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Product-Line Competition: Customization vs. Proliferation

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We study a market with customers who have heterogeneous preferences for product attributes. We consider two types of firms that compete on price and product variety: A *traditional* firm, which chooses a limited set of product configurations, and a *customizing* firm, which can produce any configuration to order. The traditional firm carries product inventories and experiences a lead-time delay. The customizing firm does not carry inventory, and its customers incur waiting costs until they receive their orders. We assume that the customizing firm has limited capacity in the short run (e.g., when it does not outsource production to high-volume manufacturers). We derive the equilibrium for a duopoly competition between the customizing firm and the traditional firm, study its characteristics, and compare it to a monopoly. We characterize conditions that favor customization under competition. We find that the customizing firm's profit is *not* monotone in the market size and its ease of customization. Similarly, a decline in the traditional firm's holding cost may increase or decrease its profit. We show that the unit cost differential between the firms crucially affects the customizing firm's ideal market size, its returns from expanding capacity, its product variety, and the way operational improvements affect its performance.

Key words: mass customization; product strategy; pricing; operations-marketing interface
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1. Introduction

Consumers are increasingly demanding products that closely match their individual preferences, and advances in manufacturing and information technologies make it possible to satisfy this demand. Traditional firms respond to the demand for variety by proliferating multiple product variants, thereby enabling consumers to find products that are close to their ideal choice.[1] An alternative approach is based on *mass customization* (MC) (Pine 1993, Feitzinger and Lee 1997, Zipkin 2001, Tseng and Piller 2003), whereby firms use a make-to-order process that gives customers exactly what they asked for by individually customizing products to their specifications. In this paper, we study the results of competition between a firm that follows the traditional approach and a mass customizing (customizing in short) firm.

There are important differences between the operations of traditional and MC firms. A traditional firm usually carries inventory and fulfills customer demand from stock. In contrast, a MC firm does not carry finished-goods inventory because it customizes to order. For example, Dell (Dell and Fredman 2000) operates with less than 4 hours of work in process inventory and practically no finished-goods inventory. There is a trade-off, however, because customers need to wait for custom orders, whereas a traditional seller can make the product immediately available from inventory.[2] We model these operational features in this paper.

Our model assumes that the MC firm has a limited capacity in the short run. An alternative assumption, whereby the MC firm has no capacity constraints, is also viable. The unlimited-capacity assumption would hold, for example, when an MC firm outsources

[1] Indeed, selection has increased significantly over time for a variety of products. For example, between the early 1970s and late 1990s, the number of distinct breakfast cereals increased from 160 to 340, the number of soft drink brands increased from 20 to 87, and the number of running shoe styles increased from 5 to 285 (Cox and Alm 1998).

[2] This delay is, for example, one of the main reasons few U.S. consumers (7% in 2000) order custom cars (Agrawal et al. 2001). Indeed, Ahlström and Westbrook's (1999) survey of manufacturing firms that adopted or were considering MC found that delay was viewed as an important shortcoming of MC.

production to high-volume manufacturers. In many situations, however, the option to outsource to high-volume manufacturers is not available or is undesirable, because MC requires higher-skilled labor, specialized business processes, special machinery, and promptness. Anderson (2004) argues that outsourcing fits the framework of traditional mass production but is problematic in the context of mass customization because "outsourcing is at odds with the inventory-less aspect of build-to-order, since outsourcing is usually a batch operation" (p. 21). Considering the effects of outsourcing on build-to-order and mass customization (BTO&MC), he concludes that "Outsourcers are unlikely to be able or willing to do BTO&MC as well as could be done internally" (p. 198). Zipkin (2001) shows that because MC imposes special requirements for information elicitation, process flexibility, and logistics, "Mass Customization actually requires unique operational capabilities" (Zipkin 2001, p. 81), which limits the ability of MC firms to outsource to high-volume manufacturers. Indeed, customization is recognized as a strategy followed by a variety of domestic industries to fight the outsourcing of production to low-cost overseas manufacturers (Keenan et al. 2004, Schuler and Buehlmann 2003, Karnes and Karnes 2000). Examples include the U.S. furniture industry (Lihra et al. 2005), the European Union apparel industry (Keenan et al. 2004), and footwear manufacturing in Finland (Sievänen and Peltonen 2006).

Limited capacity often characterizes MC firms in the short run. For example, until it builds a new factory, Dell's production capacity for custom desktop computers is bounded within each geographic region by the capacity of its factories (Anderson 2004, Dell and Fredman 2000). Custom apparel manufacturer Dolzer produces in a single facility in Germany, which determines its capacity. Boër and Dulio (2007) discuss the need to purchase new production machinery and put together new internal processes for custom shoes, as, for example, "the last of the shoe needs, in the case of custom fit, to be personalized for each customer and outsourcing its production can be very expensive" (Boër and Dulio 2007, p. 53). In contrast, many firms that do not customize use standard processes, machinery, and labor, and they can tolerate longer lead times, which facilitates outsourcing to high-volume manufacturers. In this paper, we characterize a traditional firm by unlimited capacity to make the contrast explicit.

There are, however, situations where our assumptions do not hold. In her discussion of MC, Schlosser (2004) provides examples of MC firms that keep production in house as well as others who outsource production. Unlike its desktop market, Dell outsources laptop manufacturing, giving the company greater production flexibility, and Reebok and Nike outsource the production of custom products to Confego. Thus, our assumption does not hold universally.

In our model, consumers have Hotelling-style (cf. Hotelling 1929, Lancaster 1990) heterogenous preferences for a product attribute. Our demand model is closest to Chen et al. (1998), who did not consider MC or the effect of delays. In our model, a customer evaluates a product offer by trading off price, misfit relative to her ideal point, and delay. A MC firm can customize its products to each customer's ideal point, and it chooses its unit price, which is the same for all product configurations.[3] A traditional firm chooses how many products to offer, their configurations, and its unit price, and it can reduce the average distance between its customers' ideal points and its best-matching products by increasing product variety. The traditional firm also decides on a replenishment policy for each product. We derive the equilibrium of duopoly competition between a MC and a traditional firm and study its characteristics. We solve for both firms' prices and for the traditional firm's choice of product offerings when both firms coexist (Proposition 3). Likewise, we characterize the optimal policies for a monopoly that operates either as a traditional firm or as a MC firm (Proposition 10 in Appendix A), as well as for a dual monopoly with both traditional and MC operations (Proposition 1). Our analysis enables us to study how operational and market characteristics affect the solutions and the resulting profits. For example, how does competition affect variety? What market conditions make the MC or traditional approach more profitable? How do operational improvements affect profitability? How do these depend on competitive factors?

The literature recognizes that MC is no panacea (Zipkin 2001, Agrawal et al. 2001, Ahlström and Westbrook 1999). Zipkin (2001) points out that many product markets are not attractive for MC. Pine (1993) identifies conditions under which MC is attractive vis-à-vis mass production. Indeed, there are many recent examples of firms that abandoned MC initiatives or had gone out of business selling custom products (e.g., Levi's, Reflect.com, Mattel, CMax), which makes it important to identify the conditions that make MC attractive. We characterize these conditions in terms of market size, ease of customization, and unit costs. We find that the relationship between the profitability of MC and market size is not monotone: A larger market can make MC less profitable because of the traditional competitor's scale economies. This relationship critically depends on the MC firm's unit cost

[3] In §5, we study what happens when the firms are not restricted to uniform prices, that is, when they can set a different price for each product configuration.

vis-à-vis its competitor (Proposition 6). We find that there is an ideal market size for MC and that the ideal market size decreases in the firm's cost disadvantage (Figure 1).

Contrary to one's basic intuition, we show that shorter customization times can hurt the MC firm because of its competitor's response. This is because customization delays create a degree of separation between customized and standard products, which softens price competition. When the MC firm has a weak cost position, speeding customization up reduces this separation and, with it, its profit (Proposition 7). The value of operational improvements for the traditional firm also depends on its competitive position: it benefits from improving its replenishment lead time and unit holding cost only if its unit cost vis-à-vis its competitor is sufficiently favorable (Proposition 8).

