through postponement and component modularity. As a result, the initial number of base product variants is indeed reduced to four. The company now makes only four frame sizes: E, F, G and K. The maximum overload currents are 150 amps, 250amps, 600amps and 1200amps, respectively.

In future research, we propose to analyze more general types of consumer disutility functions and multi-dimensional customer preference. For example, we can consider another factor that may affect customers' utility function — waiting time for a custom product. In addition, the downward product substitution problem under stochastic demand is also worth investigating within our general framework.

Appendix

1. Proof of Lemma 1

i) When $\nu \geq \omega = 1$, taking derivative of the profit function regarding θ_n, we have

$$f(\theta_n)[p_0 - c_0' + (a - c_1)\theta_n] - c_1'[F(\theta_n) - F(\theta_{n-1})]$$

$$= f(\theta_n)[p_0 - c_0' + (a - c_1)\theta_n] - c_1' f(\underline{\zeta})(\theta_n - \theta_{n-1})$$

$$\geq f(\theta_n)[p_0 - c_0' + (a - c_1)\theta_n] - c_1' f(\theta_n)(\theta_n - \theta_{n-1})$$

$$= f(\theta_n)[p_0 + a\theta_n - c_0' - c_1\theta_n - (c_1 + c_3)(\theta_n - \theta_{n-1})]$$

$$= f(\theta_n)[p_0 + a\theta_{n-1} - c_0' - c_1\theta_n - c_3(\theta_n - \theta_{n-1}) + (a - c_1)(\theta_n - \theta_{n-1}) \geq 0,$$

where $\theta_{n-1} < \underline{\zeta} < \theta_n$ is based on the Lagrangian Theorem. Thus $f(\underline{\zeta}) \leq f(\theta_n)$. The last inequality holds because the company collects a non-negative profit on sales to customer $x = \theta_{n-1}$ based on the base product θ_n, i.e., $p_0 + a\theta_{n-1} - c_0' - c_1\theta_n - c_3(\theta_n - \theta_{n-1}) \geq 0$.

ii) A direct result from i).

2. Proof of Proposition 1

The first-order condition w.r.t. θ_i is $F(\theta_i) - F(\theta_{i-1}) + f(\theta_i)(\theta_i - \theta_{i+1}) = 0$ for $i = 1, ..., n-1$. When $\nu = \omega = 1$, it becomes $2\theta_i - \theta_{i-1} - \theta_{i+1} = 0$. We also know that $\theta_0 = 0, \theta_n = 1$. Thus $\theta_i = F(\theta_i) = i/n$, $i = 1, ..., n$. It is straightforward to verify that the Hessian matrix H is positive definite ($x^{\intercal} H x > 0$, $\forall x \in R$, $x \neq 0$) thus FOC is sufficient for global optimal.

3. Proof of Proposition 2

When $\nu > \omega = 1$, $F(x) = x^{\nu}$. Using the FOC, the result can be obtained. It is also easy to check that $\partial^2 c/\partial\theta_i^2 > 0$ at the point where FOC is satisfied.

4. Proof of Proposition 3

Applying the Lagrangian Theorem to FOC $F(\theta_i)-F(\theta_{i-1})+f(\theta_i)(\theta_i-\theta_{i+1})=0$, we get $f(\underline{\zeta})(\theta_i-\theta_{i-1})+f(\theta_i)(\theta_i-\theta_{i+1})=0$,where $\theta_{i-1}<\underline{\zeta}<\theta_i$. Hence, $\Delta_{i+1}/\Delta_i=(\theta_{i+1}-\theta_i)/(\theta_i-\theta_{i-1})=f(\underline{\zeta})/f(\theta_i)<1$ when $f(\cdot)$ is increasing. Similarly, $F(\theta_i)-F(\theta_{i-1})-f(\theta_i)[F(\theta_{i+1})-F(\theta_i)]/f(\overline{\zeta})=0$, where $\theta_i<\overline{\zeta}<\theta_{i+1}$. Thus, $\Delta F_{i+1}/\Delta F_i=[F(\theta_{i+1})-F(\theta_i)]/[F(\theta_i)-F(\theta_{i-1})]=f(\overline{\zeta})/f(\theta_i)>1$.

