The Design and Introduction of Product Lines
When Demand Is Uncertain

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Abstract

This paper presents a model of the design and introduction of a product line that consists of a high-end model and a low-end model under conditions of demand uncertainty. The firm is uncertain \textit{a priori} about demand for the product line, which can turn out to be either high or low, and learns the actual demand conditions only after at least one product in the line has been introduced. We find under low levels of demand uncertainty that the firm introduces both models in the first period; at higher levels of uncertainty, the firm prefers sequential introduction and delays design of the second product until the second period. When the level of demand uncertainty is intermediate, the firm’s first product should be of lower quality than one produced by a myopic firm that does not take product line effects into consideration. The quality of the second product depends on realized demand. If realized demand is high, the firm’s second product should be a higher-end model; if demand turns out to be low, the firm’s second product should be a lower-end model or it should replace the first product with a lower-end model. When the level of demand uncertainty is high, the firm optimally presents a first product that is of greater quality than one produced by a myopic firm. Then, if demand turns out to be high, a low-end model should be added to the product line. But if demand turns out to be low, the firm should replace the first product with a new lower-end model.

\textit{Key words}: product line; product introduction; demand uncertainty


1. Introduction

Often firms that launch new products plan and introduce, whether immediately or over time, a product line that consists of a number of different models that are all based on the same core design. For example, Volkswagen launched the sixth generation of its compact car, the Golf, in 2009, presenting seven models that differ only by engine size and configuration and by the cars’ finish and trim. The Apple iPod line of MP3 players consists of eight models that range from the iPod Shuffle with 1 gigabyte of memory at $49 to the iPod Touch with 32 gigabytes at $399.\(^1\)\(^2\) Invariably, even with the best market research available, a firm launching a new product faces some uncertainty regarding market conditions and eventual acceptance of the product in the market. This makes specification of new product configurations one of the most important and difficult tasks faced by managers (Urban and Hauser 1993). These decisions become even more difficult when a manager must choose the configuration not for a single model but for a number of different models in a product line. Introducing multiple new models over a short span of time in a dynamic industry that changes day by day poses difficult problems to managers: Should all of the models be designed in advance and introduced simultaneously into the market? Or should the design and introduction of some models be delayed until the market reaction to earlier models in the product line can be ascertained? And, if so, which models should be introduced first and which should be delayed? How should these decisions affect the design of each of the models? These are important managerial questions that we endeavor to clarify in this paper by investigating how demand uncertainty should affect firms’ decisions regarding the design and introduction of product lines.

\(^1\) Early 2009 data.
\(^2\) Delineating the boundaries of product lines is not always straightforward. Formally, in line with the definitions in the formal model outlined in the paper, one can think of the iPod family as consisting of four different product lines: the Shuffle, Nano, Classic, and Touch with two, two, one, and three models respectively.
The optimal design of a product line has been a core question in the product line literature dating back to the seminal paper by Mussa and Rosen (1978) (see also Dobson and Kalish 1988; Moorthy and Png 1992; Johnson and Myatt 2003; Villas-Boas 2004; Carlton and Dana 2008; Che, Narasimhan, and Padmanabhan 2010; and Krishnan and Zhu 2006). In these models, consumers differ in how much they value product quality. The firm knows the distribution of consumer tastes for quality but cannot identify the taste of individual consumers. These papers determine the optimal product line to offer to consumers such that the firm’s profit will be maximized. An implicit assumption in all of the papers is that all of the different models in the product line are introduced to the market at the same time. Moorthy and Png (1992) considered a product line that consisted of two models. But instead of looking at the question of optimal design, they assumed that the models’ qualities were a given and asked whether the firm should introduce the models simultaneously or sequentially. They showed that the firm should introduce both products simultaneously when cannibalization is not a problem; when it is a problem, the firm should prefer a sequential introduction that starts with a high-end model and later adds a low-end product. Moorthy and Png (1992) relaxed the assumption of simultaneous introduction but maintained an assumption that the demand distribution is known.

In this paper we expand the literature on product line design by extending the analysis to situations in which the firm is uncertain about the distribution of consumer tastes for quality in the market and asking how this demand uncertainty should affect the design and introduction of the product line.

Other papers on product development have demonstrated the importance of uncertainty for firms’ decisions. Padmanabhan, Rajiv, and Srinivasan (1997) considered how consumer uncertainty regarding network externalities in the market might affect a firm’s introduction
decisions and showed that asymmetric information might provide a rationale for sequential introduction by the firm. Similarly, Keck and Rao (1987) considered how consumer uncertainty regarding novel technologies can affect entry and segmentation decisions. Chatterjee and Sugita (1990) and Tyagi (2006) focused on the way in which demand uncertainty affects competitive new-product introductions. These papers, however, did not consider the case in which firms introduce product lines instead of single products.

