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Multi-Product Quality Competition: Impact of Resource Constraints

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W e study a multi-product firm with limited capacity where the products are vertically (quality) differentiated and the customer base is heterogeneous in their valuation of quality. While the demand structure creates opportunities through proliferation, the firm should avoid cannibalization between its own products. Moreover, the oligopolistic market structure puts competitive pressure and limits the firm's market share. On the other hand, the firm has limited resources that cause a supply-side fight for adequate and profitable production. We explicitly characterize the conditions where each force dominates. Our focus is on understanding how capacity constraints and competition affect a firm's productmix decisions. We find that considering capacity constraints could significantly change traditional insights (that ignore capacity) related to product-line design and the role of competition therein. In particular, we show that when the resources are limited, the firm should offer only the product that has the highest margin per unit capacity. We find that this product could be the diametrically opposite product suggested by the existing literature. In addition, we show that for intermediate capacity levels, whereas the margin per unit capacity effect dominates in a less competitive market, proliferation and cannibalization effects dominate in a more competitive market.

Key words: product-line; limited capacity; competition; quality differentiation; OM-marketing interface *History:* Received: January 2011; Accepted: March 2012, after 1 revision.

1. Introduction

Multi-product firms account for 91% of the output in US manufacturing and they often make short- to medium-term adjustments in their product-lines (Bernard et al. 2006). It is reported that 68% of the multi-product US manufacturing firms alter their product mix, 12% by dropping at least one product, 11% by adding at least one product, and 45% by both adding and dropping at least one product in the medium term. However, success of these product-line decisions depends largely on the firm's existing production capacity. Many furniture manufacturers (e.g., Rieke Office Interiors, Elgin, IL) produce custom and standard furniture using the same fixed capacity. In another example, the available capacity of a flexible machine (machining time) is allocated between high-and low-quality products where a higher quality product requires slower machining speeds (smooth finish) thereby taking a longer time to produce. Similarly, Turo Tailor produces both its mass-produced and custom-tailored suits in its factory in Kuopio, Finland (Sievänen and Peltonen 2006), in which a custom-tailored suit uses

more of the available factory time compared with a mass-produced suit.

The majority of the firms in services are also multiproduct. For example, public or private, many universities are constrained by space for student housing, while they offer a range of dorm room types with different sizes and amenities at various prices (Pryor 2006). The cruise line industry is another example where differentiated product-lines are the norm. They offer a wide range of staterooms from small rooms (119 sq. ft.) to luxurious suites with private jacuzzis and grand pianos (> 2000 sq. ft.). In this industry, supply capacity is notoriously limited (Cruise Travel Specialist 2010). There is a backlog for new builds around the world's shipyards, and refurbishing the existing ships is the rule of the game. Upgrading to premium services is also an option in many information technology products where users can have access to larger storage space, bandwidth usage, or datatransfer capabilities. In another example, airlines offer differentiated products such as economy, business, and first-class seats. They offer a subset of these products in their aircrafts, and passengers self-select from this subset on a specific origin-destination pair. The

subset often changes in the short to medium term. For example, while Cathay Pacific Airways offered no first-class seats on route San Francisco to Hong Kong in March of 2008 (in addition to 2520 business and 21,504 economy-class seats), they chose to offer 632 first-class seats in December of the same year (in addition to 2370 business and 16,274 economy-class seats).¹ We also note the increased competition during the same time period on that route.²

For airlines, changing the seating configuration in an aircraft is a common short- to medium-term solution, and it is a minor operation that is accomplished fairly easily.³ Even a complete refurbishing and refitting⁴ (that is, above and beyond a minor seat rearrangement) may take as little as 21 days.⁵ Hence, the specific type and volume of offerings can be adjusted with short- to medium-term commitments without making investments for new aircrafts.

In all of the above-mentioned examples, the supply capacity constraint becomes extremely important and often characterizes firms' operations. Under those conditions, ignoring supply capacity while deciding the product-line could be sub-optimal. However, due to traditional organizational structure, firms often do not determine product-line decisions taking supply capacity into account, even though the ability to produce depends on it critically. For example, the airline industry is a well-known example where capacity constraints are a part of the product-mix decisions "as an error term at best."⁶ Our aim is to understand the inefficiencies caused as a result of this omission.

In this article, we explicitly model such situations in practice where capacity constraints need to be taken into consideration ahead of time. We analyze the optimal short- to medium-term product-line decisions when the resources may be limited. In particular, we consider multiple quality-differentiated products that differ not only in their unit operating costs and prices (based on quality), but also in the resources they consume per unit. In such a situation, there are three interactions at play: (i) there is an intra-firm competition among the products for the demand; (ii) there is an intra-firm competition among the products for the resource capacity; and (iii) there is an inter-firm competition for the market share. In this setting, we explore a number of important research questions such as: What is the impact of supply capacity limitations on optimal product-line choice? How does the optimal product line change with intensity of competition?

Compared to a traditional firm that makes marketing and operations decisions sequentially, we show that a firm that integrates marketing and operations decisions can have better profits. Moreover, the product-mix decisions might be different. Among other results, we have the following key findings.

- We find that the optimal product-line choice should depend not only on price discrimination and cannibalization but also on efficient resource utilization. We show that, in designing their product-lines, firms need to consider the margin per unit capacity in addition to the trade-off between price, quality, and demand. For example, it is well known that when supply constraints are disregarded and the cost structure favors the high-quality product, a firm should offer only the high quality product. However, we prove that the firm may benefit from including a lower quality product in its product-line when capacity is scarce. Interestingly, in this case, firms offer more product variants because of the supply constraint.
- As opposed to the findings in the literature (that ignore capacity constraints), we find that more intense competition may result in a product-line policy change for the firm when the supply capacity is limited. We show that for intermediate capacity levels, whereas the margin per unit capacity effect dominates in a less competitive market, proliferation and cannibalization effects dominate in a more competitive market. In particular, when there is an increasing cost-to-quality ratio, increasing competition forces the firm to drop the product with better margin per unit capacity, and when there is a decreasing cost-to-quality ratio, increasing competition forces the firm to add the product with lower margin per unit capacity to its productline.