5. Proof of Proposition 4

i) When $\nu>\omega=1$, $F(x)=x^\nu$, thus $f(x)=\nu x^{\nu-1}$ and $F^{-1}(y)=y^{1/\nu}$. Therefore, $c_{es}=c_1'[1-(\frac{1}{2})^{1+\nu}]$, $c_{ef}=c_1'[\frac{1}{2}+(\frac{1}{2})^{1+\frac{1}{\nu}}]$, and $\Delta c=c_{es}-c_{ef}=\frac{1}{2}c_1'[1-(\frac{1}{2})^{\frac{1}{\nu}}-(\frac{1}{2})^\nu]$.

To have $\Delta c\geq 0$, we need to show $(\frac{1}{2})^{\frac{1}{\nu}}+(\frac{1}{2})^\nu\leq 1$. It is easy to see that equality holds when $\nu=1$ or $\nu\to\infty$. Let $g(\nu)=(\frac{1}{2})^{\frac{1}{\nu}}+(\frac{1}{2})^\nu$. Its derivative is $g'(\nu)=(2^{-\frac{1}{\nu}}\frac{1}{\nu^2}-2^{-\nu})\ln 2=\frac{2^{-\nu-\frac{1}{\nu}}}{\nu^2}(2^\nu-\nu^2 2^{\frac{1}{\nu}})\ln 2$. Let $h(\nu)=2^\nu-\nu^2 2^{\frac{1}{\nu}}$. Then $h'(\nu)=2^\nu\ln 2-2\nu 2^{\frac{1}{\nu}}+2^{\frac{1}{\nu}}\ln 2=2\nu\cdot 2^{\frac{1}{\nu}}[\frac{\ln 2}{2\nu}(2^{\nu-\frac{1}{\nu}}+1)-1]$. Let $l(\nu)=\frac{\ln 2}{2\nu}(2^{\nu-\frac{1}{\nu}}+1)-1$. Since $(2^{\nu-\frac{1}{\nu}})'=2^{\nu-\frac{1}{\nu}}(1+\frac{1}{\nu^2})\ln 2>0$, thus $2^{\nu-\frac{1}{\nu}}\uparrow$. We discuss the value of $g(\nu)$ on different intervals.

(a) $\nu\in[1,\frac{3}{2}]$ We know $l(\nu)\leq\frac{\ln 2}{2\nu}(2^{\frac{3}{2}-\frac{2}{3}}+1)-1<\frac{0.9641}{\nu}-1<0$. Thus $h'(\nu)<0$. Since $h(1)=0$, therefore $h(\nu)\leq 0$. Hence, $g'(\nu)\leq 0$. As $g(1)=1$, then $g(\nu)\leq 1$.

(b) $\nu\in[\frac{3}{2},2]$ Similarly, $l(\nu)\leq\frac{\ln 2}{2\nu}(2^{2-\frac{1}{2}}+1)-1<\frac{1.3269}{\nu}-1<0$. Thus $h'(\nu)<0$. Since $h(\frac{3}{2})<0$, therefore $h(\nu)<0$. Hence, $g'(\nu)<0$. As $g(\frac{3}{2})<0.9836<1$, then $g(\nu)<1$.

(c) $\nu\in[2,2.4]$ Since $(\frac{1}{2})^{\frac{1}{\nu}}\uparrow$ and $(\frac{1}{2})^\nu\downarrow$, $g(\nu)<(\frac{1}{2})^{\frac{1}{2.4}}+(\frac{1}{2})^2<0.9992<1$.

(d) $\nu \in [2.4, e]$ Similarly, $g(\nu) < (\frac{1}{2})^{\frac{1}{e}} + (\frac{1}{2})^{2.4} < 0.9644 < 1$.