Demand uncertainty can affect the firm’s decisions regarding both design of the models in the product line and their relative introduction. First, demand uncertainty complicates the design problem of developing products that satisfy the incentive-compatibility constraints. Second, observing the market reaction to the first model introduced can reduce the firm’s uncertainty. This may provide an incentive for the firm to delay the design and introduction of some of the models. To understand how these effects should impact the firm’s decisions, we develop a model of introduction of a product line that consists of two vertically differentiated products under conditions of demand uncertainty and derive the optimal product design and introduction sequence for the firm.

The results show that demand uncertainty can indeed lead the firm to introduce a product line sequentially rather than simultaneously. If the level of uncertainty is low, it is optimal to use simultaneous introduction. But with higher levels of uncertainty the ability to adjust the second product’s design to better fit actual market conditions is more beneficial than having multiple products in the market earlier—so sequential introduction becomes optimal.

Optimal product qualities are impacted by demand uncertainty in a nontrivial, nonmonotonic way. We compare the quality of products introduced by a firm that behaves optimally to the quality of products introduced by a myopic firm (one that does not take into account the effect of
current decisions on future product introductions). We find that a firm that behaves optimally produces higher quality first product than one that behaves myopically when demand uncertainty is either high or low. When demand uncertainty is at an intermediate level, a firm that behaves optimally presents a first product of lower quality. These changes in the relative product quality are a reflection of the way in which the firm responds to uncertainty when designing and introducing a product line. When the level of uncertainty is low, it is optimal to use simultaneous introduction—or, if exogenous factors preclude simultaneous introduction, to introduce a high-end model first. As demand uncertainty increases to an intermediate level, the firm should switch to a sequential introduction in which the quality of the second product is contingent on realized demand—high quality if demand turns out to be high and low quality otherwise. To enable this approach when there is an intermediate level of uncertainty, the firm should introduce a relatively low-quality model in the first period. When the level of demand uncertainty is high, the firm should introduce the high-end model first.

The results show the importance of managers understanding the demand uncertainty facing the firm because the optimal response in terms of product design and introduction sequence changes with the level of uncertainty. They also help explain the range of introduction sequences observed in practice. Depending on the level of uncertainty it may be optimal to observe simultaneous introductions, high-to-low sequential introductions, or low-to-high introductions. In section 2 we describe the model. Section 3 presents the results of the analysis and Section 4 discusses some of the implication of the results.
2. Model

A monopolist has an opportunity to offer various models of a product in a new category. Each consumer needs at most one unit in that product category. We are interested in understanding which models the seller will offer in the marketplace and the order in which those products will be introduced. To capture introduction-order effects, we assume that there are two selling periods and that the seller plans to introduce no more than two products to the market.\(^3\) We then look at which models the seller will introduce and the period in which they will be offered.

Let \( p_i \) be the price of product \( i \), \( \delta_i \) the quality of product \( i \), and \( \phi \) a parameter that captures a consumer’s taste (willingness-to-pay) for quality. Here we use the term “quality” broadly to refer to all of the relevant aspects of the product, such as performance, features, reliability, and aesthetics, that affect the product’s perceived desirability.

**Assumption 1 (consumer utility):** The net utility for a consumer from purchasing product \( i \) is \( \phi \delta_i - p_i \). A consumer purchases the product \( i \) that provides the highest net utility as long as that utility is not negative.

**Assumption 2 (demand):** Demand in each period is composed of a unit mass of consumers whose taste for quality is distributed uniformly over \([0, \bar{\alpha}]\). Each consumer buys at most one unit.

Following the existing product line literature, we capture the fact that consumers differ in their intensities of preference for quality with a uniform distribution (see, for example, Mussa and Rosen (1978)). However, while the existing literature assumes that this distribution is known to the firm, we capture the fact that the firm may have some uncertainty regarding the distribution of consumers’ tastes by modeling the upper bound of the distribution, \( \bar{\alpha} \), as a random variable.

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\(^3\) Looking at product lines consisting of two products is sufficient to capture the dynamics of product introduction in our model since the firm’s uncertainty is completely resolved following introduction of the first model.
Taking our cue from the diffusion literature we also assume that the demand in the market is stationary over time and thus that the taste distribution is the same for both periods. This is similar to the assumption of stationary demand facing firms entering new product categories like in the models of Dockner and Jorgensen (1988), and Eliashberg and Jeuland (1986). The idea is to try and capture in a simple way the fact that consumers become aware of new products only over time, and that new consumers are created all the time as teens mature for example. An alternative is to assume that all consumers are aware of the products from the start and new consumers do not enter the market in later periods. This would be similar to some durable goods models (e.g. Desai and Purohit 1998, 1999). In the appendix we present the analysis of this case as well. The results point to two problems with assuming that there is no entry of new consumers: First, under such demand conditions and sequential introduction of products, at each point in time only one product has positive sales while all others have zero sales. This does not accord with the empirical observation that multiple products in a product line enjoy positive sales at the same time even if introduced sequentially. Second, we show that under these demand conditions it is never optimal to use a low and high introduction sequence as in the iPod example described before. Since one of the aims of this paper is to explore whether such low-high sequences can be optimal without resorting to arguments about exogenous technological constraints, in the paper we concentrate on the case when new consumers enter the market in the second period.\(^4\)