The rest of the article is organized as follows. The next section provides the literature review. Our model and the resulting equilibrium are presented in section 3. Section 4 discusses the effects of competitive intensity on the product-line choices of the firms. Our concluding remarks are presented in section 5.

2. Related Literature

Optimal product-line design is an important and well-studied problem in economics and marketing literatures. The stream of research on quality (vertical) differentiation was pioneered by Mussa and Rosen (1978). Moorthy (1984) was the first to introduce this framework into the marketing literature, and finds that a monopolist chooses inefficient quality levels due to cannibalization concerns. Bhargava and Choudhary (2001) discuss when it is optimal for a monopolist to offer vertically differentiated products (as opposed to selling a single product) depending on the cost-to-quality ratio of the products. Desai (2001) characterizes how differences in taste affect the impact of cannibalization on product-line choice. We contribute to the above stream of articles by jointly considering both the supply and the demand side of product-line management. None of these articles takes into account resource capacity constraints, which is the key driver of our results.

The oligopolistic Cournot (quantity) competition where firms offer vertically differentiated products is also a well-studied problem. Gal-Or (1983) finds that average quality decreases as the competition intensity increases, and Banker et al. (1998) finds the same result when firms are symmetric and quality improvement costs do not depend on the number of firms in the market. In contrast, we find that increasing competition intensity can result in a higher average quality due to the capacity constraint. De Fraja (1996) shows that an incumbent responds to market entry by reducing its product variety, while Johonson and Myatt (2003) find that, unless the demand model is such that marginal revenue is increasing in some regions, market entry never induces an incumbent to expand its product-line. In our model, marginal revenue is decreasing everywhere, but we show that market entry can still lead to an incumbent to expand its product-line because of the resource constraints. Different from these articles, we explicitly model the supply constraint, which leads to opposite results in some cases regarding the impact of competition on the product-lines. Drivers of these results are discussed in detail in the article, but essentially this is because of how competition affects firms' capacity allocation.

We also contribute to the literature that consider coordination between marketing and operations decisions (Eliashberg and Steinberg 1993). Crittenden (1992) discusses the coordination between marketing and manufacturing and points that capacity allocation is the most critical issue the two functions need to address (p. 41). On the basis of her simulation studies, she suggests 18 rules for making capacity-allocation decisions (e.g., prioritize the most profitable customers). Shapiro (1977) states that capacity planning is one of eight major issues that requires close cooperation between marketing and manufacturing. Finally, Lovelock (1984) provides qualitative capacity-allocation prescriptions for a capacity-constrained service organization that serves multiple customer segments. The closest example to our work is Monroe and Zoltners (1979), who study the pricing of a product-line taking into account scarcity of resources. They argue that resource scarcity can be due to shortages in some raw materials. Similar to our article, the firm decides how to allocate the common resource among its products. However, unlike our article the demands of products are independent of each other, and, in addition, their discussion is restricted to a monopoly. Krajewski et al. (2010) explain how a firm's final

production mix critically depends on its capacity through the measure of the unit margin per unit resource required to produce one unit of that product. However, unlike our article, they study a traditional firm where the market-related parameters such as pricing and projected demand are determined by the marketing department and used as fixed inputs in the production-related problems. Our aim is to understand the inefficiencies caused as a result of this sequential decision making and emphasize the importance of coordination at the product-line design stage.

Our work is also related to the articles that study the effects of operational elements on a firm's product-line (Ramdas 2003). Dobson and Yano (2002) consider a shared resource used for offering a product-line similar to our setup, but their model is different from ours in that products have independent demands, so cannibalization is not a factor. Netessine and Taylor (2007) study the interplay between a firm's production technology (production to order vs. production to stock) and its vertically differentiated product-line. Dobson and Kalish (1988), Chayet et al. (2009), and Yayla-Kullu et al. (2011) consider a shared resource used for offering a product-line similar to our setup. However, none of these articles investigates the simultaneous effects of multi-product competition and operational capacity. With this article, we aim to contribute to the above literature by incorporating such a capacity constraint as well as the competitive influence.

In summary, in this article, we simultaneously study economic forces including product proliferation, cannibalization, resource utilization, and competition. These forces are all identified as "critically important" by their respective academic fields, that is, marketing, economics, and operations management. However, the existing literature lacks a study that investigates these forces in an integrated framework. In this article, we acknowledge the fact that each and every one of these forces is very important, and we identify conditions on costs, qualities, and resource limitations that favor each force. We further show that these conditions are affected by the level of competition in the marketplace.

3. Multi-product Oligopoly with Capacity Constraints

In this section, we present the model and then discuss the resulting equilibrium. When presenting our model, first we describe the supply side, then we go over our demand model, and finally we discuss how we model the competition.

We consider $n \ge 1$ (competing when n > 1) firms with limited capacities in the short to medium term. Index *j*:1..*n* indicates the firms. Each firm has the technological capability to offer multiple products. It can serve a subset of *m* products that have differing levels of quality. Index i:1..m indicates the products. Note that m could be an arbitrarily large number, which allows the firms to offer a large menu of offerings drawn from an arbitrarily fine grid of qualities as in Johnson and Myatt (2003, 2006). Different from the literature, each firm has a capacity of K_j . The firm decides how to allocate its limited capacity to the products (including not to allocate any capacity to one of the products) to maximize the profitability.