(e) $\nu \in [e, 4]$ $g(\nu) < (\frac{1}{2})^{\frac{1}{4}} + (\frac{1}{2})^{e} < 0.9929 < 1$.

(f) $\nu \in [4, 5]$ $g(\nu) < (\frac{1}{2})^{\frac{1}{5}} + (\frac{1}{2})^{4} < 0.9331 < 1$

(g) $\nu \in [5, +\infty]$ Let $z(\nu) = 2^{\nu} - 2^{\frac{1}{5}}\nu^2$. Then $z'(\nu) = 2^{\nu}\ln 2 - 2^{\frac{6}{5}}\nu$ and $z''(\nu) = 2^{\nu}\ln^2 2 - 2^{\frac{6}{5}}$. Since $z''(5) > 0$, thus $z''(\nu) > 0$. As $z'(5) = 2^5 \ln 2 - 2^{\frac{6}{5}}5 > 0$, we get $z'(\nu) > 0$. Because $z(5) = 2^5 - 2^{\frac{1}{5}}5^2 > 0$, we have $z(\nu) > 0$. Since $2^{\frac{1}{\nu}} \downarrow$, therefore $2^{\nu} - \nu^2 2^{\frac{1}{\nu}} > 2^{\nu} - 2^{\frac{1}{5}}\nu^2 = z(\nu) > 0$. Hence, $g'(\nu) > 0$. Since $g(\nu) \to 1$ as $\nu \to +\infty$, we claim $g(\nu) \leq 1$.

In conclusion, we get $c_{es} \geq c_{ef}$ when $\omega = 1$ and $\nu \geq 1$ for the case of $n = 2$. Equality holds when $\nu = \omega$ or $\nu \to +\infty$.

ii) $c_{es} = \frac{c_1'}{n} \sum\limits_{i=1}^{n} i[F(\frac{i}{n}) - F(\frac{i-1}{n})] = \frac{c_1'}{n}\left(n - \sum\limits_{i=1}^{n-1} F(\frac{i}{n})\right) = \frac{c_1'}{n}\left(n - \frac{n-1}{2}\right) = \frac{c_1'(n+1)}{2n}$. (By the symmetry of beta distribution when $\nu = \omega$, $F(\frac{n-i}{n}) + F(\frac{i}{n}) = 1$ for $i = 1, ..., n-1$.)

$c_{ef} = \frac{c_1'}{n} \sum\limits_{i=1}^{n} F^{-1}(\frac{i}{n}) = \frac{c_1'}{n}\left(\sum\limits_{i=1}^{n-1} F^{-1}(\frac{i}{n}) + 1\right) = \frac{c_1'}{n}\left(\frac{n-1}{2} + 1\right) = \frac{c_1'(n+1)}{2n}$. (By the symmetry of beta distribution when $\nu = \omega$, $F^{-1}(\frac{i}{n}) + F^{-1}(\frac{n-i}{n}) = 1$ for $i = 1, ..., n-1$.)

Therefore, $c_{es} = c_{ef} = (1 + 1/n)c_1'/2$.

iii) Let F_2 be the c.d.f. of the beta distribution with parameters ν' and ω'.

$c_{es}' = \frac{c_1'}{n} \sum\limits_{i=0}^{n} [1 - F_2(\frac{i}{n})] = \frac{c_1'}{n} \sum\limits_{i=0}^{n} F(\frac{i}{n})$ (Since $F(\cdot)$ and $F_2(\cdot)$ are reflective about the point $(\frac{1}{2}, \frac{1}{2})$, $1 - F_2(\frac{i}{n}) = F(\frac{n-i}{n})$ for $i = 1, ..., n$.)

$c_{ef}' = \frac{c_1'}{n} \sum\limits_{i=0}^{n} F_2^{-1}(\frac{i}{n}) = \frac{c_1'}{n} \sum\limits_{i=0}^{n} [1 - F^{-1}(\frac{i}{n})] = \frac{c_1'}{n}[(n+1) - \sum\limits_{i=0}^{n} F^{-1}(\frac{i}{n})]$ (Since $F(\cdot)$ and $F_2(\cdot)$

are reflective about the point $(\frac{1}{2}, \frac{1}{2})$, $F_2^{-1}(\frac{i}{n}) = 1 - F^{-1}(\frac{n-i}{n})$ for $i = 1, ..., n$.)

