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Analysis of industry equilibria in models with sustaining and disruptive technology

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This paper analyzes a special type of technology evolution, referred to in the literature as disruptive technology vs. sustaining technology. In general, “old” products based on sustaining technology are perceived to be superior to the “new” ones based on disruptive technology. However, the latter have distinctive features that allow them to attract an exclusive set of customers. Examples include netbooks vs. netbooks, hard-disk drives vs. solid-state drives, laser printers vs. inkjet printers, etc. We consider a model with an established firm and an entrant firm that have heterogeneous product-offering capabilities: the established firm can offer either or both types of products while the entrant firm can only offer new products. Firms make capacity, pricing, and quantity decisions that maximize their ex-ante profit. Within this framework, we analyze deterministic games with perfect information and stochastic games with uncertain valuation of the disruptive technology. Equilibrium decisions are discussed under various market conditions, as well as under dedicated vs. flexible capacity assumptions.

While over-investment and over-production may occur in a stochastic game with dedicated capacities, the equilibrium capacity decisions seem to be more “rational” if the established firm utilizes flexibly capacity, or if the dedicated capacity can be converted ex-post (albeit at some expense).

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1. Introduction

In October 2007, ASUS unveiled its first netbook computer—Asus Eee PC 701, a mini-laptop-like gadget with 7-inch display, keyboard 15% smaller than the traditional one, Intel Celeron 900 M processor, 512 MB of RAM, and up to 16 GB solid-state hard drive. These features were far below the standard laptop configurations at that time, in which processors were usually twice as fast, RAMs four times as large, and hard drives had capacity going up to 500 GB. However, during the first quarter after its release, the sales of Eee PC 701 surged up to 350,000 units (Engadget.com, 2007). This triggered other laptop manufacturers, such as Dell and Acer, to offer their own netbooks as well. By the end of 2007, ASUS alone sold close to 350,000 units of Eee PC 701, which were typically more than twice as heavy (e.g., 14” Thinkpad T 60 weighs around 5.2 lb). Netbooks also come with irresistible price tags: Asus Eee PC 701 started from $250, which amounted to less than 30% of the average amount paid for a laptop.

The idea of netbooks has its “… roots in the One Laptop per Child (OLPC) project championed by former MIT media director Nicholas Negroponte; the original idea was to create a low-cost PC that would give young people access to the Internet and help kids in emerging markets access the world of information and communication on the Internet. (PCMagazine.com, 2008)” Moreover, for business customers netbooks act like travel companions that possess strong mobile communication ability (but cannot fulfill the need for sophisticated computations) without adding much weight to their luggage. In addition, companies may benefit from significant savings on IT procurement through this alternative (Reuter.com, 2009; ZDNetAsian.com, 2009). Thus, netbooks gain their market share by sacrificing computation capability in return for mobility and cost-saving.

In recent decades, many industries have experienced similar technology evolutions, in which a new technology traded off core-function performance for evolutionary side-function improvements. For instance, in the mid-’1980s, when the 3.5-inch hard disk drive (HDD) was introduced in the market that had previously been dominated by the 5.25-inch HDD, it sacrificed capacity to achieve greater portability, and more recently solid-state drives (SSDs) were introduced in the market dominated by HDDs, and
they traded off capacity, writing speed, etc. to achieve less noise and greater temperature tolerance. One can think of numerous similar examples—ink-jet printers vs. laser printers, on-line retailing vs. mortar-and-brick retailing, Voice-over-Internet Protocol (VoIP) phones vs. landline services, hybrid electric vehicles vs. regular vehicles, to mention just a few. Christensen (2003) introduced the terms sustain ing technology and disruptive technology to describe such phenomena:

Most new technologies foster improved product performance. I call these sustaining technologies. (...) What all sustaining technologies have in common is that they improve the performance that mainstream customers in major markets have historically valued. (...) Disruptive technologies emerge: innovations that result in worse product performance, at least in the near-term. (...) But they have other features that a few fringe (and generally new) customers value. Products based on disruptive technologies are typically cheaper, simpler, smaller, and frequently, more convenient to use. (Christensen, 2003, p. xviii).