We find that custom products have a larger market share in competitive markets when the cost disadvantage of MC is large (Proposition 4). We also observe that the traditional firm competes by achieving an efficient scale for each product variant, optimally balancing the costs of inventory and customer misfit. A variant's efficient scale is determined by operational considerations and is independent of the competitor. Competitive considerations determine the number of standard product variants and their total market share rather than the efficient scale.

Our results underscore the importance of the unit cost difference between the firms as a driver of the market outcome. They suggest that operational excellence and MC are complements under competition. When we analyze the relation between the MC firm's cost disadvantage (or advantage) and its ideal market size, its returns from expanding capacity, and the effects of operational improvements, the results go in diametrically opposite directions depending on the unit cost difference between the firms. Furthermore, the traditional firm benefits from improvements in its lead time and unit holding cost only if it has a sufficiently large cost advantage.

Because our results were derived under the assumption of limited MC capacity, we examine their sensitivity to this assumption. We perform a series of numerical studies where the MC firm's capacity is determined endogenously, at a cost, and find that the above results continue to hold.

1.1. Literature Review

MC is a growing area of research. We briefly summarize the findings of earlier work that used location-based demand models and considered MC in competitive contexts.[4] Alptekinoğlu and Corbett (2008) study duopoly competition between a traditional firm and a MC firm, finding that the former can attain positive profit even with a cost disadvantage. Mendelson and Parlaktürk (2008) study duopoly competition where each firm decides whether to sell a (single) standard product or a custom product. Dewan et al. (2003) consider two symmetric firms offering a (single) standard product and a range of custom products in a circular market, showing that a firm can deter entry by overcustomizing its product in a sequential entry game. Syam et al. (2005) also consider two symmetric firms that can customize two attributes, and they study which attributes are customized in equilibrium, finding that either both firms choose not to customize any attribute or both customize one (the same) attribute. The assumption of equal (zero) unit costs, which leads to symmetric strategies, is critical in Dewan et al. (2003) and Syam et al. (2005). The above literature focused on firms' product and pricing decisions without considering two important operational characteristics: inventory fulfillment and queuing delays. In this paper, we explicitly model both operational features, incorporating the stocking of standard products and the make-to-order nature of custom products (which entails queuing delays), in addition to product variety and pricing. For a monopoly, Alptekinoğlu and Corbett (2007) also incorporate similar elements, and they identify the customer segments served by each product type.

Xia and Rajagopalan (2006) study duopoly competition where each firm can choose to sell either standard or custom products, and they also incorporate customization delay using a different approach from ours. Unlike our model, their customizing firm has no capacity constraints and its customization delay is deterministic, so it is independent of congestion or utilization (as discussed earlier, there are settings where this assumption is reasonable). They also do not model the fulfillment of standard products, which do not incur holding costs in their model. Modeling these elements allows us to generate insights on the effects of market and firm operational characteristics on the firms' profitability (e.g., Propositions 6–8). On the other hand, Xia and Rajagopalan (2006) analyze the firms' market-entry decisions, which we do not.

The differences between the two models also lead to diametrically opposite results. In Xia and Rajagopalan (2006), the traditional firm offers only *one* product variant in equilibrium when the customizing competitor is present. In contrast, the traditional firm offers *multiple* products in our model. Furthermore, similar to Alptekinoğlu and Corbett (2008), Xia and Rajagopalan (2006) find that the traditional firm offers less product variety when competing against a customizing firm compared to a standard monopoly.

[4] Jiang et al. (2006) consider MC in a monopoly context.

We find that a traditional firm can offer fewer or more product variants than a *dual* monopoly, depending on the firms' operating costs. Furthermore, we find that even a costless capacity improvement may adversely affect the MC firm's profit. In contrast, a costless shorter lead time in Xia and Rajagopalan (2006) always increases the customizing firm's profits.

Our base model restricts the firms to uniform prices as in Alptekinoğlu and Corbett (2008), Syam et al. (2005), and Xia and Rajagopalan (2006). However, Piller and Stotko (2002), Riemer and Totz (2003), Wind and Rangaswamy (2001), Mendelson and Parlaktürk (2008), Jiang et al. (2006), and Dewan et al. (2003) show that it is also valuable to consider the role of price customization. In §5, we briefly discuss what happens when each firm can set a different price for each product configuration (the detailed analysis is in the online supplement, which is provided in the e-companion).[5]

Beyond MC, there is a rich and diverse literature on product variety (Lancaster 1990, Ho and Tang 1998, Yano and Dobson 1998). A large branch of this literature examines the problem from the supply side, studying how firms cope with product variety and how it affects performance (Zipkin 1995, Lee and Tang 1997, Swaminathan and Tayur 1998, Thonemann and Bradley 2002). Another branch focuses on the demand side (Shocker and Srinivasan 1979, Green and Krieger 1985). Chen et al. (1998) derive an algorithm for computing the optimal product line, and De Groote (1994) studies the coordination between a firm's product line, determined by its marketing division, and its process flexibility, determined by its manufacturing division. There is also a rich literature on make-to-order vs. make-to-stock production. Some examples are Rajagopalan (2002) and Dobson and Yano (2002). Papers in this stream usually take the firm's product line as given and determine which items should be made to order or to stock. An exception is Netessine and Taylor (2007), who also consider quality choice by a monopoly. They find that whereas information asymmetry always leads to distortions from the efficient product line in make-to-order production, with make-to-stock these distortions can be eliminated. A number of papers find, as we do, that greater capacity or superior technology can hurt a firm under competition. For example, Carr et al. (2002) show that, when competing firms have stochastic variability in their capacities, reducing variability or increasing the mean capacity can hurt the firm because it increases the intensity of price competition. Balasubramanian (1998) finds that, for a direct seller

Table 1 Notation and Parametric Assumptions

Symbols	Assumptions
Θ: Product space	$\Theta = [0, 1]$
θ: Customer type	$\theta \in \Theta$
ζ: Product type	$\zeta \in \Theta$
w: Reservation value	$w > \dfrac{3\gamma r}{2} + c_t$
r: Intensity of customer preferences	$r > 0$
c: Unit cost	$\left(2\gamma - \dfrac{1}{2}\right) r - \dfrac{v(\mu-\gamma\lambda)}{(\mu-\lambda(1-\gamma))^2} < c_c - c_t < \dfrac{3\gamma r}{2} - \dfrac{v(\mu-\lambda)}{\mu^2}$
p: Unit price	
λ: Total demand rate	$\lambda > 0$
μ: Customization rate	$\mu > \lambda$
v: Customer sensitivity to delay	$v > 0$
W: Waiting time for a product	
S: Fixed order cost	$S > 0$
h: Unit holding cost	$h > 0$
l: Order lead time	$l \geq 0$
γ: Efficient scale for a standard product	$\gamma \leq 1/4$
Q^*: Optimal order quantity	
k: Safety stock factor	
Π: Expected profit rate	

competing against mass marketers, under certain conditions the direct seller will target only a fraction of the market even if it is costless to target the entire market.

In the remainder of this paper, we present our model in §2, discuss the monopoly benchmarks in §3, and study the competition between a traditional firm and a MC firm in §4. In §5 we discuss extensions to our model, and our concluding remarks are in §6. All proofs are in the online supplement.

2. Model

We consider a market with customers who have heterogenous preferences for product attributes. Similar to Chen et al. (1998) and De Groote (1994), we model the product space $\Theta = [0, 1]$ using a Hotelling line (cf. Hotelling 1929, Lancaster 1990), with each product $\zeta \in \Theta$ characterized by its location on the unit line segment.[6] This can represent, for example, the size or color of a piece of apparel. We consider two types of firms, a *traditional* firm that sells standard products and a *mass-customizing* firm that sells individually customized products. Each firm maximizes its expected profit. In the remainder of this section, we specify our demand model and describe the firms' operations. Our notation and parametric assumptions are summarized in Table 1.

[5] An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

[6] This is also known as horizontal or spatial differentiation (cf. Tirole 1988). See Lancaster (1979) for a discussion of mapping location models to characteristics spaces.