From assumptions 1 and 2 we can derive the following demand system for this market setting (see the appendix for the details of these derivations):

\(^4\) We can also consider a more general demand formulation that combines the Desai and Purohit approach with entry of new consumers in the second period. Unfortunately such a formulation turns out not to be amenable to analytical solution. Numerical analysis conducted by the authors indicate that a more general model generates the result of wither of the extreme cases depending on the amount of new consumers entering in the second period: If many new consumers arrive we get the results reported in the paper based on the stationary demand assumption, otherwise we get the results under the no new consumers assumption as reported in the appendix.
(1) \[ Q = 1 - \frac{P}{\tilde{\alpha} \delta} \]

if only a single product is offered in the market, or

\[ q_l = \frac{p_h \delta_h - p_l \delta_l}{\tilde{\alpha} \delta_l (\delta_h - \delta_l)} \]
\[ q_h = 1 - \frac{p_h - p_l}{\tilde{\alpha} (\delta_h - \delta_l)} \]

if a product line consisting of two products with qualities \( \delta_h \) and \( \delta_l \) (\( \delta_h > \delta_l \)) is offered.

Assumption 3 (uncertainty): The firm is uncertain a priori about consumers’ valuations. Specifically, the value of the random variable \( \tilde{\alpha} \) can be high (with probability \( \frac{1}{2} \)) such that \( \tilde{\alpha} = \alpha + k \), \( k \geq 0 \) or it can be low (with probability \( \frac{1}{2} \)) such that \( \tilde{\alpha} = \alpha - k \), \( k \geq 0 \). The firm learns the realized value of \( \tilde{\alpha} \) only after introduction of the first product.

As a result, the firm’s decision about the quality of the product to introduce in the first period is made while uncertainty remains regarding the true demand condition—specifically, the willingness-to-pay in the market. After the first product is introduced, the firm learns the realized value of \( \tilde{\alpha} \) by observing consumers’ response to the product. But at that point the firm can no longer change the design of the first product. It can, however, change the price and we assume that the firm can adjust price in response to actual demand conditions. Thus, decisions regarding the first-period price plus all of the second-period decisions (the quality of the product introduced in the second period and the price of both products) are made after demand is known. Said differently, only design of the product(s) introduced in the first period is determined while the firm is uncertain about market conditions. Note that learning the true demand condition follows introduction of the first product and is not just a matter of learning over time. Thus, it is not possible for the firm to simply wait and learn more about the realized value of \( \tilde{\alpha} \) before introducing the product into the market.
**Assumption 4 (production):** The marginal cost of production is increasing and convex in the quality of the produced unit and constant in the number of units produced. There are no economies of scope related to production of more than one product.

On the production side, we capture the fact that high-end units cost more to produce than low-end units and that costs usually rise at an increasing rate with the quality of the product (Mussa and Rosen 1978). Specifically, we assume a quadratic cost function $C = c\delta^2$ where $C$ is the cost of producing one unit of a product of quality $\delta$.

The seller must decide which products to introduce, their quality, the order in which to introduce them, and the prices to charge for the products in each period. The decision sequence is: \(^5\)

**Stage 1:** The firm chooses the level of quality of the first product it will introduce to the market. After that introduction, the firm learns about the state of demand in the market.

**Stage 2:** The firm determines the first-period price.

**Stage 3:** The firm decides the level of quality for the second product and how many products to offer in the second period (either both products or only the new one).

**Stage 4:** The firm determines the second-period price(s).

Note that in this decision process we assume that it is optimal for the firm to develop two products. Product development, however, is costly. If such costs are sufficiently high, the firm could choose to develop only one product. Since we are interested only in situations in which the firm introduces a product line, we limit our analysis to cases in which development costs are sufficiently low and the firm’s optimal decision is to develop two products. Further, we assume that development costs are independent of the quality of the product design. Therefore, since the

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\(^5\) For simultaneous introductions in which the firm introduces both products in the first period, stages 1 and 3 change accordingly.
firm develops two products in all cases, development costs are identical and do not affect the analysis in this paper.

We find the firm’s optimal decisions by working backward from stage 4. With a second-period product line consisting of two products of qualities $\delta_h, \delta_l$, the firm chooses second-period prices for both products that maximize the profit function: 

$$\Pi_2 = q_l (p_l - c\delta_l^2) + q_h (p_h - c\delta_h^2)$$

(where $q_l$ and $q_h$ are given by the demand systems (equations 1 and 2)). This optimization yields the optimal second-period price for each product:

$$p_h^* = \frac{1}{2} \delta_h [\bar{\alpha} + c\delta_h]$$

$$p_l^* = \frac{1}{2} \delta_l [\bar{\alpha} + c\delta_l]$$

(3)

The firm chooses the second product’s quality, $\delta_2$, to maximize the second-period profit, $\Pi_2 (p_l^*, p_h^*, \bar{\alpha}, \delta_l)$:

$$\delta_2^* = \arg \max_{\delta_2} \Pi_2 (p_l^*, p_h^*, \bar{\alpha}, \delta_l),$$

(4)

where $\delta_1$ is the quality of the product introduced during the first period. Note that the preceding optimization problem captures both the possibility that $\delta_h = \delta_1$ and that $\delta_l = \delta_1$.