As disruptive technology does not usually provide a “better” product at the very beginning, it can often be dismissed by incumbent firms who at that time provide “better” products. However, disruptive technology does serve an emerging market that is not covered by the sustaining technology—teenagers who cannot afford a full-size laptop, home users who cannot afford the price of an inkjet printer, environmentalists that fervently support hybrid electric cars, etc. Moreover, as the disruptive technology itself improves, the functionalities that have been sacrificed early on may improve and disruptive technology may enter the existing market of sustaining technology. A good example would be digital cameras, which today dominate the film cameras, and some key camera manufacturers had already announced discontinuing their film camera lines (New York Times, 2006). Failing to recognize the hidden threat of disruptive technology can have severe consequences, as illustrated by the bankruptcy of Polaroid in 2001, which was in great extent due to neglect of the emerging digital market. Thus, in the presence of sustaining and disruptive technologies, the firms are confronted with the following questions:

1. Should an established firm with sustaining technology introduce the disruptive technology at the same time?
2. How should established and entrant firms make their operational investment decisions in a riskless environment?
3. How does the uncertainty in disruptive technology affect operational decisions of both firms?

2. Literature

The concept of disruptive technology was introduced in the early 1990's (Christensen, 1992; Bower and Christensen, 1995). During the following ten years, Christensen (2003), Christensen and Raynor (2003), and Christensen et al. (2004) documented many ups and downs faced by the firms whose business was conducted in the presence of disruptive technology. They argue that incumbent firms with sustaining technology may fail due to inefficient resource allocation between the original sustaining technology and the new disruptive technology. Some of the authors call for more constructive frameworks and rigorous theories in better conceptualization of these ideas (Danneels, 2004; Christensen, 2006).

While most research on this topic falls in the area of strategy (e.g., Christensen et al., 2000; Gilbert and Bower, 2002) or empirical analysis (e.g., Agarwal and Bayus, 2002; De Figueiredo and Silverman, 2007), there are a few recent modeling papers as well. Schmidt and Porteus (2000a) studied incomplete substitution between products based on disruptive and sustaining technology with decentralized firms or a centralized firm. Adner and Zemsky (2005) analyzed how the threat of disruptive technology depends upon various factors including the numbers of firms, and the corresponding impact on different aspects of the industry. Van der Rhee et al. (2007) examined how firms in a duopoly make their technology adoption decisions under different market conditions.Druehl and Schmidt (2008) compared different encroachment strategies for firms to harness the disruptive technology at the same time with the sustaining technology.

In most of these papers, firms are restricted to adopt only one type of technology. Schmidt and Porteus (2000b) modeled a game between an incumbent and an entrant, in which they examined how capability for cost reduction and innovation affect the equilibrium investment decisions. Adner and Zemsky (2005) in their extension discussed multi-technology firms. Both papers imply that firms will choose only one type of technology in an equilibrium, even if they are allowed to apply both technologies at the same time. Schmidt and Porteus (2007) studied how complementarities may affect firms’ investment and pricing decisions.

Our paper differs from the existing literature in several respects. First, we look at firms with heterogeneous product-offering capabilities, by allowing the incumbent to adopt either or both technologies, while restricting the entrant to work with disruptive technology only. We believe that it is important to make a distinction between established and entrant firms in their ability to offer different types of technologies—as the sustaining technologies are more mature and their markets are usually dominated by strong players, an entrant may simply choose to start with alternative technologies. On the other hand, disruptive technologies are likely to have lower entry barriers, which makes them easier to implement by either firm.

Second, we address capacity decisions, which are critical from the operations management perspective, but have not yet been explored within the current framework of disruptive technology. Capacity constraints may have a great impact on equilibrium outcomes. As noted by Kreps and Scheinkman (1983), a capacity-constrained Bertrand game may yield the same equilibrium as a corresponding Cournot game (unlike the uncapacitated game, which may leave both firms with zero profit). We apply a similar idea in our game with a two-product duopoly market, and we identify the corresponding equilibria. In our model, the equilibrium may consist of both firms simultaneously offering products based on disruptive technology, at the same price level. This is in contrast to some previous results (Schmidt and Porteus, 2000b; Adner and Zemsky, 2005), in which the established firms would only select one type of technology given the choice of two.