2.1. Customer Choice

Customers trade off price, disutility of waiting, and disutility of sacrifice from the ideal product in their decision making. Specifically, when a type-θ customer buys a product configuration ζ, her utility is equal to

$$U(\theta,\zeta,p,W)=w-p-r|\zeta-\theta|-vW, \quad \theta,\zeta\in\Theta, \quad (1)$$

where the reservation price $w>0$ is the customer's willingness to pay for her ideal product. The customer's utility then decreases by p, the product's unit price, and by $r|\zeta-\theta|$ because of the disutility of misfit relative to her ideal choice, where $r>0$ is the intensity of customer preference and $|\zeta-\theta|$ is the distance from her ideal choice. The customer can avoid the latter by buying the product customized exactly for her ideal configuration, i.e., $\zeta=\theta$. Finally, the customer's utility also decreases by vW because of the disutility of delay, where W is the delay and $v>0$ is the customers' sensitivity to delay. Customers incur delays waiting either for a custom product or for a backordered standard product.

We assume that the firms do not make their state information available to customers: Similar to Van Ryzin and Mahajan (1999) and Cachon and Harker (2002), customers do not observe the queue length of the customizing firm and the inventory position of the traditional firm. Thus, the customer makes her decision based on the average delay to maximize her expected utility. We derive the average delays in the following.

Customers arrive to the market according to a Poisson process with rate, or demand intensity, λ, and they differ only in their ideal products $\theta\in\Theta$. In particular, their ideal product types are uniformly distributed on Θ, independent of the arrival process. Upon arrival, the customer observes the product offerings (prices and types) and decides whether to buy a product and what product to buy. If buying a product (standard or customized) yields nonnegative utility, the customer purchases one unit of the product that gives her the highest utility. Let $\Theta_c, \Theta_i\subset\Theta$ be the sets of customer types who buy a customized product and standard product i, respectively. Then,

$$\Theta_c=\Big\{\theta\in\Theta\colon w-p_c-v\mathbb{E}[W_c] \geq \max\Big(\max_j[w-p_j-v\mathbb{E}[W_j]-r|\zeta_j-\theta|],0\Big)\Big\}. \quad (2)$$

Similarly,

$$\Theta_i=\Big\{\theta\in\Theta\colon w-p_i-r|\zeta_i-\theta|-v\mathbb{E}[W_i] > \max\Big(\max_{j\neq i}[w-p_j-r|\zeta_j-\theta|]-v\mathbb{E}[W_j],\; w-p_c-v\mathbb{E}[W_c]\Big) \text{ and } w-p_i-r|\zeta_i-\theta|-v\mathbb{E}[W_i]\geq 0\Big\}. \quad (3)$$

Here, we adopt the convention that, when a customer is indifferent between two products, she breaks the tie in favor of the socially efficient outcome, buying the product customized for her type, and similarly she buys a product when she is indifferent to not buying. Because the customer types and the arrival process are independent, the arrival sequence of customers who buy customized products form a Poisson process with rate λ_c; similarly, customers who buy standard product variant i form a Poisson process with rate λ_i. Clearly, λ_c and λ_i are determined by the product offers in the market and by λ. Specifically,

$$\lambda_c=\lambda\int_{\theta\in\Theta_c}d\theta \quad \text{and} \quad \lambda_i=\lambda\int_{\theta\in\Theta_i}d\theta \quad \text{for } i\colon 1,\ldots,n. \quad (4)$$

Note that Equations (2)–(4) depend on each other as the expected delays $\mathbb{E}[W_i]$, $\mathbb{E}[W_c]$ are functions of the demand rates λ_i, λ_c.

2.2. Mass-Customizing Firm

A MC firm customizes its product to each configuration $\theta\in\Theta$. It sets a unit price p_c and incurs unit cost c_c. In our main model both the MC and the traditional firms are restricted to uniform prices, and in the online supplement we also study what happens when they can set a different price for each product type (see §5 for a brief discussion).

The MC firm customizes to order and does not carry inventory. Customer orders are queued, and the firm fulfills them on a first-come-first-served basis. Specifically, customization times are exponentially distributed with rate μ, which reflects the ease of customization and the firm's customization capacity. As shown in the discussion of customer choice, the demand for customized products follows a Poisson process with rate λ_c; hence, the MC firm is characterized by an M/M/1 queue. Therefore, the average delay for a customized product is

$$\mathbb{E}[W_c]=1/(\mu-\lambda_c). \quad (5)$$

The customization capacity is exogenous in our main model; i.e., it cannot be changed within the timescale of our model. In §5, we discuss what happens when the customizing firm can choose its capacity.

2.3. Traditional Firm

The traditional firm offers a limited variety of standard products. It decides its unit price p_t, how many products to offer n, and their configurations $\zeta_i\in\Theta$ for $i\colon 1,\ldots,n$. Once the firm determines its product offers, it outsources the production to a supplier with replenishment lead time l, and it replenishes its stocks at a fixed cost S per order at unit cost c_t. For each unit in stock, the firm also incurs inventory holding cost h per unit time. The traditional firm is considered to have unlimited supply.

The firm applies a continuous inventory review policy for each product variant, where it follows a (Q, R) policy: The firm determines the replenishment batch size Q_i for each product variant i, and it orders Q_i units whenever its inventory position falls below $d_i + k\sigma_i$, where d_i and σ_i are the mean and the standard deviation of the lead time demand for product variant i and k is the *safety stock factor* (cf. Silver et al. 1998, Axsäter 1995). Our results are independent of the specific value of k, and §5 discusses what happens when k is chosen endogenously. The firm backorders any unmet demand, which is fulfilled once the stocks for that variant become available. The delay due to backorders inflicts a cost on the firm's customers and affects their product choice (see (1)).

Following the discussion of customer choice, the demand for product variant i follows a Poisson process with mean λ_i; thus, $d_i = \lambda_i l$ and $\sigma_i = \sqrt{\lambda_i l}$. We adopt the normal approximation for Poisson demand (cf. Hadley and Whitin 1963, §4.9). The firm's average number of backorders for product variant i at any time is given by

$$B(Q_i) = \sigma_i^2[(1+k^2)(1-\Phi(k)) - k\phi(k)]/(2Q_i), \qquad (6)$$

and its annual total inventory holding and fixed order cost is

$$C(\lambda_i, Q_i) = S\lambda_i/Q_i + h(Q_i/2 + \sigma_i k + B(Q_i)), \qquad (7)$$

where $\Phi(\cdot)$ is the cumulative distribution and $\phi(\cdot)$ is the probability density function of a unit normal random variable.[7] From now on, the term *fulfillment cost* will refer to the sum of the inventory holding cost and the fixed order cost of the traditional firm. Following (6) and Little's law, the average delay for standard product variant i due to backorders is

$$\mathbb{E}[W_i] = [(1+k^2)(1-\Phi(k)) - k\phi(k)]\sigma_i^2/(2Q_i\lambda_i). \qquad (8)$$

The following lemma specifies the optimal order quantity for a standard product, which will be helpful for characterizing a traditional firm's optimal policy throughout this paper.

Lemma 1. *The optimal order quantity for a standard product with demand rate λ_i is*

$$Q^*(\lambda_i) = \sqrt{\lambda_i\left(\frac{2S}{h} + [(1+k^2)(1-\Phi(k)) - k\phi(k)]l\right)}. \qquad (9)$$

Furthermore, we define

$$\gamma = \sqrt[3]{\frac{h}{\lambda r^2}\left(\frac{2S + l(v/2+h)[(1+k^2)(1-\Phi(k)) - k\phi(k)]}{\sqrt{2S + lh[(1+k^2)(1-\Phi(k)) - k\phi(k)]}} + k\sqrt{lh}\right)^2}, \qquad (10)$$

which, as shown in Propositions 1 and 3 in the following, is the optimal market share or the *efficient scale* for a standard product variant. We make a few parametric assumptions in order to focus on more interesting scenarios. We assume that γ is small enough so the market share of a single variant of the standard product does not exceed 25%. Specifically, we assume $\gamma \le 1/4$. This is needed only for our nonmonotonicity results in Propositions 5 and 6. Furthermore, we assume that the reservation value of customers w is high enough so the market is covered in equilibrium, which is not uncommon in Hotelling models of competition (Syam et al. 2005, Dewan et al. 2003, Thisse and Vives 1988), and a sufficient condition in our setting is $w > 3\gamma r/2 + c_t$. We assume that the unit cost differential between standard and customized products $|c_t - c_c|$ is sufficiently small so both standard and customized products are offered in equilibrium; that is, customized products always have a positive market share, and there is at least one standard product variant. Specifically, for duopoly we consider the case $\underline{c} < c_c - c_t < \bar{c}$ where[8]

$$\underline{c} = \left(2\gamma - \frac{1}{2}\right)r - \frac{v(\mu - \gamma\lambda)}{(\mu - \lambda(1-\gamma))^2} \quad \text{and} \quad \bar{c} = \frac{3\gamma r}{2} - \frac{v(\mu - \lambda)}{\mu^2}. \qquad (11)$$

For monopoly, this happens when $3\gamma r/2 - v\mu/(\mu - (1-\gamma)\lambda)^2 < c_c - c_t < 3\gamma r/2 - v/\mu$; otherwise only one type of product is offered. Finally, we assume $\mu > \lambda$, so that $\mathbb{E}[W_c(\lambda_c)] < \infty$ for all $\lambda_c < \lambda$.