Each unit of product *i* has quality q_i requiring s_i units of the capacity. Firm *j* offers product *i* at a constant marginal cost of c_{ii} .⁷ Following the notation in the literature (Bhargava and Choudhary 2001, Jing 2006, Johnson and Myatt 2003), we order the products so that $q_m > q_{m-1} > \cdots > q_1 > 0$. In our analysis, we also assume $c_{jm} \ge c_{j,m-1} \ge \cdots \ge c_{j1} > 0$ and $s_m \ge s_{m-1} \ge \cdots \ge s_1 > 0$ to avoid trivial cases. Although more interesting results are found when higher quality products consume strictly more resources than the lower quality products, we will point out the cases where results continue to hold true when s_i is the same for all products. Indeed, for the airline example, first-class seats are perceived as better quality ($q_2 > q_1$); they are bigger in size ($s_2 > s_1$), and it costs more to serve them $(c_2 > c_1)$ due to higher number of flight attendants, food and drinks, etc.

We adopt the classical vertical differentiation demand model (cf., Moorthy 1984, Mussa and Rosen 1978, Tirole 1988). The customers vary in their willingness to pay for quality. Specifically, the customer types θ are uniformly distributed⁸ in the unit interval [0,1] with unit total mass. Because the market size is normalized to 1 with this assumption, capacity parameter (K_j) should be interpreted as the capacity-to-market size ratio. When type θ customer buys product *i* at the market-clearing price p_i , her utility is equal to $U(q_i, p_i, \theta) = \theta q_i - p_i$. Therefore, the measure of quality q_i should be interpreted as the scaled monetary value of quality, as a customer θ is willing to pay θq_i for this product (cf. Johnson and Myatt 2003, p. 753).⁹

If the customer does not buy a product, her utility is zero. Thus, each customer has multiple options, buying a product from the menu of offerings or not buying a product at all, and she chooses the one that maximizes her utility as in Bhargava and Choudhary (2001) and Johnson and Myatt (2003, 2006). This yields $0 \le \theta_1 \le \theta_2 \le \cdots \le \theta_m \le 1$ such that customers in $[0, \theta_1)$ do not buy a product, customers in $[\theta_1, \theta_2)$ buy product 1,..., and customers in $[\theta_m, 1]$ buy product *m*. This assumes that when customers are indifferent, they choose buying over not buying and higher quality product over others. So, the demand for product *i* is $D_i = \theta_{i+1} - \theta_i$. It is straightforward to show that the marginal customer θ_i who is indifferent between buying products *i* and (i - 1) is given by $\theta_i = (p_i - p_{i-1})/(q_i - q_{i-1})$, and, similarly, the marginal customer θ_1 who is indifferent between buying product 1 and not buying a product at all is given by $\theta_1 = p_1/q_1$. Thus, we can express the demands for different product types given the price vector (**p**) as follows:

$$D_{i}(\mathbf{p}) = \begin{cases} 1 - \frac{p_{i} - p_{i-1}}{q_{i} - q_{i-1}}, & i = m; \\ \frac{p_{i+1} - p_{i}}{q_{i+1} - q_{i}} - \frac{p_{i} - p_{i-1}}{q_{i} - q_{i-1}}, & 1 < i < m; \\ \frac{p_{i+1} - p_{i}}{q_{i+1} - q_{i}} - \frac{p_{i}}{q_{i}}, & i = 1. \end{cases}$$
(1)

Note that price discrimination, product proliferation, and cannibalization are well-known conflicting forces for a firm in such a vertically differentiated demand model (cf. Moorthy 1984, Mussa and Rosen 1978, Tirole 1988). Ignoring the capacity constraint and competitive interactions, if a firm offers a single product of high quality (product h), the sales would be equal to $(1 - \frac{p_h}{q_h})$. Introducing a second product of lower quality (product *l*) may increase the overall demand by $(\frac{p_{li}}{q_{li}} - \frac{p_{l}}{q_{l}})$, which would be the benefit of proliferation. Moreover, through price discrimination, the firm further benefits from offering multiple products in the market. However, under the same conditions, some customers switch from buying the high-quality product to buying the low-quality product, reducing the high-quality sales by $(\frac{p_h - p_l}{q_h - q_l} - \frac{p_h}{q_h})$, which is known as *cannibalization*. In the existing literature, product-line choice centers on deciding the quality differentiation in the product line, where firms analyze the trade-offs associated with the benefits of product proliferation and the effects of cannibalization that arise from the introduction of a new product. Analysis of such models in terms of competition, cost, and market conditions provides insights into whether firms should offer a high- or a low-quality product.

In this article, firms participate in a multi-product quantity (Cournot) competition as in Johnson and Myatt (2003, 2006). Each firm *j* simultaneously decides how to allocate its capacity among the *m* product types. In particular, the firm decides how many units of each product to offer, that is, $w_j = (w_{j1}, \ldots, w_{jm})$. This in turn determines its menu of offerings. Note that the firm does not have to use all of its available capacity, that is $\sum_i s_i w_{ji} \leq K$, and this inequality can hold strictly. Given the firms' product offerings $\mathbf{w} = (w_1, \ldots, w_n)$, corresponding prices $\mathbf{p}(\mathbf{w})$ are given by the solution of following equations:

$$D_i(\mathbf{p}) = \sum_j w_{ji} \qquad \forall i.$$

Note that $D_i(\mathbf{p})$ is as given in equation (1). In equilibrium, given the competitors' offerings w_{-i} , each

firm *j* chooses its product offerings w_j to maximize its profit Π_j , which is given by

$$\Pi_j(w_j, w_{-j}) = \sum_{i=1}^m (p_i(w_j, w_{-j}) - c_{ji}) w_{ji}.$$
 (3)

Let us also define the feasible product offerings for capacity K_i as follows:

$$W_K = \{(w_{ji}) : \sum_i s_i w_{ji} \le K_j\}$$

We look for a Nash equilibrium w_i^* which solves

$$w_j^* = \arg \max_{w_j \in W_{K_j}} \Pi_j(w_j, w_{-j}^*) \tag{4}$$

LEMMA 1. As Π_j is jointly concave in w_j on convex set W_K , which is defined by linear constraints, the equilibrium can be obtained by solving the first-order conditions.