Finally, we study the impact of uncertain disruptive technology on operational decision making. Capacity reservation and production postponement (see, e.g., Van Mieghem and Dada, 1999; Spinler and Huchzermeier, 2006; Jin and Wu, 2007; Anupindi and Jiang, 2008) as well as flexible capacity (see, e.g., Fine and Freund, 1990; Van Mieghem, 1998; Chod and Rudi, 2006) are not new in literature. However, to our knowledge we are the first to analyze the game in which two parties have asymmetric product portfolios.

The paper is organized as follows. We first introduce our model in Section 3. Section 4 studies two deterministic games: one with dedicated capacity and the other with flexible capacity; in Section 4.2, we discuss the impact of model parameters on equilibrium outcomes and illustrate analytical findings with numerical examples. Section 5 extends the analysis from Section 4 by introducing uncertainty into the valuation of disruptive technology—three stochastic games are discussed with various assumptions on the flexibility level of the capacities. We conclude in Section 6, and due to space constraints we present all proofs in the on-line technical appendix.
3. Model description

We study a market with two kinds of products—products based on sustaining technology, which we denote by S, and products based on disruptive technology, which we denote by D. Our model consists of two firms, which we call Firm 1 and Firm 2. Firm 1 is an established firm that dominates the market for product S, and can also include product D in its portfolio. Firm 2 is an entrant firm that can manufacture and sell only product D. There are several real-life examples that fall into this framework. For instance, Dell has been a computer manufacturer since 1984, and its product and services portfolio now offers a full line of desktop and notebook computers, business servers, monitors, TVs, etc. As an example of Firm 1, Dell has the option to decide if it wants to include a new type of product/service into its portfolio. Indeed, it did not introduce netbooks until September of 2008 (after ASUS). On the other hand, Fujiyama Computers, an example of Firm 2, is a Chinese manufacturer of consumer electronics that has only netbooks in its offering of personal computers.

We denote by \( v_i \) and \( p_i, i \in \{S,D\} \), the customer’s valuation for product i and the price of product i, respectively. Thus, the customer’s utility from purchasing product i equals \( v_i - p_i \). Customers will buy the product that gives them the highest non-negative utility, \( \max(v_i - p_S, v_D - p_D, 0) \), and if both utilities are negative they will not buy any product. Notice that we allow customers to choose at most one of the products; the case in which a customer may choose to have both products at the same time (e.g., a netbook for travel and a traditional notebook for local use) could be a possible extension of this model, but it is not within the scope of this paper.

We assume that there is a flexible market with size \( M \) in which customers consider buying both products, S and D, and a dedicated market sized \( m \) in which only product D is considered.\(^1\) Specifically, let us denote by \( \theta \) the customers’ type, with a small \( \theta \) implying a high-end customer. In addition, let \( s \) and \( d \), which we call value factors, denote the rate of increase in valuations as the customer type increases from low-end to high-end. We assume \( s > d \) to rule out some trivial cases. Then, for product S, we have \( v_S = s(M - \theta) \), \( \theta \in [0,M] \), and for product D, \( v_D = d(M + m - \theta) \), \( \theta \in [0,M + m] \).

The valuation pattern of the two technologies (linear utilities in which product D has a flatter valuation curve compared with product S) has been commonly applied in modeling competition involving disruptive technology—see, for instance, Schmidt and Porteus (2000a, 2007), Schmidt and Druehl (2005) and Druehl and Schmidt (2008), in which both \( s \) and \( M \) are normalized to 1. Fig. 1 depicts some possible realizations of the valuations as \( s \) and \( d \) take different values. One may observe that both products have a similar set of high-end customers. In other words, the superior performance over side-function in product D is well recognized by high-end customers (\( \theta \) close to 0) that put more weight on the core-functions, which have not been weakened too much in product D. The competition between the two products is then much more intense than in the case in which products D and S are designed exactly for the opposite ends of the market; this instance is not within the scope of this paper and we refer readers to Druehl and Schmidt (2008) for relevant discussions.

The valuation function is modeled as an inverse demand function when a single product exists in the market. For example, when the price of product \( S \) satisfies \( p = v_S(\theta) \) for some \( \theta \in [0,M] \), customers within \([0,\theta]\) are willing to buy \( S \) in the absence of \( D \), and we can write the corresponding demand function as \( Q_S(p) = M - \frac{p}{s} \), \( p \in [0,sM] \). Similarly, we have \( Q_D(p) = M + m - \frac{p}{d} \), \( p \in [0,d(M + m)] \).