Before proceeding with the analysis, we note that our model and results immediately extend to more general settings. We can allow for a fixed product overhead cost per standard product variant. Also, customization times can assume more general distributions, that is, the customizing firm may be characterized by an M/G/1 queue; and the cost of customer misfit may be extended to $|\zeta - \theta|^\alpha$ with $\alpha > 0$, i.e., the misfit cost may be nonlinear (convex or concave). We can also allow the reservation value w of standard and customized products to be different because of differences in perceived quality, which would allow for vertical differentiation (Tirole 1988) with exogenous quality levels.[9] All of our analyses go

[7] This is the standard approximation (Hadley and Whitin 1963). The exact expressions are not analytically tractable. However, one can numerically compute the optimal policy following Zipkin (1986) and thus numerically compute the equilibrium. In the online supplement, we follow this approach and show that our insights carry over. We thank Paul Zipkin for suggesting this idea.

[8] This is necessary and sufficient.

[9] A careful review of our proof shows that the analysis is driven by the product margins $m_i = w_i - c_i$ for $i = c, t$, where we have assumed $w_c = w_t = w$. Because we allow for different value of c_c and c_t, m_c is already different from m_t; hence, the proofs pass through when $w_c \neq w_t$.

through with these extensions; however, they do not enhance our insights.

3. Monopoly Benchmarks

This section considers the monopoly benchmarks. Contrasting these results with the duopoly case helps us better understand the effects of competitive factors. The results for a monopoly that sells only either standard or custom products are straightforward and are stated in Appendix A. Let us consider a dual monopoly with both traditional and MC operations. It chooses the prices of standard and customized products and the portfolio of standard products, that is, the number of standard product variants and their configurations, to maximize its *total* expected profit from both traditional and MC operations.[10] For ease of exposition, we relax the integrality of number of products n, i.e., we assume that we can treat n as a continuous variable; Salop (1979), De Groote (1994), and Balasubramanian (1998) make a similar relaxation. The following proposition describes the firm's optimal policy.

Proposition 1. *Consider the optimal product line of a monopolist that can sell both standard and customized products. The firm offers*

$$n = (1-\lambda_c/\lambda)/\gamma$$

standard products and chooses their positions $(\zeta_1, \zeta_2, \ldots, \zeta_n)$ *so each has the same market share. The prices of customized and standard products are set at*

$$p_c = w - v/(\mu-\lambda_c) \quad \text{and}$$

$$p_t = w - \gamma r/2 - \frac{lv[(1+k^2)(1-\Phi(k)) - k\phi(k)]}{2Q^*(\gamma\lambda)}, \tag{12}$$

where $Q^*(\cdot)$ *is given by* (9) *and*

$$\lambda_c = \mu - \sqrt{\frac{v\mu}{3\gamma r/2 - (c_c - c_t)}}. \tag{13}$$

By Proposition 1, customers in $[\zeta_i - \gamma/2, \zeta_i + \gamma/2]$ buy standard product variant i for $i\colon 1, \ldots, n$, and the remaining customers, whose fit with standard products is inferior, buy products that are exactly customized for their type (customers have no incentive to buy mismatching customized products, because all customized products are sold at the same price).

In choosing the number of standard product variants, the firm trades off its gross margin against its fulfillment costs. The firm could charge higher prices if it were to increase product variety; however, this would increase its fulfillment costs because of the loss of scale within each variant. Under the optimal policy, each standard product has the same market share γ (products need not be located symmetrically), which yields the unit profit $w - c_t - 3\gamma r/2$. It is straightforward to show that this is the maximum achievable profit margin for a standard product.

In designing its product line, the firm essentially decides on the market share it will allocate to its traditional $(1-\lambda_c/\lambda)$ and MC (λ_c/λ) operations. Its traditional product line then consists of the number of standard product variants needed to obtain that share, where each variant has the same market share γ that maximizes the profit margin. The firm chooses the market share allocations so that its marginal profit from standard and customized products (with respect to their demand rates) are equal; that is, $w - c_t - 3\gamma r/2 = (d/d\lambda_c)[\lambda_c(w - c_c - \mathbb{E}[W_c(\lambda_c)])]$.

The following proposition describes how the firm's policy changes with the operational and market parameters.

Proposition 2. (i) λ_c *decreases in* λ *and increases in* r.
(ii) λ_c *increases in* h *and* l.
(iii) λ_c *increases in* μ.

Proposition 2(i) shows that the demand rate of customized products λ_c (as well as their market share) decreases when the total demand rate λ increases. When the market gets larger, the firm prefers to serve a more than proportionally larger share of the market with standard products because standard products benefit from economies of scale whereas customized products do not. In contrast, the firm increases the market share of customized products when the intensity of customer preferences r increases. Not surprisingly, Proposition 2(ii) shows that the firm allocates a smaller share to standard products serving fewer variants when the firm's holding cost h and lead time l increase.[11] Finally, Proposition 2(iii) shows that a shorter customization time leads to a larger market share for customized products.

4. Duopoly Competition Between a Traditional and a Customizing Firm

In this section, we study duopoly competition between a traditional firm and a customizing firm. The traditional firm competes by providing a variety of

[10] For examples of firms with both traditional and MC operations, see Seifert (2002) and Piccoli et al. (2003). For a discussion of the advantages of this approach at National Bicycle, see Kotha (1995).

[11] λ_c need not increase or decrease in the fixed order cost S. Specifically, $d\lambda_c/dS > 0$ if and only if $S > (v/2 - h)l[(1+k^2)\cdot(1-\Phi(k)) - k\phi(k)]/2$. Interestingly, a higher setup cost can help convince customers that the firm would order larger quantities and thus the average backorder delays would be small; see (6). This induces the firm to allocate a larger share to standard products when the customers' sensitivity to delay is sufficiently large.

standard products whereas the customizing firm competes by customizing its product for each individual customer. The firms also differ in their operations: The traditional firm fulfills customer demand from stock whereas the customizing firm does not carry inventory and customizes to order.

The firms simultaneously determine their competitive product offerings to maximize their expected profits; in other words, no firm observes the other's decisions at the time of its decision making. They set prices p_t and p_c, and the traditional firm also determines the number of its product variants n and their configurations $\zeta_i \in \Theta$ for $i\colon 1, \ldots, n$.[12] As they arrive, customers choose from the product offerings to maximize their utility. Note that we assume that the reservation value of customers w is high enough so all customers buy a product in equilibrium.[13] The following proposition characterizes the equilibrium under competition.