In the first period there is a single product of quality $\delta_1$ in the market. Since sales in the first period do not affect second-period sales, the firm sets the first-period price to maximize the profit function $\Pi_1 = Q(p - c\delta_1^2)$ given the demand system (equation 1). This optimization yields the optimal first-period price:

$$p^* = \frac{1}{2} \delta [\bar{\alpha} + c\delta].$$

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6 Equation 3 describes the expressions for the case when it is optimal for both products to have positive sales. If only one product has positive sales, the optimal price is given by $p^* = \frac{1}{2} \delta [\bar{\alpha} + c\delta]$. 


Finally, at stage 1 the firm must choose the quality of the first product before the true demand condition is known. Thus, $\delta_1$ is set to maximize the firm’s expected profits over the first and second periods:

$$\delta_1^* = \arg \max_{\delta_1} E\{\Pi_1(p^*, \bar{\alpha}) + \Pi_2(p_1^*, p_2^*, \delta_2^*, \bar{\alpha})\}$$

$$= \arg \max_{\delta_1} \left[ \frac{1}{2}[\Pi_1(p^* | \bar{\alpha} = \alpha + k) + \Pi_2(p_1^*, p_2^*, \delta_2^* | \bar{\alpha} = \alpha + k)] \right]$$

$$+ \frac{1}{2}[\Pi_1(p^* | \bar{\alpha} = \alpha - k) + \Pi_2(p_1^*, p_2^*, \delta_2^* | \bar{\alpha} = \alpha - k)] \right].$$

3. Results

Proposition 1 describes the firm’s optimal introduction decisions (with the optimal product qualities given in Table 1):

**Proposition 1:** The optimal product line introduction strategy is:

When $k \leq 0.25\alpha$, introduce both products ($\delta_h$ and $\delta_1$) in the first period.

When $0.25\alpha < k < 0.443\alpha$, introduce product $\delta_1$ in the first period; add a higher-end product, $\delta_2$ ($> \delta_1$), in the second period if demand is high and a lower-quality product, $\delta_2$ ($< \delta_1$), if demand is low.

When $0.443\alpha < k < 0.487\alpha$, introduce product $\delta_1$ in the first period; add a higher-end product, $\delta_2$ ($> \delta_1$), in the second period if demand is high and replace $\delta_1$ with $\delta_2$ if demand is low.

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7. We do not include a discount rate in the formulation of equation 6. We discuss the effect of a discount rate on the results later.

8. All proofs are given in the on-line appendix.
When $0.487\alpha < k$, introduce a product, $\delta_1$, in the first period that will sell only if demand is high; in the second period, expand the product line and introduce a new, higher-quality product, $\delta_2 (> \delta_1)$, if demand is high and replace $\delta_1$ with $\delta_2$ if demand is low.

If simultaneous introduction is not possible because of some exogenous constraint, then it is optimal to introduce product $\delta_1$ in the first period and add a lower-end product $\delta_2 (< \delta_1)$ in the second period when $0 < k < 0.0964\alpha$ and optimal to follow regime B describe above when $0.0964\alpha < k < 0.25\alpha$. For $k > 0.25\alpha$, regimes B, C, and D hold.

Proposition 1 shows the complex effect that demand uncertainty has on optimal firm decisions regarding both introduction and design of product lines. The presence of demand uncertainty can lead the firm to choose to introduce products in a line sequentially rather than simultaneously.

Result 1: The firm should introduce both products in a line simultaneously only when uncertainty is low ($k < 0.25\alpha$).

When demand uncertainty is sufficiently high, delaying design of the second product to allow the firm to optimize it to actual market conditions is more beneficial than the immediate potential profits gained from having more than one product available in the first period and the firm will introduce products sequentially. This shows that one reason for the many observable instances of sequential introduction can be seen as optimal responses by firms to demand uncertainty.9

The flip side of result 1 is that sequential introduction is optimal only if waiting to learn about the actual demand condition affects the optimal design of the second product. As can be seen from Table 1, in all of the cases of sequential introduction (excluding 1(E), which is optimal only under exogenous constraints) the quality of the second product depends on whether demand is

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9 In Moorthy and Png (1992), sequential introductions result from cannibalization between the products in the line. One way to think about the effect of uncertainty is that it makes it harder a priori to design products that will not cannibalize each other.
high or low. The value of sequential introduction in these cases stems from the firm’s ability to adjust product quality—if quality is exogenous, much of the benefit of sequential introduction disappears. Of course, the optimal quality of the second product will not be simply a function of the demand condition; it also will be constrained by the quality of the first product introduced by the firm. Thus, to take full advantage of the benefits of sequential introduction, the firm should take this effect into account when deciding on the quality of the first product. Figure 1 shows the optimal quality of the first product under sequential introduction and also the quality of a product introduced by a myopic firm that does not take providing a second product into account.