Finally, when the capacity is dedicated for sustaining and disruptive technology, we denote the unit capacity costs as \( c_S \) and \( c_D \), respectively, and we use \( c_F \) for flexible capacity that can be used for either technology.\(^2\) We assume that marginal capacity costs for products based on sustaining technology exceed those of products based on disruptive technology, and that flexible capacity cost exceeds both of them, i.e., \( c_F \geq c_S \geq c_D \). This has been commonly observed in real life, as disruptive technology aims to capture the low-end market. Furthermore, we neglect any production cost in this paper. As has been discussed in literature (e.g., Van Mieghem, 1998), if market clearing prices are applied, then a problem with positive production costs can be straightforwardly transformed into one with zero production costs by using \( p \) as the unit margin instead of the actual price and by having \( M \to (M-\text{cost of } S) \) and \( m \to (m+\text{cost of } S)-\text{cost of } D(d) \).

3.1. Capacity-production game

Consider a two-stage capacity-production game between the two firms. In the first stage, the firms make simultaneous capacity decisions, \( y_1 = (y_{S1}, y_{D1}) \) and \( y_2 = (0, y_{D2}) \). In the second stage, the firms simultaneously determine the production quantities of their products, \( q_1 = (q_{S1}, q_{D1}) \) and \( q_2 = (0, q_{D2}) \). Finally, market prices are determined based on the quantity decisions \( q = (q_1, q_2) \). Market clearing prices, which are given in the following lemma, will apply after the quantity decisions:

\(^1\) We assume the existence of a market dedicated to product D because product S may not be desirable to some low-end customers, e.g., those with limited funds or limited space.

\(^2\) To simplify the analysis, especially for the model with uncertainty, we assume that both firms incur equal marginal capacity costs for products based on disruptive technology. We note, however, that the analysis conducted with \( c_F = c_S \) for the deterministic case generated results similar to those presented here. We discuss this further in Section 4.2.
Lemma 1. Given quantities \( q_S \) and \( q_D = q_{D1} + q_{D2} \), the market clearance prices are

\[
p_D = d(M + m - q_S - q_D), \quad p_S = sM - sq_S - dq_D.
\]  

Proof. Given market price \( p_S \) for product \( S \) and \( p_D \) for product \( D \), the customer \( \theta_0 \) who is indifferent between buying product \( S \) at price \( p_S \) and product \( D \) at price \( p_D \) is:

\[
\theta_0 = M - \frac{dm - p_D}{s - d} - \frac{1}{s - d} p_S.
\]

As can be seen from Fig. 2, customers in \([0,\theta_0]\) prefer product \( S \) over \( D \) (and either product is better than buying nothing), those in \([\theta_0,M + m - p_D/d]\) prefer \( D \) over \( S \) (and either product is better than buying nothing), and the rest will not make any purchase under the pricing scheme \((p_S, p_D)\). (1) is obtained by letting \( q_S = \theta_0 \) and \( q_D = M + m - p_D/d - \theta_0 \). \( \square \)

Note that we implicitly assume that, although there might be two different firms offering product \( D \) at the same time, there is only one market price for it. This, however, should not be considered a very strong assumption. As shown by Huang and Sošić (2009), a “capacity-pricing” game (in which the second-stage decision is on prices instead of production quantities) will yield the same equilibrium. This suggests that firms are likely to price their products at the same level even if they have the option of not doing so.

4. Competition between established and entrant firms

In this section, we study the equilibrium of the capacity-production game described in Section 3.1 when all parameters are deterministic. Clearly, in deterministic case firms would not benefit from excess capacity investment, thus in all cases the capacity decision is the same as quantity decision. With a slight abuse of wording, we use “production quantity” and “capacity” interactively in this section.