All proofs appear in the Appendix. This lemma shows that the most general form of the problem with asymmetric costs and asymmetric capacities is easily solvable. Following the literature, we will characterize our results using symmetric firms. However, we will complement these results with corollaries and numerical examples to show how they generalize to a wider range of parameters.

In the following, we characterize the Nash equilibrium in closed form when there are symmetric firms in the market, that is, all firms have the same capacity K, and they have access to the same production technology resulting in the same production costs c_i .¹⁰ After we present our results in the following two propositions, we will show how some interesting results generalize to asymmetric capacity and asymmetric cost cases.

We also present our results for two product types, that is, m = 2. Index *i*:*h*,*l* indicates the highand the low-quality products, respectively. Keeping the product set with two variants makes our analysis tractable, allowing us to focus on our key research question and characterize the impact of capacity constraints on firms' product-line choices under competition. Note again that following each result, we will present numerical examples to show how our results continue to hold with a greater number of product variants, and how these are contradicting to the existing literature. We define threshold capacity levels \overline{K} that are functions of the number of firms (n) which are explicitly stated in the Appendix. These thresholds are useful for describing the firms' optimal policy.

Propositions 1 and 2 describe the oligopolist firm's equilibrium product offerings when there is an increasing cost-to-quality ratio (i.e., $c_h/q_h > c_l/q_l$) and a decreasing cost-to-quality ratio (i.e., $c_h/q_h < c_l/q_l$), respectively. The role of cost-to-quality ratio has attracted considerable attention in the vertically differentiated product-line design literature (Bhargava and Choudhary 2001, Jing 2006, Johnson and Myatt 2003). It is a measure of productivity¹¹ where inputs (i.e., unit operating costs) are weighed against outputs (i.e., perceived quality levels by the customers). When there is an increasing (decreasing) cost-to-quality ratio, cost structure favors low- (high-) quality product, and proliferation (cannibalization) dominates the product-line decisions when supply capacity is disregarded. In the following, we will show how including the capacity constraints changes this established perception in the product-line design.

PROPOSITION 1. Suppose $c_l/q_l < c_h/q_h$. The game has a symmetric pure strategy Nash equilibrium as follows:

- 1. If $q_l c_l \ge q_h c_h$, the firm offers only product L for all capacity levels.
- 2. If $q_h c_h > q_l c_l$ and $\frac{q_h c_h}{s_h} < \frac{q_l c_l}{s_l}$, then if $K \le \bar{K}_1^{(n)}$, the firm offers only product L; if $K > \bar{K}_1^{(n)}$, the firm offers both products L and H.
- 3. If $q_h c_h > q_l c_l$ and $\frac{q_h c_h}{s_h} \ge \frac{q_l c_l}{s_l}$, then if $K \le \overline{K}_2^{(n)}$, the firm offers only product H; if $K > \overline{K}_2^{(n)}$, the firm offers both products Land H.

With a single-product setup, Jing (2006) defines a *relative cost efficiency* and show that the low-quality firm may be the most profitable one due to costly production of higher quality products. In Proposition 1 Part (1), we extend his result to a multi-product competition case in the existence of capacity constraints. When there is enough relative cost efficiencies inherent in the low-quality product (i.e., $q_l - c_l \ge q_h - c_h$), focusing on the low-quality product and "going cheap" is the optimal strategy for the firm.

Parts (2) and (3) describe what happens when the maximum profit margin for the high-quality product (i.e., $q_h - c_h$) is greater. In this case, we find that the firm's optimal product-line critically depends on its capacity. The margin per unit capacity ($(q_i - c_i)/s_i$) is the ratio of maximum profit margin a firm can achieve from product *i* to the resources required to produce one unit of that product. This is a well-known measure of efficiency in the operations literature (cf. Krajewski et al. 2010) However, this literature largely ignores the demand-side effects. We show that for a successful execution, all three effects

(price discrimination, cannibalization, and capacity utilization) should be simultaneously taken into account at the product-line design stage.

When capacity constraint is disregarded, a firm would offer both product types in Proposition 1 Parts (2) and (3) to benefit from price discrimination in both monopoly and oligopoly.¹² In the presence of capacity constraints, there are two forces in play. The firm considers margin per unit capacity to maximize the profit it can generate with its limited capacity K, at the same time it aims to benefit from *proliferation* to maximize the surplus it can extract from the market. When the capacity is plenty compared with the market size (large K), proliferation effect dominates and the firm offers both product types, and this is consistent with the findings of studies that ignore the capacity constraints. In contrast, when the capacity is scarce (small *K*), margin per unit capacity effect dominates and the firm offers only the product type with the higher margin per unit capacity. In Part (2), this is product L and in Part (3), this is product H. We characterize the critical capacity thresholds \overline{K} for both cases (note that these are explicitly stated in the Appendix). Note that both $\bar{K}_1^{(n)}$ and $\bar{K}_2^{(n)}$ are equal to zero when products L and H have equal margins per unit capacity, that is Parts (2) and (3) in Proposition 1 are consistent with each other at the boundary. We would also like to point out that the results presented in Proposition 1 Parts (1) and (3) continue to hold true when $s_h = s_l$.

Moreover, both $\bar{K}_1^{(n)}$ and $\bar{K}_2^{(n)}$ increase as the gap between margin per unit capacity of the two products increases. Intuitively, as the gap increases, the impact of margin per unit capacity in the firms' product-line becomes more prevalent. To visualize such an impact, we provide Figure 1. In this figure, we present two examples¹³ to show how the optimal product-line strategy changes depending on the resource consumption parameters. Note that for the same cost, quality, and capacity levels, changes in resource consumption parameters have a direct impact on the margin per unit capacity which indirectly affects the capacity thresholds. Figure 1a presents an example that is relevant to Proposition 1. The parametric set also fits Johnson and Myatt's (2003) "decreasing returns to quality" conditions (i.e., both c_i/q_i and $(c_{i+1} - c_i)/(q_{i+1} - q_i)$ are increasing for all *i* in the product range). Hence, when neither margin per unit capacity nor the capacity constraints are taken into account, the optimal strategy is to offer both products. This result is visible at the origin in Figure 1a. However, as the resource consumption parameters change, margin per unit capacity level changes. This forces the firm to move away from the original strategy of offering both products. This counterexample shows that all kinds of strategies (only high, only low, and both products) are plausible when capacity is limited. The impact is more prevalent when the high-quality product consumes more of the critical resource than the low-quality product.