Table 1: Product qualities

<table>
<thead>
<tr>
<th>Simultaneous introduction ( (k &lt; 0.25\alpha) )</th>
<th>( \delta_1 )</th>
<th>( \delta_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta_{lh} = \frac{4(\alpha^2 - k^2) - 16\sqrt{16k^4 - 17k^2 \alpha^2 + \alpha^4}}{15c\alpha} ); ( \delta_{ll} = \frac{\delta_{lh}}{2} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sequential introduction: ( \alpha )</td>
<td>( \frac{\alpha + k + c\delta_1}{3c} )</td>
<td>( \delta_1 ) ( \frac{1}{2} )</td>
</tr>
<tr>
<td>regime B ( (0.25\alpha \leq k &lt; 0.443\alpha) )</td>
<td>High demand: ( \frac{\alpha + k + c\delta_1}{3c} )</td>
<td>Low demand: ( \frac{\delta_1}{2} )</td>
</tr>
<tr>
<td>Sequential introduction: ( \alpha )</td>
<td>( \frac{\alpha + k + c\delta_1}{3c} )</td>
<td>( \delta_1 ) ( \frac{1}{2} )</td>
</tr>
<tr>
<td>regime C ( (0.443\alpha \leq k &lt; 0.487\alpha) )</td>
<td>High demand: ( \frac{\alpha + k + c\delta_1}{3c} )</td>
<td>Low demand: ( \frac{\alpha - k}{3c} )</td>
</tr>
<tr>
<td>Sequential introduction: ( \alpha )</td>
<td>( \frac{\alpha + k + c\delta_1}{3c} )</td>
<td>( \delta_1 ) ( \frac{1}{2} )</td>
</tr>
<tr>
<td>regime D ( (0.487\alpha &lt; k) )</td>
<td>High demand: ( \frac{\alpha - k}{3c} )</td>
<td>Low demand: ( \frac{\alpha - k}{3c} )</td>
</tr>
<tr>
<td>Sequential introduction: ( \alpha )</td>
<td>( \frac{\alpha + k + c\delta_1}{3c} )</td>
<td>( \delta_1 ) ( \frac{1}{2} )</td>
</tr>
<tr>
<td>regime E ( (0 \leq k &lt; 0.0964\alpha; ) ( For 0.0964\alpha \leq k &lt; 0.25\alpha ) refer to regime B results above)</td>
<td>High demand: ( \frac{\alpha - k}{3c} )</td>
<td>Low demand: ( \frac{\alpha - k}{3c} )</td>
</tr>
<tr>
<td></td>
<td>( \frac{16(\alpha^2 - k^2) - 2\sqrt{64k^4 - 74k^2 \alpha^2 + 10\alpha^4}}{27c\alpha} )</td>
<td>( \delta_1 ) ( \frac{1}{2} )</td>
</tr>
</tbody>
</table>
Result 2: Under sequential introduction, compared to products of a myopic firm, the first product’s optimal quality is higher when demand uncertainty is low, lower when demand uncertainty is intermediate, and higher when demand uncertainty is high.

Result 2 shows that the optimal quality of the first product changes in a nontrivial way in response to demand uncertainty and that sometimes it will be higher and other times it will be lower than the product quality chosen if the (myopic) firm does not take into account the impact the first product will have on the second product. We can clearly identify three different regions in Figure 1 that are characterized not only by the comparison to the myopic firm but also by the breaks in quality level that occur when the optimal decisions of the firm change in response to uncertainty. These breaks correspond to the change from regime E to B and regime C to D in proposition 1.

Figure 1: First-product quality: optimal vs. myopic
\[(\alpha = 1; c = 1)\]
To understand the reasons for the pattern that emerges from proposition 1 and results 1 and 2, note that with endogenous qualities the higher-end model in the product line will always have higher expected margins (otherwise it would not be optimal to introduce the higher-end model). Therefore, the firm has an incentive to try and introduce the higher-end model as soon as possible because of the higher profit potential. On the other hand, making a “mistake” in the design of a product—and therefore missing the market—has more adverse consequences in the case of the high-end model because of the higher margins. So when demand is uncertain, the firm also has more incentive to delay designing and introducing the high-end model until it can be certain that the design is right. It is the interplay between these two forces that leads to the pattern of results reported in proposition 1.
When demand uncertainty is low, the benefit of optimizing the second product based on actual conditions is small. Therefore, delaying introduction of the second product until the second period is not optimal. The firm prefers to introduce both products immediately so it can maximize its profit potential in the first period (proposition 1, part A). If, for some reason, simultaneous introduction is not possible, then it is optimal to introduce a higher-quality product in the first period and a lower-quality product in the second period (proposition 1, part E). These results—that either a simultaneous introduction or a high-low sequence is optimal when the level of demand uncertainty is low—are consistent with the findings of Moorthy and Png (1992), in which, in a model with no demand uncertainty, demonstrated that these two options are the optimal ones.