4.1. Dedicated capacity

Let us first consider a model in which capacity is dedicated to each type of technology, with costs \( c_S \) for product \( S \) and \( c_D \) for product \( D \). We will use \( c_S = c_S/s \) and \( c_D = c_D/d \) to denote the standardized marginal costs, and we will incorporate them into the original market sizes to denote the standardized market sizes:

\[
\overline{M} = M - c_S, \quad m = m + c_S - c_D, \quad \text{and} \quad \overline{M} + m = M + m - c_D.
\]  

We let \( \gamma = d/(s - d) \) be defined as the technology factor, with \( \gamma = 3\gamma + 2 \). We then have the following results describing equilibrium decisions on capacity investment and prices:

**Theorem 1.** In the capacity-production game with \( M > \overline{c}_S \) and \( M + m > \overline{c}_D \), both firms will have a non-empty product portfolio and

1. if \( \overline{M} \leq \gamma \), both Firm 1 and 2 offer only product \( D \):

\[
y_D = q_{D1} = \frac{M + m}{3}, \quad p_D = \frac{d(M + m)}{3} + c_D.
\]

2. if \( \gamma < \overline{M} < \gamma \), Firm 1 offers both products and Firm 2 offers \( D \):

\[
y_S = q_S = \frac{M - \gamma m}{2}, \quad y_D = q_{D1} = \frac{(1 + \gamma)m - M - m}{2},
\]

\[
y_{D2} = q_{D2} = \frac{M + m}{3}, \quad p_S = \frac{s}{2} - \frac{d}{3}m + c_S, \quad p_D = \frac{d}{3}M + m + c_D.
\]

3. if \( \gamma \leq \overline{M} \), Firm 1 offers only product \( S \) and Firm 2 offers \( D \), \( q_{D1} = 0 \) and

\[
y_S = q_S = q_1 = \frac{2(\gamma + 1)M - \gamma M + m}{3\gamma + 4},
\]

\[
p_S = \frac{s(2(\gamma + 1[M - \gamma M + m])}{3\gamma + 4} + c_S,
\]

\[
y_{D1} = q_{D1} = q_2 = \frac{(\gamma + 1)(2M + m - M)}{3\gamma + 4},
\]

\[
p_D = \frac{d(\gamma + 1)(2M + m - M)}{3\gamma + 4} + c_D.
\]

**Theorem 1** merits some additional discussion. The first case, \( \overline{M} \leq \gamma \), describes a situation in which the disruptive technology receives high customer valuation. Thus, it may generate a larger dedicated market, which increases the value of the technology factor, \( \gamma \), and decreases the value of the market ratio, \( \overline{M} \). It is, then, likely that Firm 1 may drop product \( S \) from its portfolio and offer product \( D \) only.

The third case, \( \gamma \leq \overline{M} \), describes a situation in which disruptive technology is not overly successful. Consequently, both \( \gamma \) and \( \gamma \) are small, and the market ratio may be rather large. Under such a scenario, Firm 1 benefits by keeping \( D \) out of its portfolio and focusing on \( S \) only.

Finally, if the disruptive technology achieves a moderate success, the market ratio is within a closed interval determined by the technology factors, \( \gamma < \overline{M} < \gamma \), and Firm 1 should offer both products. By comparing prices in the last two cases, we can conclude that exclusion of product \( D \) from Firm 1’s portfolio leads to underpricing of \( S \) and overpricing of \( D \). In the first two cases of
Proposition 1

(i) \( y_1 > y_2 \), where \( y_1 = y_2 \) only in a semi-duopoly case, i.e., \( \frac{m}{M} \leq \gamma \).
(ii) \( p_S > p_D \) whenever Firm 1 includes product \( S \) in its portfolio, i.e., \( \frac{m}{M} > \gamma \).

Proof. Part (i) follows from Theorem 1, which implies that \( y_1 = y_2 = \frac{m}{3M} \) when \( \frac{m}{M} \leq \gamma \) (first two cases in the Theorem), and \( y_1 - y_2 = \frac{1}{3(M - \gamma)}(3\gamma - 2M) > 0 \) when \( \frac{m}{M} > \gamma \) (last case). For part (ii), note that \( p_S - p_D = \frac{M(\gamma - M)}{M} \) when \( \frac{m}{M} > \gamma \), and \( p_S - p_D = \frac{1}{3(M - \gamma)}(3\gamma - 2M) > 0 \) when \( \gamma < \frac{m}{M} < \gamma \).