Next, we will present a multi-product example for Proposition 1 in Figure 2.¹⁴ We would like to show that the analytical results shown in the proposition continue to hold when there are more than two products. This example fits into Proposition 1 Part (2) where the firm with very limited resources only offers a single product of lowest quality. Then, as the firm meets the capacity thresholds, it introduces the products one by one (based on their margin per unit capacity). Finally, only the firm with lots of resources could offer all of the products. Note that this example also satisfies Johnson and Myatt's (2003) "decreasing returns to quality" conditions. However, the example presents a situation under resource constraints. Then, it becomes a counterexample and shows that offering all products may not be the optimal strategy when supply limitations are taken into consideration. For



Figure 1 Optimal Product Line Strategy



Figure 2 Optimal Product Mix When There Are Decreasing Returns to Quality

example, when capacity-to-market size ratio (*K*) is 0.5, only the top 14.8% of the market (that is ordered by the customers' valuations for quality) choose to make purchases. Among these, the top 1.32% buy product 3, 8.58% in the middle buy product 2, and the lower 4.90% buy product 1.

Next, we will discuss how the traditional practice would be outperformed in profits by the propositions presented in this article. Imagine a traditional firm where the marketing and operations departments make sequential decisions. In this example, the marketing department will determine the product line and prices following Johnson and Myatt (2003). Sequentially, the operations department will determine the final product mix following the bottleneckbased production scheduling, as that takes margin per unit capacity into account (Krajewski et al. 2010). The first row of Table 1 shows the prices (p_i) , final sales (w_i) , and the profits when the parameters are as in Figure 2 and capacity-to-market size ratio (K) is 0.1.¹⁵ Note that although the marketing department would like to have all the products in the product mix, the operations department cannot satisfy all the demand due to capacity constraints. The second row of Table 1 shows the same variables when the firm chooses to follow the integrated optimization method (taking resource constraints into account at the productline design stage) presented in this article. A simple comparison of the profits shows that our integrated approach outperforms the existing literature by 207.5%.

So far we have described the equilibrium when there is an increasing cost-to-quality ratio (i.e., $c_h/q_h > c_l/q_l$). The following proposition describes what happens when there is a decreasing cost-toquality ratio (i.e., $c_h/q_h < c_l/q_l$).

PROPOSITION 2. Suppose $c_h/q_h \le c_l/q_l$. The game has a symmetric pure strategy Nash equilibrium as follows:

- 1. If $\frac{q_l c_l}{s_h} < \frac{q_l c_l}{s_l}$, then if $K \leq \bar{K}_1^{(n)}$, the firm offers only product L; if $\bar{K}_1^{(n)} < K \leq \bar{K}_2^{(n)}$, the firm offers both products L and H; if $K > \bar{K}_2^{(n)}$, the firm offers only product H.
- 2. If $\frac{q_h c_h}{s_h} \ge \frac{q_l c_l}{s_l}$, the firm offers only product H for all capacity levels.

In this case, when the capacity constraint is disregarded, a firm would offer only product H to avoid *cannibalization* within its products both in monopoly and oligopoly.¹⁶ With capacity constraints, the firm also considers *margin per unit capacity* $(q_i - c_i)/s_i$. Part (2) describes the trivial case, that is when the margin per unit capacity is larger for product H. Here, both cannibalization and margin per unit capacity effects favor product H, and the firms always offer only product H. This case also covers when $s_h = s_l$.

In contrast, in Part (1), these two forces work in opposite directions, as margin per unit capacity favors product L, whereas the cannibalization effect

Table 1. Comparison of the Optimal Solution Discussed in This Paper with the Traditional Practice When There Are Decreasing Returns to Quality

Method	<i>p</i> ₅	<i>p</i> ₄	<i>p</i> ₃	<i>p</i> ₂	<i>p</i> ₁	W5	W4	W ₃	W ₂	W1	Profit
Model ignoring resource constraints	\$17.50	\$12.75	\$8.25	\$4.00	\$0.79	_	_	-	2.42%	0.62%	0.0255
Integrated model	_	_	_	\$4.84	\$ 0.90	-	_	-	1.43%	8.53%	0.0529

favors product H. The equilibrium can result in all three possible options (sell only low-quality, only high-quality, or both products). When the capacity is large, the cannibalization effect dominates, and the firms sell only product H, which is in line with the studies in the literature that ignore capacity constraints. At the other extreme, when the capacity is low compared to the market size, the margin per unit capacity effect dominates and the firms sell only product L. Finally, for intermediate capacities the firms sell both product types.

The implications of margin per unit capacity (represented by the changes in the resource consumption parameters) for Proposition 2 can be visualized in Figure 1b. The parametric set also fits Johnson and Myatt's (2003) "increasing returns to quality" conditions (i.e., c_i/q_i is decreasing for all *i* in the product range). Hence, at the origin, it is optimal to focus only on the high quality. Similar to Proposition 1, as the resource consumption parameters change, margin per unit capacity levels change, and all kinds of strategies (only high, only low, and both products) are plausible, which is a contradiction to the existing literature (Johnson and Myatt 2003, 2006).

Similar to Figure 2, Figure 3 presents a multi-product example for Proposition 2.¹⁷ This example fits into Proposition 1 Part (1) where the firm with very limited resources only offers a single product of lowest quality. As the resources increase, the firm introduces additional products one by one (based on their margin per unit capacity). When the firm reaches intermediate levels of capacity, it does not have to bear the burden of low-price–low-quality products and starts to drop them from its product line. Finally, only the firm with lots of resources have the luxury to focus on the highest quality product. Note that this example satisfies Johnson and Myatt's (2003) "increasing returns to quality" conditions. Then, the example becomes a counterexample and shows that focusing only on the high quality may not be the optimal strategy when resources are limited.