By introducing both products before demand is known, the firm forgoes the opportunity to optimize the second product’s design to meet actual market conditions. As demand uncertainty increases, the benefits of optimizing the second product based on actual conditions are much greater and more than offset the loss of some profit potential that would be generated by releasing the product in the first period. So sequential introduction becomes optimal. The benefits from adjusting the high-end model to actual market conditions are greater (because of the higher margin for that product) and, therefore, even though there is an incentive to launch the high-end model earlier, it is optimal for the firm to launch a product of somewhat lesser quality in the first period (see Figure 1). Then, if demand turns out to be high, the firm can launch an optimized, high-end model in the second period. If demand turns out to be low, the firm can launch a still lower quality model in the second period (proposition 1, parts B and C). The quality of the first product represents a compromise between the need to maximize second-period profits by offering a product that is *ex post* as close as possible to optimal (especially at
the high end if demand turns out to be high) while avoiding giving up too much potential profit in the first period. Lowering the quality of the first product reduces the risk that the product will not appeal to consumers if demand turns out to be low and “guarantees” the firm a certain amount of profit in the first period regardless of the state of demand while also not constraining the firm too much in its ability to introduce an optimized, high-end product in the second period if demand turns out to be high.

At high levels of uncertainty it becomes more difficult to find a good compromise level for the quality of the first product. A level of quality that will generate positive profits when demand is low forfeits most of the profit potential if demand is high and vice versa. Because it is more important to capture the increased profit potential if demand turns out to be high,\(^\text{10}\) the first product’s quality level will be biased toward the optimal level for the high-demand condition. At high levels of uncertainty, however, that means a greater mismatch with market conditions if demand turns out to be low, to the point that the firm prefers to discontinue the first product and replace it with a new second-period product optimized for the low-demand condition (proposition 1, part C). Thus, when uncertainty is great enough, we may observe a firm replacing existing products with new ones instead of adding new products alongside the old ones.

At even higher levels of uncertainty, the inability to find a good compromise quality level leads the firm to ignore the possibility of demand being low and to introduce a product that is optimized for the high-demand condition (proposition 1, part D). In a sense, the firm’s optimal decision is to bet on demand being high even though, \textit{a priori}, the probability of that is only 50%. When that is the best approach, of course, it is optimal for the firm to raise the quality of the first product (this is clearly seen in the jump upward in the first product’s quality as shown on

\(^{10}\) This rationale is similar to findings in the economic literature on investment under uncertainty: with increased uncertainty, the marginal profitability of capital may rise and investment therefore increases (Abel 1983).
the right side of Figure 1). If this bet on demand being high succeeds, the firm follows with a low-end product in the second period; otherwise, the first product is pulled from the market and a redesigned product that better meets the realized demand condition is introduced in its place.

### 3.1 Product quality and product line length

The fact that the first product is designed when the firm is uncertain about the demand condition means that the first product’s quality will not be optimal *ex post*. Its quality represents a compromise between conditions of high and low demand. The quality will be too low (in an *ex post* optimality sense) if demand turns out to be high and too high if demand turns out to be low. Also, the length of the product line—that is, the size of the difference in quality between the high-end and the low-end product—will necessarily be smaller than optimal if demand turns out to be high and larger than optimal if demand turns out to low.\(^\text{11}\)

Consider, for example, part E of proposition 1 \((0 < k < 0.0964\alpha)\): The firm introduces a high-end product in the first period but the quality of the product is still necessarily lower than the *ex post* optimal level if demand turns out to be high. As a result, the second period’s lower-end product will also be of lower quality than the *ex post* optimum because of incentive-compatibility constraints given the lower (than optimal) quality of the first-period product. Since the quality of the second-period product is no longer affected by uncertainty about demand, the difference between the lower-end product’s quality and the level of quality that is optimal *ex post* is smaller than the same difference for the first, high-end product. Thus, the product-line length will be shorter than is optimal *ex post* if demand turns out to be high.

On the other hand, if demand turns out to be low, the quality of the high-end product exceeds the optimal *ex post* level. As a result, the low-end product’s quality also will exceed the optimal

\(^{11}\) The exception is regime D in proposition 1 in which the firm ignores the possibility of low demand and designs the product under an assumption that demand will be high. In that case, if demand turns out to be high, the product line is exactly the same length as the optimal *ex post* product line.
level because the incentive-compatibility constraints are less severe given the higher quality of the first-period product and that product’s relative lack of appeal to consumers in the market. However, since the quality of the second-period product is not affected by uncertainty about demand, the difference between the actual and optimal quality for the low-end product will be smaller than the same difference for the high-end product. Thus, the length of the product line is greater than optimal if demand turns out to be low. Similar rationales apply when the firm operates as proscribed in parts A, B, and C of proposition 1.