Proposition 3. *When traditional Firm t competes with customizing Firm c, the firms set prices*

$$p_c = c_c + \frac{v\lambda_c}{(\mu-\lambda_c)^2} + \frac{\lambda_c \gamma r}{2(\lambda-\lambda_c)} \quad \text{and}$$

$$p_t = p_c + \frac{v}{\mu-\lambda_c} - \frac{\gamma r}{2} - \frac{lv[(1+k^2)(1-\Phi(k)) - k\phi(k)]}{2Q^*(\gamma\lambda)}, \tag{14}$$

where $Q^*(\cdot)$ is given by (9) and λ_c is given by the solution of

$$\frac{v(\mu+\lambda_c-\lambda)}{(\mu-\lambda_c)^2} + \frac{\lambda_c\gamma r}{2(\lambda-\lambda_c)} = \frac{3\gamma r}{2} - (c_c - c_t). \tag{15}$$

The traditional firm offers

$$n = (1-\lambda_c/\lambda)/\gamma \tag{16}$$

product variants and chooses their positions ($\zeta_1, \zeta_2, \ldots, \zeta_n$) so each has an equal market share. These result in expected profit rates

$$\Pi_t = \frac{v(\lambda-\lambda_c)^2}{(\mu-\lambda_c)^2} \quad \text{and} \quad \Pi_c = \frac{v\lambda_c^2}{(\mu-\lambda_c)^2} + \frac{\lambda_c^2\gamma r}{2(\lambda-\lambda_c)}. \tag{17}$$

An explicit solution for λ_c in (15) is provided in Appendix B. Note that the standard products need not be positioned symmetrically.

In the remainder of this section, we discuss the implications of our results. As will be clear in the following, the unit cost differential $c_c - c_t$ plays a critical role in our analysis. We use the term Firm c's cost disadvantage to refer to $c_c - c_t$, which need not be positive; similarly, Firm t's cost disadvantage refers to $c_t - c_c$. Throughout, the cost disadvantage basically refers to the firm's unit cost in excess of its competitor, which can be negative. The condition $c_c - c_t \in (\underline{c}, \bar{c})$ (where $\underline{c}, \bar{c}$ are defined in (11)) ensures the existence of a solution $\lambda_c \in (0, \lambda(1-\gamma))$ to (15) so that both firms have positive market shares and the traditional firm has at least one standard product.

4.1. Product Variety

Competition does affect product variety, and it is important to understand how. Does competition lead to more product variants? Does it lead to greater prevalence of customized products in the marketplace? To address these questions, let n^{duo} denote the number of standard products offered by a traditional firm, let λ_c^{duo} denote the demand rate of customized products in duopoly competition, let n^{d-mon} and λ_c^{d-mon} be the corresponding expressions for a dual monopoly, and let n^{s-mon} and λ_c^{s-mon} be the corresponding expression for a monopoly that sells either only standard or only custom products.

Proposition 4. (i) $n^{s-mon} > n^{duo}$.

(ii.a) *For $(1-\gamma)r/\gamma > 3v\lambda/(\mu-(1-\gamma)\lambda)^2$ there exists $c^* \in (\underline{c}, \bar{c})$ such that $n^{d-mon} > n^{duo}$ and $\lambda_c^{d-mon} < \lambda_c^{duo}$ if and only if $c_c - c_t > c^*$.*

(ii.b) *For $(1-\gamma)r/\gamma \le 3v\lambda/(\mu-(1-\gamma)\lambda)^2$, $n^{d-mon} > n^{duo}$ and $\lambda_c^{d-mon} < \lambda_c^{duo}$ for $c_c - c_t \in (\underline{c}, \bar{c})$.*

Part (i) of the proposition extends the findings of Alptekinoğlu and Corbett (2008) and Xia and Rajagopalan (2006) to our setting (which accounts for queuing and inventory effects). It shows that in a duopoly, rather than increase its product variety to lessen the customization advantage of its opponent, the traditional firm chooses to reduce the number of variants it sells to ease the competition. The second part addresses the effect of competition on product variety by comparing the case where both firms are controlled by the same decision maker to the case where they are controlled by competing decision makers. It shows that competition can lead to more market share for standard or custom products in the marketplace depending on the firms' costs.[14] Specifically, competition leads to fewer standard products with a smaller total share in the marketplace when the cost disadvantage of customized products $c_c - c_t$

[12] In addition, the traditional firm also determines the optimal replenishment batch size Q_i for each product variant i, where its optimal batch size is specified in (9).

[13] A sufficient condition for duopoly is $w > 3\gamma r/2 + c_t + v/(4(\mu-\lambda))$.

[14] Note that $(\underline{c}, \bar{c})$ refers to the open interval between $\underline{c}$ and $\bar{c}$. Recall that $\underline{c}$ and $\bar{c}$ are defined in (11) and that both firms earn positive profits when $c_c - c_t \in (\underline{c}, \bar{c})$.

is sufficiently large (and vice versa). This happens because a dual monopoly always chooses a more efficient product portfolio compared to the competing firms, serving a larger portion of the market with customized products when $c_c - c_t$ is small.

Our results show how the traditional firm competes on product variety. First, it determines the efficient scale γ of each product variant that balances the lower fulfillment costs that result from a larger scale against the higher costs of customer misfit. The firm's efficient scale is independent of its competitor—it depends only on the firm's own parameters. This means that the firm can trade off its operational parameters (e.g., order cost S, replenishment lead time l, etc.) independent of the competition. However, once the efficient scale is determined, the competitive conditions affect the number of product variants the firm will offer. It is interesting to note that the efficient scale in a duopoly is the same as in a (single and dual) monopoly. This is because the effect of the traditional firm's price changes on the market share of a product variant is the same, because all customer types have an equal outside option in both cases (zero for monopoly, $w - p_c - \mathbb{E}[W_c]$ for duopoly).

4.2. Market Conditions Favoring Mass Customization

In this section, we discuss the effect of market parameters on the profitability of MC as well as the traditional approach. Our results provide useful insights for firms considering MC.

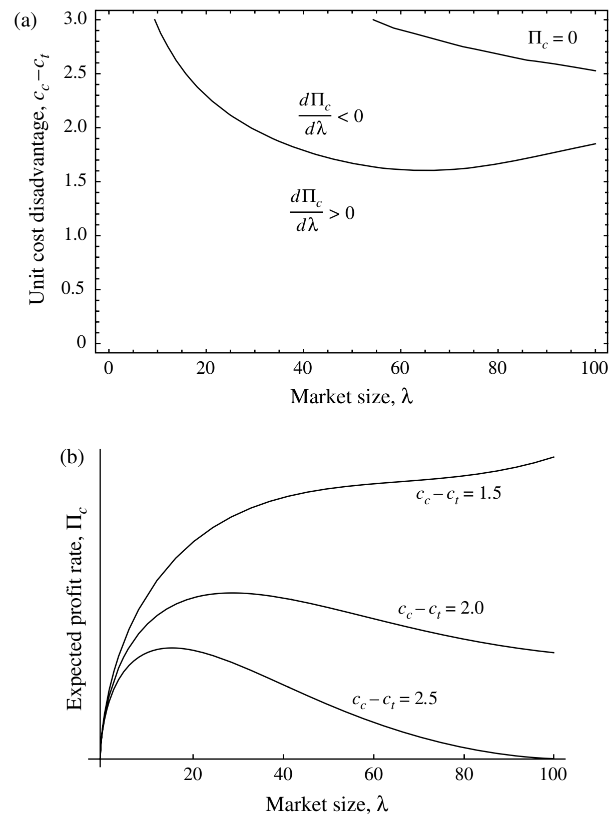
We first consider the effect of the intensity of preferences r.

Proposition 5. (i) *There exists $c^* \in (\underline{c}, \bar{c})$ such that $d\Pi_t/dr < 0$ if and only if $c_c - c_t > c^*$.*
(ii) $d\Pi_c/dr > 0$.

As expected, markets with customers that have strong preferences give advantage to the customizing firm, which fully satisfies these preferences. Thus, the customizing firm is better off in markets where customers care a lot about their ideal products. It is interesting that this may also benefit the traditional firm. In particular, this happens when the traditional firm's unit cost is sufficiently high relative to its competitor. In this case, although a larger r makes customers more averse to standard products, the traditional firm benefits from a milder price competition due to a larger gap between standard and customized products.

The effect of market size is more intricate. In §3, for a dual monopoly we have shown that the demand rate of customized products λ_c decreases when the market size λ increases, as the alternative (standard products) benefits from economies of scale. The following proposition shows that the effect of market size is not monotone in duopoly competition.