The comparison to the existing literature is even more significant in this case. Like the previous proposition, imagine a traditional firm where the marketing and operations departments make sequential decisions. Following Johnson and Myatt (2003), the marketing department decides to focus on the highest quality product, and the final production is decided by the operations department, based on the capacity constraint. When the parameters are the same as in Figure 3 and the capacity to market size ratio (K) is 0.4, the result of the sequential approach is presented in the first row of Table 2. The second row shows the result when the firm chooses to follow the integrated optimization method presented here. A simple comparison of the profits show that our integrated approach outperforms the existing literature by 293%.

In the following corollaries, we will present results of more general formulations considering asymmetric industries.

Proposition 2 shows that capacity constraints can induce firms to sell more product variants. In the same spirit, the following corollary considers competition between firms with asymmetric capacities, and it shows that the firm with the smaller capacity can offer more product variants than the firm with the higher capacity. We define another constant \bar{k}_1 , which is a function of q_l, q_h, s_l , and s_h ; it is explicitly stated in the Appendix.

COROLLARY 1. Suppose $c_h/q_h \leq c_l/q_l$ and $\frac{q_h - c_h}{s_h} < \frac{q_l - c_l}{s_l}$. Consider Firms A and B with capacities $K_A < K_B$. Firm A sells both products L and H whereas Firm B sells only product H in equilibrium when $\min(K_B, \frac{2\bar{k}_1K_A + K_B}{3}) \geq \bar{k}_2^{(2)} \geq \frac{2K_A + K_B}{3}$ where $\bar{k}_1 > 1$.





Method	<i>p</i> ₅	<i>p</i> ₄	<i>p</i> ₃	<i>p</i> ₂	<i>p</i> ₁	W5	W4	W ₃	W2	<i>W</i> ₁	Profit
Model ignoring resource constraints	\$4.13	_	_	-	_	1.33%	_	-	-	-	0.015
Integrated model	_	_	\$2.82	\$1.86	\$0.92	_	_	3.85%	1.54%	3.08%	0.044

Table 2. Comparison of the Optimal Solution Discussed in This Article with the Traditional Practice When There Are Increasing Returns to Quality

Contrary to basic intuition, the corollary shows that the smaller firm offers more product variants than the larger firm. In the setting of the corollary, product L has a better margin per unit capacity, but it is not profitable to sell due to its cannibalization of product H when the capacity constraint is ignored. Thus, the larger firm sells exclusively product H to avoid cannibalization, whereas the smaller firm includes product L in its product line to benefit from its better margin per unit capacity.

In the following corollary, we show that similar counterintuitive results continue to hold when firms have more generalized cost structures. We define two cost thresholds (\bar{c}_1 and \bar{c}_2) and three new capacity thresholds (\bar{k}_2 , \bar{k}_3 , \bar{k}_4), which are also explicitly stated in the Appendix.

COROLLARY 2. Suppose $s_h/q_h > s_l/q_l$. Consider Firms Y and Z that have firm-specific cost structures (c_{ji}) such that $c_{jh}/q_h \le c_{jl}/q_l$ and $\frac{q_h - c_{jh}}{s_h} < \frac{q_l - c_{jl}}{s_l}$ and both firms have the same capacity K. Firm Z is the more efficient firm $(c_{zh} < c_{yh})$ when $c_{zh} < \bar{c}_1$ and $c_{yh} > \bar{c}_2$. Then, Firm Y sells both products L and H whereas Firm Z sells only product H in equilibrium when $\min(\bar{k}_2, \bar{k}_3) > K > \bar{k}_4$.

Contrary to basic intuition, the corollary shows that the firm with higher costs offers more product variants than the other one. Note that, in this setting resource efficiency, as measured by the resource consumption-to-quality ratio (s_i/q_i) of product *i*, is better for the low-quality product. Resource efficiency is a measure of productivity where inputs (resources required to produce one unit of the product) are weighed against outputs (perceived quality levels by the customers). Recall that when there is decreasing cost to quality $(c_{ih}/q_h \le c_{il}/q_l)$, the firm considers the benefits of resource utilization against cannibalization. When the firm is in hardship (either due to less capacity as in Corollary 1 or higher costs as in Corollary 2), we show that the result is similar: the disadvantaged firm offers both products. However, the advantageous firm (i.e., with cost efficiency in this case) is more concerned with cannibalization and would rather focus on the high-quality product only.

Overall, in this section, we show that the oligopolist firm's product line depends critically on its capacity. The firm should carefully weigh the profit margins of the products with their corresponding resource consumptions. The margin per unit capacity is a key measure of production effectiveness, especially when the resources are scarce. For limited resource levels, the product that has the highest margin per unit capacity should be selected and offered in the market. This can either be a high- or low-quality product. When the firm has sufficient resources, we confirm that the price discrimination and cannibalization forces continue to dominate the optimal short- to medium-term product-line decisions.

4. Impact of Competition on Product Variety

In this section, we study how capacity constraints together with the competitive forces affect the product mix offered in the market. We will compare the firm's product-line in two market scenarios. The firm competes with (n - 1) firms in the first scenario (i.e, there are (n) symmetric firms in total), and it competes with (n) firms in the second scenario (i.e, there are (n + 1) symmetric firms in total). Note that in the second scenario, not only the total number of firms, but also the total supply capacity is greater than the first scenario, while the market size is the same (i.e., unit size).