3.2 The effect of impatience

So far we have assumed that the firm is patient and does not discount future profits (second-period profits). When the firm is impatient and discounts future profits compared to the first period, that impatience may affect the firm’s decisions. We introduce impatience into the model by modifying equation 6 to include a discount factor:

$$
\delta^*_i = \arg \max_{\delta} E\{ \Pi_1(p^*_i, \tilde{\alpha}) + e^{-r} \Pi_2(p^*_i, p^*_h, \delta^*_2, \tilde{\alpha}) \}
$$

(7)

$$
= \arg \max_{\delta} \left[ \frac{1}{2} \Pi_1(p^*_i | \tilde{\alpha} = \alpha + k) + e^{-r} \Pi_2(p^*_i, p^*_h, \delta^*_2 | \tilde{\alpha} = \alpha + k) \right] + \frac{1}{2} \Pi_1(p^*_i | \tilde{\alpha} = \alpha - k) + e^{-r} \Pi_2(p^*_i, p^*_h, \delta^*_2 | \tilde{\alpha} = \alpha - k) \right]
$$

where $r \geq 0$ is a discount factor for which higher values represent more impatience on the firm’s part. Before discussing the results, we should note that conceptually the model in the paper does not apply to situations with a high level of impatience. The fact that the firm plans to introduce a product line, possibly sequentially, implies that the firm is not too impatient. Nonetheless, considering the effect of impatience provides additional insight into the forces affecting product line decisions. The direct effect of impatience is to reduce the present value of the second-period profit. Consequently, sacrificing potential first-period profit to increase the potential for profit in the second period becomes less attractive as the discount factor rises. Figure 2 depicts the regions
for different introduction regimes as a function of the level of uncertainty \((k)\) and the discount factor \((r)\).\(^{12}\) As can be seen in Figure 2, regimes B and C are no longer optimal when the discount factor is sufficiently high regardless of the level of uncertainty. Betting on demand being high (regime D), on the other hand, becomes more attractive with a higher discount factor because, as the first-period profit becomes relatively more important, the temptation to bet and potentially get a greater first-period profit becomes greater. The reduced attractiveness of regimes B and C and increased attractiveness of regime D leads to switching to regime D and betting on demand being high at lower levels of uncertainty when the discount factor is high.

Since regime A involves simultaneous introduction of both products in the first period, thus increasing the potential profit from period 1, we might expect that switching between regime A and regime B/C will occur at higher levels of uncertainty as the discount factor increases. However, that is not the case and the switching point between regime A and regime B/C remains the same regardless of the level of impatience (up to the point that regime D becomes optimal). Even though regimes B and C become less attractive compared to regime A because the net present value of the second-period profit decreases, the importance of ensuring a high level of first-period profit grows. As we discussed before, the lower quality of the first product under regimes B and C is less risky in terms of first-period profit potential than introduction of both products under regime A at high levels of uncertainty. This effect tends to make regimes B and C more attractive than regime A and cancels the reduced attractiveness due to increased impatience. Thus we see that impatience has the effect of causing the firm to choose a riskier approach at high levels of uncertainty but does not change the firm’s approach at low levels of uncertainty.

\(^{12}\) We treat regimes B and C as one region in Figure 2. The differences between these two regimes are inconsequential for the discussion in this section.
Figure 2: The effect of the discount factor and uncertainty on the optimal introduction sequence
\((\alpha = 1; c = 1)\)

4. Conclusions

This paper models the optimal product design and introduction sequence a firm should use when introducing a product line. In our model, the firm is initially uncertain about demand for the product line and learns the actual demand condition only after introduction of the first product. The basic tension in the model results from the urge, on one hand, to introduce products quickly to appeal to more consumers and the need, on the other hand, to delay introduction of some products to optimize their design for the actual market condition.
We show that the level of demand uncertainty impacts the firm’s optimal decisions. When uncertainty is low, the firm should introduce the two products simultaneously. At higher levels of uncertainty, the value of the opportunity to adjust the product line to actual market conditions is greater and the firm is better off using a sequential introduction. We find that at intermediate levels of uncertainty the firm should first introduce a product of relatively lower quality (compared to the myopic quality level) and then, if demand turns out to be high, the first product should be followed by a higher-end product. If demand turns out to be low, the first product should either be followed by a lower-end product or replaced with a new product that better meets the demand.