$c_{es} > c_{ef}$ if and only if $(n+1) - \sum_{i=0}^{n} F(\frac{i}{n}) > \sum_{i=0}^{n} F^{-1}(\frac{i}{n})$, and consequently if and only if $c'_{es} < c'_{ef}$.

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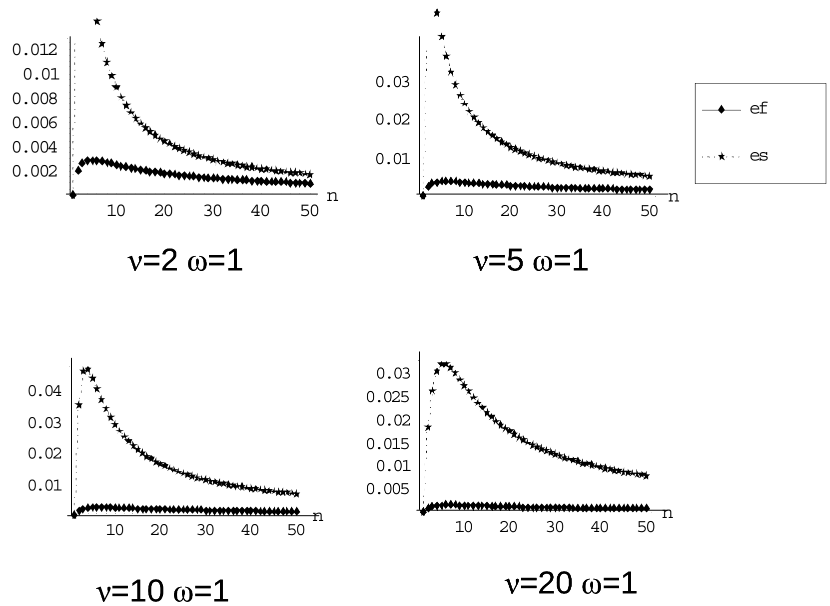

Figure 1: Comparison of Equal Fractile Policy and Equal Space Policy ($\omega = 1$)

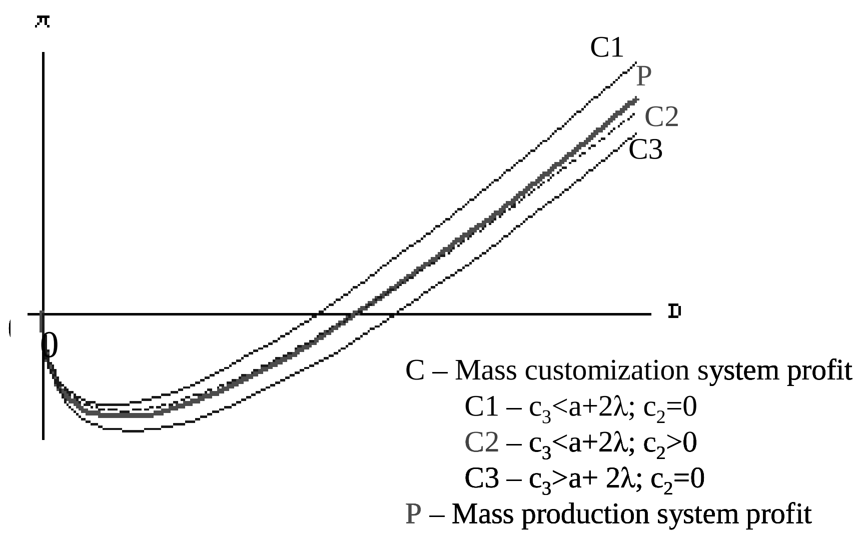

Figure 2: Comparison of Mass Customization with Mass Production