The impact of increasing competition on the firm's product-line has been studied extensively in the literature. However, we note that these studies have not considered capacity constraints. Johnson and Myatt (2003) studied a model where an incumbent faces entry and provided many examples from various industries including computers, airlines, and watches illustrating how incumbents react to market entry. They note that in some of these examples the incumbent expanded its product-line, for example, adding a lower quality alternative. In some other examples, the incumbent pruned its product-line and stopped selling some of its product variants. Johnson and Myatt (2003) explained these outcomes through differences in the marginal revenue functions. They concluded that when the marginal revenue is decreasing the incumbent never responds by expanding its productline. In our model, the marginal revenue is everywhere decreasing, but an incumbent can respond to entry by expanding its product-line due to capacity constraints. Thus, we show that differences in capacity levels and the relations between the costs, qualities, and resource consumptions can also explain when an incumbent will expand or prune its productline upon a competitor's market entry.

Similar to Propositions 1 and 2 in 3, we describe the results for increasing and decreasing cost-to-quality cases (i.e., $c_h/q_h > c_l/q_l$ and $c_h/q_h < c_l/q_l$) separately in Propositions 3 and 4.

PROPOSITION 3. When $c_l/q_l < c_h/q_h$ and $q_h - c_h > q_l - c_l$, the product variety increases with increasing competition as follows:

- 1. When $(q_h c_h)/s_h < (q_l c_l)/s_l$, for $\bar{K}_1^{(n+1)} < K < \bar{K}_1^{(n)}$, the firm sells only product L when competing against (n 1) firms, whereas it sells both products when competing against (n) firms.
- 2. When $(q_h c_h)/s_h > (q_l c_l)/s_l$, for $\bar{K}_2^{(n+1)} < K < \bar{K}_2^{(n)}$, the firm sells only product H when competing against (n 1) firms, whereas it sells both products when competing against (n) firms.

Following our discussion of Proposition 1, recall that there are two forces at play in this case: margin per unit capacity $((q_i - c_i)/s_i)$ and product proliferation. That is, a firm aims to maximize the profit it can generate given its limited capacity (making the product with higher margin per unit capacity attractive), and the surplus it can extract from the market (making price discrimination attractive). When the capacity is small for a firm, the margin per unit capacity effect dominates, and it offers only the product with better margin per unit capacity. In contrast, when its capacity is large, the proliferation effect dominates, and it offers both product types.

How does a more intense competition alter this picture? Existence of more firms in the market decreases the benefit of proliferation, because of reduced market share due to competition. But, it also weakens the margin per unit capacity effect, as the total supply capacity also increases in the market. More firms contribute to increasing supply in the market, allowing the proliferation effect to dominate, which leads to the firm selling both product types (not only the product with better margin per unit capacity). Hence, the firm sells only the product with better margin per unit capacity in a less competitive market, and it sells both products in a more competitive market for intermediate capacities in Proposition 3. Note that for very large (small) capacity levels, the proliferation (margin per unit capacity) effect dominates in all cases, and they result in the same product mix.

The product with higher margin per unit capacity can be identified as the "upgrade" product using the terminology in the Johnson and Myatt (2003, 2006) studies. The "baseline" product in our case would be the other one. In a tight capacity environment, the firm would choose to focus only on the upgrade markets. However, with greater competition, a firm's individual output reduces. This relaxes the pressure of the capacity constraint. In that more competitive situation, the firm introduces the baseline product to the market as it relaxes the capacity constraints for the upgrade markets. Hence, the market observes a greater product variety due to increased competition.

We would also like to point out that the result presented in Proposition 3.2 holds true even when $s_h = s_l$. Now, we describe the effect of competitive intensity for decreasing cost-to-quality case.

PROPOSITION 4. When $c_l/q_l > c_h/q_h$ and $(q_h - c_h)/s_h < (q_l - c_l)/s_l$, the product variety decreases with increasing competition as follows: for $\bar{K}_2^{(n+1)} < K < \bar{K}_2^{(n)}$, the firm sells both products when competing against (n - 1) firms, whereas it only sells product H when competing against (n) firms.

Recall that the firms balance the margin per unit capacity and cannibalization effects in the decreasing cost-to-quality case (see the discussion of Proposition 2). When the capacity constraint is not binding, the cannibalization effect dominates, and the firms offer only product H. Note that margin per unit capacity condition in Proposition 4 favors product L as $(q_h - c_h)/s_h < (q_l - c_l)/s_l$. When resources are limited, this effect dominates and the firms sell product L either only by itself or together with product H depending on how small the capacity is. For medium capacity levels, the balance between the marketing concerns (the cannibalization effect) and the operational constraints (the margin per unit capacity effect) are altered by the level of competition. Reduced market share due to increasing number of firms serving the same market amplifies the marketing concerns. This allows the cannibalization effect to dominate, and the firm would not sell one of its product variants as competition intensifies in Proposition 4.

In Proposition 4, the average quality of a product sold is non-decreasing in the number of competing firms, as a higher number of competing firms sell only product H and a fewer number of competing firms sell both products L and H. In other words, the competition intensity increases the average quality sold in this case. This is in contrast to Gal-Or (1983) and Banker et al. (1998), who show that the average quality sold decreases with the intensity of competition.¹⁸ In this case, the firms seeking efficient resource utilization sell product L in addition to product H, which reduces the average quality. However, increasing competitive intensity increases the demand-side concerns, allowing the cannibalization effect to dominate, which favors product H. Thus, increasing competition induces firms to sell only product H, resulting in a higher average quality.

Overall, Propositions 3 and 4 characterize when increasing competition induces a firm to expand or prune its product-line, and the factors that characterize the outcome are the relationships between the costs, qualities, and resource consumptions of the products. Note also that the capacity constraint is the key driver of these results: When capacity constraint is disregarded (i.e., unlimited capacity), the optimal product-line is independent of the degree of competition.

5. Concluding Remarks

In this article, we study short- to medium-term product-line decisions in a competitive context jointly considering the trade-offs in both the supply and the demand side. On the demand side, firms want to benefit from product proliferation and avoid cannibalization, while on the supply side, firms want to allocate their limited resources to products that generate the best bang for the buck, where selling one additional unit of a product leaves less resource capacity for other products.