Figure 1 Effect of Market Size ($S = 3$, $h = 0.15$, $k = 0.75$, $l = 6$, $v = 20$, $r = 80$, $\mu = 100$)**: (a) Regions in Which the Customizing Firm's Profit Increases or Decreases in Market Size; (b) Customizing Firm's Profit Rate as a Function of Market Size at Various Unit Cost Differentials**



Proposition 6. (i) $d\Pi_t/d\lambda > 0$.
(ii.a) *If $\gamma r \le 2v\lambda/\mu^2$ then $d\Pi_c/d\lambda > 0$.*
(ii.b) *If $\gamma r > 2v\lambda/\mu^2$, there exists $c^* \in (\underline{c}, \bar{c})$ such that $d\Pi_c/d\lambda < 0$ for $c_c - c_t > c^*$.*

An increase in market size has two effects. It increases the size of the "pie," so each firm worries less about its market share and more about its profit margin, potentially softening the competition. But it also helps the traditional competitor decrease its unit fulfillment cost as a result of scale economies that characterize its operations. These effects have asymmetric impacts on the customizing and traditional firms. Both effects favor the traditional firm, consistent with Proposition 6(i). On the other hand, they affect the customizing firm in opposite directions, and Proposition 6(ii) shows that an increase in market size may increase or decrease the customizing firm's profit. One can show that the traditional firm's unit fulfillment cost is equal to γr, and the proposition shows that when this is small there is not much to be gained from economies of scale; hence, the larger pie effect dominates. However, when γr is large, the customizing firm's profit decreases in market size if its cost disadvantage is above a threshold. Figure 1(a) shows the regions in which the profit of the customizing firm increases or decreases because of a larger market size, and Figure 1(b) shows the firm's expected profit rate for various unit cost differentials. The figures show that the customizing firm has an ideal market size when its cost disadvantage is large. Furthermore, Figure 1(a) shows that this ideal market size decreases in the firm's cost disadvantage. This is because the traditional opponent cannot compete effectively in a small market because of its high unit fulfillment cost. On the other hand, when the customizing firm's cost disadvantage is small, it can compete with the traditional firm head-to-head and it always prefers a larger market. Finally, when the customizing firm's cost disadvantage is in the middle in Figure 1(a), its profit decreases in market size unless the market is either sufficiently small or sufficiently large. This is because the traditional opponent cannot effectively compete in a small market, and the competition is mild in a large market. Overall, the firms' competitive cost positions (determined by their unit cost differential) plays a critical role in determining the outcome. We find that the behavior in Figures 1(a) and 1(b) is consistent based on looking at several choices of parameters. Specifically, we have considered all combinations of $S = 2, 3, 4$, $h = 0.10, 0.15, 0.20$, $l = 5, 6, 7$, $v = 10, 20, 30$, and $r = 60, 80, 100$.

4.3. Improving Operations

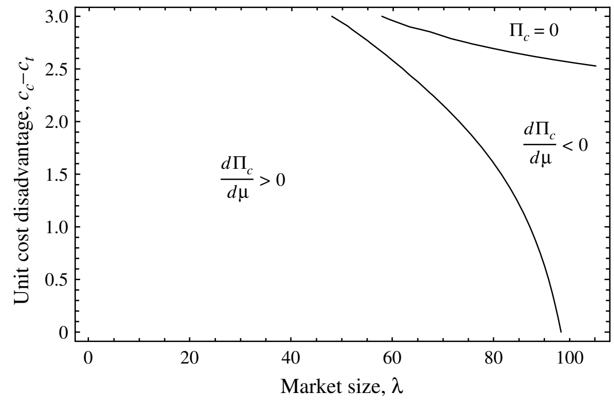
We will now discuss the effect of firms' operational parameters on their profitability. Mainly, we consider the effect of improving the customization times and the traditional firm's holding cost and replenishment lead times.

We begin with the effect of improving the expected time needed to customize each unit, $1/\mu$, which reflects the capacity of the customizing firm as well as the difficulty or complexity of customization. Intuition suggests that customization should be more attractive when it takes less time. This always holds for a monopoly, but increasing μ may actually adversely affect the customizing firm in duopoly. The following proposition shows that the outcome critically depends on the firm's competitive position, which is determined by the unit cost differential.

Proposition 7. (i) $d\Pi_t/d\mu < 0$.
(ii.a) *If* $\mu \geq 2\lambda$ *then* $d\Pi_c/d\mu > 0$.
(ii.b) *If* $\lambda < \mu < 2\lambda$ *then there exist* $c^* \in (\underline{c}, \bar{c})$ *such that* $d\Pi_c/d\mu < 0$ *for* $c_c - c_t > c^*$.

As might be expected, a shorter customization time always hurts the traditional firm. However, this can also be detrimental to the customizing firm itself, and the unit cost differential between the firms plays an important role in determining the outcome. When customization is not very fast and the MC firm's cost disadvantage is above a threshold, improving its customization time hurts the customizing firm. Intuitively, longer customization delays create a degree of separation between customized and standard products, which softens the intensity of competition. When the customizing firm has a weak competitive position (i.e., an unfavorable unit cost differential), it is not in its best interest to undermine this differentiation by speeding customization up through capacity expansion or design improvements even when these are free. Overall, the firm is more likely to benefit from a capacity expansion when it has a stronger competitive cost position (i.e., a more favorable unit cost differential). Figure 2 shows the regions in which the customizing firm's profit increases or decreases when it improves its customization rate. It also shows the region (top right) where the firm does not attain a positive market share. Interestingly, the figure shows that a larger market size can make capacity expansion undesirable (put differently, a smaller market size can make a larger capacity more attractive). This happens because a large market strengthens the traditional competitor, and therefore the customizing firm may prefer longer customization times to distance itself. Note that if the customizing firm could *credibly* convince its competitor that it would not use all of its available capacity (deliberately delaying product delivery), it could have been better off in some cases. However, once prices are set, using all of its capacity always increases the customizing firm's profit. Hence, such behavior is not an equilibrium in our model.

Figure 2 **Effect of Improving Expected Customization Time,** ($S = 3$, $h = 0.15$, $k = 0.75$, $l = 6$, $v = 20$, $r = 80$, $\mu = 100$)



We now turn to the effect of improving the traditional firm's operations. We consider the effects of the unit holding cost h and replenishment lead time l. Clearly, lower holding costs and shorter replenishment lead times are always desirable absent competition. However, our results show that these improvements require careful analysis in duopoly competition.

Table 2 Comparative Statics and Firm Policies in Monopoly and Duopoly

	Traditional				MC		
	Monopoly	Dual monopoly	Duopoly		Monopoly	Dual monopoly	Duopoly
n	Largest	Middle/smallest	Middle/smallest	λ_c	Largest	Middle/smallest	Middle/smallest
$d\Pi_t/d\lambda$	$+$	$+$	$+$	$d\Pi_c/d\lambda$	$+$ or 0	$-$	$+$ or $-$
$d\Pi_t/dr$	$-$	$-$	$+$ or $-$	$d\Pi_c/dr$	0	$+$	$+$
$d\Pi_t/d\mu$	N/A	$-$	$-$	$d\Pi_c/d\mu$	$+$	$+$	$+$ or $-$
$d\Pi_t/dh$	$-$	$-$	$+$ or $-$	$d\Pi_c/dh$	N/A	$+$	$+$
$d\Pi_t/dl$	$-$	$-$	$+$ or $-$	$d\Pi_c/dl$	N/A	$+$	$+$

Proposition 8. (i) *There exists* $c^* \in (\underline{c}, \bar{c})$ *such that* $d\Pi_t/dh < 0$ *and* $d\Pi_t/dl < 0$ *if and only if* $c_c - c_t > c^*$.
(ii) $d\Pi_c/dh > 0$ *and* $d\Pi_c/dl > 0$.

Similar to our discussion of customization times, the traditional firm does not benefit from improving its replenishment lead time or holding cost when its competitive position is weak. Basically, the firm benefits only when the cost differential $c_c - c_t$ is above a threshold. On the other hand, these improvements always decrease the customizing opponent's profit.