At high levels of uncertainty, the firm should use a betting approach that involves first introducing a high-end product designed specifically for high demand (this product will not garner any sales if demand turns out to be low). If demand indeed turns out to be high, the firm should add a second, lower-end product. If demand turns out to be low, the firm should remove the first product from the market and replace it with a new one that better suits demand. Finally, if the firm can only use sequential introductions, we find that at low levels of uncertainty the firm should introduce a high-end product first, followed by a low-end product.

These findings extend our understanding of how firms’ product line decisions are affected by uncertainty. First, they explain why we observe different product line introduction sequences in various industries. Casual observation shows that firms often introduce product lines sequentially rather than simultaneously. Moorthy and Png (1992) described how Volvo launched a lower-end model, the four-cylinder Volvo 740, only seventeen months after introducing the higher-end six-cylinder Volvo 760. In other cases, we can observe firms first introducing a lower-end model
that is followed by a higher-end model.\textsuperscript{13} When Toyota launched the second-generation Camry in the U.S., it started with a V4 engine model, only later adding a V6 engine to the line. In October 2001, Apple launched the first model of the iPod MP3 player with a 5 gigabyte hard drive, followed in March 2002 by a higher-capacity model with a 10 gigabyte hard drive. Why do we observe these different introduction sequences? Our answer is that they may well be the result of optimal responses by firms to demand uncertainty they face, and that this response can lead to sequential introductions with the second product possibly of higher (or lower) quality than the first product introduced.\textsuperscript{14}

It is interesting to note in this context that managers seem to be aware of the importance of uncertainty and its possible impact on their decisions. We asked managers participating in executive education classes if and why they think firms should concentrate first on introducing and developing the high-end or low-end models in a product line. A sizable minority (about 35\%) indicated that firms should concentrate first on the low end rather than the high end. The most common factor mentioned in support of the low-end-first recommendation was the reduction of risk or uncertainty. Typical comments were “appeal to a wider market and a lower risk level,” “learn market needs from consumers’ reactions,” and “more certain revenue stream to help develop future models.”

Second, the results provide important direction to managers regarding how to guide initial development efforts towards the low-end and/or high-end products in the line.

\textsuperscript{13} In looking at cases in which the low-end model was introduced first, we should be careful to distinguish between situations in which there was no technical ability to launch a better model at the time of the first launch and those in which there was no such technological constraint. In all of the cases described in this paper, the technology existed to introduce the higher-end model at the time of the launch of the first product.

\textsuperscript{14} One can contrast this uncertainty explanation with the cannibalization explanation of Moorthy and Png (1992), which can only account for situations when the second product is of higher quality by relying on exogenous technological constraints.
Third, the results point to the central role played by uncertainty regarding acceptance of the products in the market in determining introduction decisions. It is instructive in this regard to compare our results to those obtained by Moorthy and Png (1992). In their model, there is no demand uncertainty; concerns about potential cannibalization between the two products determine the firm’s introduction decisions. If cannibalization is not a serious issue, the firm should use simultaneous introduction; otherwise, it should use a sequential high-low introduction sequence. In our model, on the other hand, uncertainty plays a key role and cannibalization is less of an issue because it can be managed through design of the product line (an option that is not available in the Moorthy and Png model) rather than solely through the introduction sequence. When there is no uncertainty in our model (when \( k = 0 \)), we find that it is optimal to use simultaneous introduction, which is consistent with the results of Moorthy and Png. Our findings, however, point to the importance of uncertainty regarding market acceptance and demand conditions. At higher levels of uncertainty, the firm is better off using sequential introduction. At intermediate levels of uncertainty, sequential introduction may result in a low-high sequence. At high levels of uncertainty, the firm is better off betting on demand being high and introducing a high-end product first. These changes in optimal policy determined by the firm’s degree of uncertainty underscore how important it is for a firm to understand the uncertainty it faces when making product line decisions.

Our model is predicated on the ability of the firm to adjust the design of the second-period product based on actual market conditions. This requires that the technological options available to the firm along the relevant quality dimensions be relatively abundant, thus enabling the firm to respond to actual conditions. The most common situations of this type are when the relevant quality dimension consists of an attribute or feature that varies continuously. The iPod’s hard
drive is one such example. Apple can choose essentially any size of hard drive (assuming the required technology exists). If, on the other hand, the technological options available to the firm are few, our model may no longer be relevant since the firm may not be able to respond to actual market conditions by changing the design of the product. Consider the case in which the quality dimension consists of inclusion or exclusion of some feature like Bluetooth capability. Once the design of the first product is complete, the firm no longer has any options remaining regarding design of the second product along that dimension. If the first product includes Bluetooth capability, the second model cannot if it is to be different from the first. In this case, the firm still must decide which product configuration to introduce first, but the decision is no longer influenced by the ability to respond to actual market conditions in the second period. Rather, it is driven by the margins and the expected profitability of the two configurations as in the Moorthy and Png (1992) model. A more complex situation arises when we consider a bundle of a number of different features, each of the includable/excludable variety. In that case, if different combinations of features can be evaluated along a single quality dimension, the model described in this paper applies.
References