Our results show that explicitly accounting for supply constraints leads to insights that differ significantly from the common intuition and assertions elsewhere in the literature, which disregards resource capacity constraints. Therefore, we conclude that failing to consider supply and demand dynamics simultaneously can lead to critically wrong product-line decisions.

We note that there could be alternative ways of modeling the capacity constraints. Including a fixed cost of new product introduction could potentially affect our results. In that case, proliferation forces would be less powerful compared with cannibalization and margin per unit capacity effects. We have also extended the model to include the optimization of capacity choices. We found that all the results remain intact when the capacity investment costs are linear. We leave the investigation of polynomial capacity investment costs as a future research direction. For that case, we expect that the margin per unit capacity effects would be more powerful and dominate in a wider range of parameters.

Notes

¹Source: Bureau of Transportation Statistics.

²HHI decreased from 52% to 36%.

³Source: Aviation Explorer. 2011. "Aircraft seat maps and airline seating charts". http://www.aviation explorer.com /aircraft airline seating charts.html.

⁴While retrofitting an airplane model by modifying seat configurations may be easy, it is seldom possible to add more physical capacity to an existing airplane model.

⁵Etihad Airways Airbus 340–600, the longest commercial aircraft in use, was done in 21 days by Lufthansa Technik (Source: *Times of Malta*. 2010. "Airbus first-class cabin refurbished before schedule". http://www.timesofmalta. com, Wednesday, 31 March.)

⁶Based on our interactions with Dr. John D. Kasarda, who is a guru in the aviation industry. He is considered the leading developer of the aerotropolis concept, which positions airports as 21st century drivers of business location and urban economic growth. (Source: *Bloomberg Businessweek*. August 20, 2007. "Home Is Where the Airport Is".)

⁷Note that Johnson and Myatt (2003) model the problem with only symmetric costs. Although in the follow-up article, Johnson and Myatt (2006) generalize the model with firm-specific costs (like we do here), the majority of their results are still presented with the symmetric costs assumption. Johnson and Myatt (2006) also mention that when firms have arbitrary costs, the implications on the product types are not clear (page 589, line 27).

⁸Uniform demand distribution assumption makes the analysis tractable, enabling us to keep our focus on the effects of capacity limitation on the product-line choice and to derive our insights. Note that this is a common assumption in the literature when the analyses with more general distributions are intractable (cf. Johnson and Myatt 2006, p. 594).

⁹There are a number of ways to measure customers' willingness to pay for quality. "Choice Modeling" is commonly used for such estimations. (Source: Daniel McFadden. "Economic Choices". *American Economic Review*, Vol. 91, No. 3, 351–378, June 2001.)

¹⁰Uniqueness of this equilibrium is shown by the author(s) in an unpublished study. Note also that De Fraja (1996) shows that any equilibrium must be symmetric when symmetric firms compete in quantities in a similar setup.

¹¹Although operational definition of productivity requires outputs/inputs, we will follow the notation in the literature and keep it as cost/quality.

¹²Note that Johnson and Myatt's (2003) "decreasing returns to quality" conditions (i.e., both c_i/q_i and $(c_{i+1} - c_i)/(q_{i+1} - q_i)$ are increasing for all *i* in the product range) are covered by the conditions stated in Proposition 1. Under those conditions, Johnson and Myatt (2003) stated that both a monopolist and competitive firms should offer both products (on pages 759 (Proposition 1) and 761 (Proposition 3)). In Johnson and Myatt (2006), although the formulation is more general with two stages to allow for strategic choices on page 594, with very similar assumptions to our study (when there are two products, two firms, with uniformly distributed customer valuations) the authors stated that in the equilibrium, the first stage is ignored by the firms, and in the second stage each firm produces both products. We show that these results are reversed when the capacity constraint is specifically modeled into the problem.

¹³In these examples, there is a single firm in the market (n = 1), there are two products with high (type h) and low (type l) quality. In part a, $q_h = 3$, $q_l = 1$, $c_h = 1.8$, $c_l = 0.3$, K = 0.05. In

part b, $q_h = 3$, $q_l = 1$, $c_h = 1.5$, $c_l = 0.75$, K = 0.02. Note that the graph presents solutions when $s_h \ge s_l$. ¹⁴In this example, there is a single firm in the market

¹⁴In this example, there is a single firm in the market (n = 1), there are five products (m = 5) and $q_5 = 20$, $q_4 = 15$, $q_3 = 10$, $q_2 = 5$, $q_1 = 1$, $c_5 = 15$, $c_4 = 10.5$, $c_3 = 6.5$, $c_2 = 3$, $c_1 = 0.59$, $s_5 = 30$, $s_4 = 20$, $s_3 = 10$, $s_2 = 4$, $s_1 = 0.5$.

¹⁵Remember that the problem is normalized to unit market size. Hence, the demand is presented in percentages, and the profits should also be interpreted relatively.

¹⁶Bhargava and Choudhary (2001) show on page 96 (Theorem 1) that the product proliferation would not be optimal when $c_{i+1}/q_{i+1} \le c_i/q_i$ for a monopolist. Then, the firm should offer a single product of highest quality. The same result is generalized to competition by Johnson and Myatt (2003) on page 761 (Proposition 5).

¹⁷In this example, there is a single firm in the market (n = 1), there are 5 products (m = 5) and $q_5 = 5.25$, $q_4 = 4, q_3 = 3, q_2 = 2, q_1 = 1, c_5 = 3, c_4 = 2.5, c_3 = 2, c_2 = 1.4, c_1 = 0.75, s_5 = 30, s_4 = 15, s_3 = 8, s_2 = 4, s_1 = 1.$

¹⁸For Banker et al. (1998), we refer to the outcome when the firms are symmetric and the costs coefficients are independent of the number of competing firms as in our model.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix A1: Capacity Thresholds Appendix A2: Proofs

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