4.4. The Effects of Competition

Our analysis shows how competitive considerations affect the firms' policies and the sensitivity of their profits to various market and operating characteristics. These results, which were proved earlier for dual monopoly and duopoly, are summarized in Table 2 (the results for a simple monopoly are straightforward; hence, we omit their proofs). In some cases, competition entirely reverses the results. For example, the changes in customization rate and market size can affect the customizing firm in diametrically opposite directions in monopoly and under competition. Also, improving the unit holding cost may be harmful for a traditional firm under competition, whereas it is always beneficial for a monopoly. Overall, we find that the unit cost differential $c_c - c_t$ plays a critical role in determining the outcome of these changes. In contrast, some of the firm's operating decisions are independent of the competition. In particular, the traditional firm's efficient scale for each product variant is independent of its competitor. Finally, some characteristics fall in between the two extremes. For example, the effect of the market size on the traditional firm's profit is different in magnitude for a monopoly and under competition, although their rates of change have the same sign.

5. Extensions

In this section, we discuss a few extensions of our model.

5.1. Customizing Firm's Capacity Choice

So far, the MC firm in our model had limited, exogenous capacity, assuming that its capacity investments require a long horizon. Here, we show what happens when the customizing firm's capacity is endogenous through a numerical study. Specifically, the customizing firm first chooses its capacity and then the firms make their pricing and product variety decisions as described in §2. The assumption that long-run capacity decisions are made first is common in the literature because of the longer timescale typically associated with capacity investments. In Appendix D in the online supplement, we provide additional numerical studies and discuss how each result in §4 extends to the endogenous capacity case in more detail.

Let the cost rate of capacity μ be $C(\mu)$. The customizing firm chooses its capacity to maximize $\Pi_c(\mu) - C(\mu)$. Proposition 3 describes the profit rate Π_c for $\mu > \lambda$. Note that $\mu > \lambda$ ensures $\mathbb{E}[W_c] < \infty$ for any market share allocation. For $\mu \leq \lambda$, when both firms earn positive profits in equilibrium, they enjoy quasimonopolistic positions: The prices are set such that in equilibrium each customer finds only one of the firm's products attractive. Thus, the customizing firm extracts all surplus of its customers. In this case, there are multiple equilibria, which are characterized in Appendix C. Our numerical study follows the convention of choosing the most competitive equilibrium among the set of equilibria, i.e., the one that maximizes consumer surplus.

Table 3 shows the equilibrium outcomes as the market size λ, the unit cost differential $c_c - c_t$, delay sensitivity v, and capacity costs vary (we fix $w = 8$, $S = 3$, $h = 0.15$, $l = 6$, $r = 80$, $k = 0.75$, and $c_t = 1$). In line with Proposition 6, the table shows that the traditional firm always benefits from a larger market.[15] In contrast, the customizing firm's profit net of investment cost, $\Pi_c - C$, may decrease in λ. In particular, for $C(\mu) = 0.15\mu$, its profit net of investment cost can decrease in λ, when its unit cost disadvantage is sufficiently large, i.e., when $c_c = 3.75$. On the other hand,

[15] When $\lambda < 4.69$, the traditional firm cannot attain positive profits and it does not offer any products (note that this violates the assumption $w > 3\gamma r/2 + c_t$).

Table 3 The Effect of Market Size and Unit Cost Differential on Firm Profits ($w = 8$, $c_t = 1$, $r = 80$, $S = 3$, $h = 0.15$, $l = 6$, $k = 0.75$)

Capacity cost, delay sensitivity	c_c	λ	Customizing firm's market share	$\Pi_c - C$	Π_t	μ	n	p_c	p_t	$\mathbb{E}[W_c]$
$C(\mu) = 0.15\mu$, $v = 20$	$c_c = 3.5$	5	0.60	6.78	0.16	25.10	7.0	7.03	3.39	0.90
		6	0.59	7.16	0.22	27.34	7.7	6.69	3.26	0.84
		7	0.58	7.43	0.27	29.32	8.3	6.42	3.16	0.79
		8	0.57	7.61	0.34	31.08	8.8	6.20	3.07	0.75
		9	0.56	7.72	0.41	32.64	9.4	6.01	3.00	0.72
		10	0.55	7.78	0.50	34.00	9.9	5.84	2.94	0.70
	$c_c = 3.75$	5	0.58	5.77	0.19	24.63	7.4	7.02	3.40	0.92
		6	0.57	5.96	0.25	26.71	8.1	6.68	3.27	0.86
		7	0.55	6.05	0.32	28.50	8.7	6.41	3.17	0.81
		8	0.54	6.06	0.41	30.03	9.4	6.19	3.09	0.78
		9	0.53	6.01	0.51	31.32	10.0	6.00	3.02	0.75
		10	0.52	5.90	0.63	32.35	10.7	5.83	2.96	0.74
$C(\mu) = 0.001e^{1.5\mu}$, $v = 10$	$c_c = 3.5$	5	0.22	0.88	26.90	4.49	16.4	5.03	4.87	2.97
		6	0.20	0.90	33.44	4.51	18.1	5.00	5.06	3.00
		7	0.17	0.91	40.12	4.52	19.6	4.97	5.20	3.03
		8	0.16	0.92	46.90	4.52	20.9	4.95	5.32	3.05
		9	0.14	0.92	53.72	4.53	22.1	4.94	5.43	3.06
		10	0.13	0.93	60.58	4.53	23.3	4.93	5.52	3.07
	$c_c = 3.75$	5	0.20	0.57	27.79	4.38	14.1	2.12	3.46	2.94
		6	0.17	0.59	34.37	4.40	15.4	2.06	3.73	2.97
		7	0.15	0.60	41.07	4.41	16.6	2.02	3.94	2.99
		8	0.14	0.60	47.85	4.42	17.7	1.98	4.12	3.01
		9	0.12	0.61	54.68	4.42	18.7	1.96	4.27	3.02
		10	0.11	0.61	61.54	4.42	19.6	1.94	4.40	3.03

it increases in λ when its unit cost disadvantage is sufficiently small, i.e., when $c_c = 3.5$.

When the customizing firm can adjust its capacity, it can benefit from queuing-related economies of scale and hence it is more likely to benefit from a larger market size. Table 3 shows that the customizing firm chooses a larger capacity as the market grows, and this mitigates the negative effect of market size on its profit to some extent. For $C(\mu) = 0.15\mu$ and $c_c = 3.75$, the customizing firm's profit decreases in market size λ after $\lambda > 8$, whereas we find that its profit starts to decrease in market size sooner, i.e., after $\lambda > 7$, if its capacity is not allowed to increase. Overall, our numerical study shows that the scale economy of the traditional competitor may still dominate and the customizing firm can get worse off. In particular, just as in the case of exogenous capacity, a larger market can increase or decrease the customizing firm's profit, and the unit cost differential plays a critical role in determining the outcome.

Furthermore, numerical studies reported in Tables 5 and 6 in the online supplement show that our insights for the effects of holding cost h and order lead time l in Proposition 8 continue to hold when the customizing firm's capacity is endogenous. Although a larger holding cost h and longer lead time l normally would make the traditional firm less profitable, these can increase the traditional firm's profit in a duopoly competition against a customizing firm when the traditional firm has a sufficiently large unit cost disadvantage. In this case, a larger h and l help the traditional firm because they result in a milder price competition. In fact, we find that endogenous customization capacity strengthens this result as the customizing firm chooses a smaller capacity for larger values of h and l in this case further reducing the intensity of competition.

5.2. Endogenous, Observable Safety Stock Factor k

In our base model, the safety stock factor was an exogenous (albeit arbitrary) constant. Alternatively, k can be a decision variable. Here, we assume that k is a decision variable that can be observed by customers[16] and that it is set together with prices. Then, we show that there exists an optimal k^* given by the next proposition.

Proposition 9. *The traditional firm chooses*

$$k^* = \arg\min_k \left(\frac{2S + l(v/2+h)[(1+k^2)(1-\Phi(k)) - k\phi(k)]}{\sqrt{2S + lh[(1+k^2)(1-\Phi(k)) - k\phi(k)]}} + k\sqrt{lh} \right)$$

[16] One can argue that customers can indeed conjecture k based on observing the firm's service level over a period of time. If k is not observable, the firm cannot credibly commit to any $k > -\infty$. This is because in equilibrium (if it exists) customers would make their decisions based on the equilibrium value of k (i.e., based on their rational expectations), not based on the actual value, and thus the firm always has an incentive to reduce k.

both in single and dual monopoly and duopoly. Furthermore, Propositions 1 *and* 3 *characterize the monopoly and duopoly equilibria where* γ *is calculated at* k^*.

Basically, k^* minimizes γ given in (10). Note that k^* does not depend on the market parameters, market size λ, and intensity of preferences r as well as the competitive factors, customization rate μ, and unit cost differential $c_c - c_t$. Thus, our results concerning these parameters can be immediately extended to allow for an endogenous k.

5.3. Uniform vs. Menu Prices

Our base model has restricted the firms to uniform prices. In the online supplement, we study what happens when the firms are allowed to set different prices for each product configuration; i.e., the traditional firm sets a vector of prices $(p_1, p_2, \ldots, p_n)$ and the customizing firm sets a price menu $p(\theta)$ for $\theta \in \Theta$. Basically, we find that many of our findings carry over to the price menu model. In particular, the customizing firm's profit does not monotonically increase in its customization rate μ and the market size λ. Furthermore, the customizing firm's unit cost disadvantage plays a critical role in determining the effect of these parameters.

6. Concluding Remarks

In this paper, we analyzed the optimal product lines of firms that sell standard or individually customized products. We modeled product-line design and fulfillment for the two types of firms. The traditional firm fulfills customer demand using its inventories, and it chooses a limited set of product configurations, whereas the customizing firm does not carry inventories, and it can make each product configuration to order. In her decision making, a customer trades off the sacrifice from her ideal product, disutility of delay, and product price. Customer waiting occurs because of customization delays and backorders of standard products. We solve for the resulting equilibrium for both monopoly and duopoly of traditional and customizing firms.

Our results are useful for identifying market conditions that make MC attractive. We show that the relationship between market size and profitability of MC is not monotone: A larger market can hurt the customizing firm's profit when it has a sufficiently large unit cost disadvantage. This happens because of the traditional competitor's scale economies. Our numerical studies show that in this case there is an ideal market size for the customizing firm, which decreases in its unit cost disadvantage.

We show that ignoring competitive forces can lead to critically incorrect decisions for firms considering mass customization. Although always beneficial for a monopoly, a larger customization capacity does not always translate into higher profits under competition. Specifically, a larger capacity, which enables shorter customization times, decreases the customizing firm's profit when the firm has a large unit cost disadvantage. Intuitively, customization delays create a degree of separation between customized and standard products, which softens the competition. When the firm has a weak competitive position, it is better off maintaining this separation. In this case, the firm can benefit from a larger capacity only after going through cost-reduction efforts.

Overall, we find that the effects of both market size and customization rate on the profitability of the customizing firm are nonmonotonic and that their desirable levels depend on the firm's competitive position. Thus, the profitability of MC depends on finding a "sweet spot" in terms of market size, ease of customization, and competitive position.

Our model has several limitations. Similar to Van Ryzin and Mahajan (1999) and Cachon and Harker (2002), for example, the customers in our model do not observe the state of the firms (e.g., queue lengths or inventory positions), customers make their decisions based on expected delays, and we do not consider dynamic substitution. In our model, customers conjecture the equilibrium demand rate of each firm given the prices and product offerings, and in turn they estimate the expected delay, as is common in the literature that considers customer choice in queuing systems (see, e.g., Afèche and Mendelson 2004 and Guo and Zipkin 2007 and references therein). In our main model, we assume a customizing firm with fixed capacity (later we relax this in §5 via a numerical study). Furthermore, as pointed out in the introduction, in some cases the MC firm may be able to expand its effective capacity, as is the case, for example, for mi adidas. Combining the operational features of our model with a model fashioned after Xia and Rajagopalan (2006) may be a promising avenue for future research.

Our results may be extended further in a number of ways. One promising direction is the relaxation of our assumption that customer types are uniformly distributed over the product space. It will be interesting to study what happens when customer preferences are concentrated around some popular products and how the degree of concentration affects the competition between the traditional and customizing firms. Another possible extension is to replace the deterministic supplier lead time assumption in our model, which corresponds to the case where the firm's suppliers have ample capacity, with a model that incorporates congestion and stochastic delay downstream in the supply chain. It is also worthwhile to consider a longer planning horizon and study the firms' market entry and production technology choices in this context.

7. Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

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Appendix A. Monopoly

Proposition 10. (i) *The optimal policy of a monopolist that sells only standard products is as follows*: $n = 1/\gamma$ *products positioned at* $\zeta_i = (i - 1/2)\gamma$ *and priced at* $p_i = w - \gamma r/2 - lv[(1+k^2)(1-\Phi(k)) - k\phi(k)]/(2Q^*(\gamma\lambda))$ *for* $i: 1, 2, \ldots, n$, *where* $Q^*(\cdot)$ *is given by* (9).[17]

(ii) *The optimal policy of a monopolist that sells only custom products is as follows*: $p_c = w - v/(\mu - \lambda_c)$ *where* $\lambda_c = \min\{\mu - \sqrt{v\mu/(w - c_c)}, \lambda\}$.

Appendix B. Addendum to Proposition 3

Equation (15) is solved by

$$\lambda_c = \frac{1}{3A}\Bigg(-B - \sqrt{B^2 - 3AB} \cdot \Bigg(\cos\left[\frac{1}{3}\arccos\left[-\frac{2B^3 - 9ABC + 27A^2D}{2(B^2 - 3AC)^{(3/2)}}\right]\right] + \sqrt{3}\sin\left[\frac{1}{3}\arccos\left[-\frac{2B^3 - 9ABC + 27A^2D}{2(B^2 - 3AC)^{(3/2)}}\right]\right]\Bigg)\Bigg), \quad \text{(B1)}$$

where

$$A = 2(2\gamma r - (c_c - c_t)),$$
$$B = 2(c_c - c_t)(\lambda + 2\mu) - (3\lambda + 8\mu)\gamma r - 2v,$$
$$C = 2(3\lambda + 2\mu)\mu\gamma r - 2(c_c - c_t)(2\lambda + \mu)\mu + 2v(2\lambda - \mu),$$
$$D = \lambda(2(c_c - c_t)\mu^2 - 3\mu^2\gamma r + 2(\mu - \lambda)v),$$

and γ is defined in (10).

Appendix C. Duopoly Equilibrium When $\mu \le \lambda$

When $\mu \le \lambda$, the following equations characterize the equilibria in which both firms earn positive profits.

$$p_c = w - v/(\mu - \lambda_c) \quad \text{and}$$
$$p_t = w - \frac{\gamma r}{2} - \frac{lv[(1+k^2)(1-\Phi(k)) - k\phi(k)]}{2Q^*(\gamma\lambda)},$$

where $Q^*(\cdot)$ is given by (9). The traditional firm offers

$$n = (1 - \lambda_c/\lambda)/\gamma$$

product variant and chooses their positions $(\zeta_1, \zeta_2, \ldots, \zeta_n)$ so each has an equal market share.

[17] De Groote (1994) provides an analog of Proposition 10(i) assuming EOQ inventory costs.

λ_c should satisfy the following inequalities,

$$\frac{v\lambda}{\mu(\mu - \lambda_c)} \ge w - c_t - \frac{3}{2}\gamma r, \quad \text{(C1)}$$

$$\frac{v\mu}{(\mu - \lambda_c)^2} \le w - c_c, \quad \text{(C2)}$$

$$\frac{v\mu}{(\mu - \lambda_c)^2} + \frac{\lambda_c \gamma r}{2(\lambda - \lambda_c)} \ge w - c_c. \quad \text{(C3)}$$

It is straightforward to show that (C1)–(C3) have a feasible solution $0 < \lambda_c < \lambda$ when $v\lambda^2/\mu^3 > (w - c_t - \frac{3}{2}\gamma r)^2/(w - c_c)$, $w - c_t - \frac{3}{2}\gamma r < v\lambda/(\mu(\mu - \lambda))$, and $w - c_c > v/\mu$.

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