The first result states that Firm 1, as an established firm with monopoly power over product \( S \), always builds higher capacity than its rival firm. If the disruptive technology is not well received (\( \frac{m}{M} > \gamma \)), Firm 1 produces and sells more in total than Firm 2. Otherwise (\( \frac{m}{M} < \gamma \)), the total production quantity of the two firms becomes equal, and Firm 1 offers some product \( D \). Such equivalence in production quantities corresponds to the outcome of the single-product Cournot game: it holds when \( S \) is not offered (\( \frac{m}{M} \leq \gamma \)), but it also carries over to the model with two products (\( \gamma < \frac{m}{M} \)). When products \( S \) and \( D \) co-exist in the market, Firm 1 loses its dominant status—when the technology of product \( D \) is improved or the dedicated market for product \( S \) becomes more competitive, Firm 1 opts to include \( D \) in its portfolio, while at the same time it keeps product \( S \) in order to serve the high-end market.

The second result states that, as long as product \( S \) stays in the portfolio, Firm 1 always charges more for it than for product \( D \). Many real-life examples (e.g., laser vs. inkjet printers, laptops vs. netbooks) support this observation. The underlying reason can be explained as follows: as we discussed in Section 3, if there is a set of customers that prefers product \( S \) to \( D \), they are at a higher end of the market than those preferring \( D \). Therefore, we should not reduce the price of product \( S \) below that of product \( D \). On the other hand, as disruptive technology becomes more competitive, selling product \( S \) at a lower price than product \( D \) would not lead to profit maximization—Firm 1 should either raise \( p_S \) and keep serving higher-end customers, or let product \( S \) vanish from the market. Indeed, this is what has been observed in many real-life instances (e.g., minicomputers)—products based on sustaining technology are likely to exit by pricing themselves out of the market.

4.2. Discussion of the equilibrium decisions

In this section, we discuss how model parameters may affect the equilibrium outcomes. Specifically, we analyze the impact of market sizes and value factors on the equilibrium capacities and prices. A brief outline of changes in product portfolio can be seen in Fig. 3. Because of the equivalence between general games and those with zero marginal costs mentioned earlier, in this section we focus on games with zero marginal costs. In what follows, we further illustrate our findings with numerical examples, and we comment on the assumption of zero marginal costs later in this section. For ease of notation, we let \( R = \frac{m}{M} \), which corresponds to \( \frac{m}{M} \) if the marginal costs are zero. Equilibrium decisions from Theorem 1 can then be simplified as shown in Table 1.

4.2.1. Impact of game parameters

We first look at the impact of market sizes, \( M \) and \( m \), on the capacity decisions. Our results follow directly from Theorem 1, hence we omit the proofs.

Proposition 2 (Impact of Dedicated Market on Capacities).

(i) (Product capacity) \( y_S \) decreases, while \( y_D \) and \( y_D' \) increase with \( m \).
(ii) (Firm capacity) \( y_1 \) decreases (resp., increases) with \( m \) when \( R > \gamma \) (resp., \( R < \gamma \)), while \( y_2 \) increases with \( m \).

![Fig. 3. Equilibrium product portfolios as game parameters vary.](image-url)
Intuitively, a larger dedicated market encourages Firm 2 to build larger capacity. In the semi-duopoly case in which Firm 1 has product D in its portfolio, Firm 1’s total capacity increases as well. However, when the disruptive technology fails to attract Firm 1 (R $\geq$ $\bar{\gamma}$), its total capacity ($y_1 = y_S$) decreases. Overall, an increase in $m$ induces both firms to put more weight on product D. We illustrate this with the example depicted in Fig. 4(a), where we assume that $M = 120, m$ varies within [0, 180], $s = 4$ and $d = 2$ (which implies that $\bar{\gamma} = \frac{1}{12} = 1$ and $\bar{\gamma} = 2 + \frac{3}{4} = 5$).

**Proposition 3** (Impact of Flexible Market on Capacities).

(i) (Product capacity) If $R \geq \bar{\gamma}$, $y_S$ and $y_D$ increase with $M$, while $y_{do}$ decreases with $M$.

(ii) (Firm capacity) Both $y_1$ and $y_2$ increase with $M$.

As the customers in the flexible market value both products S and D, the total production of each firm increases with $M$. Note that Firm 1 puts more weight on product S—that is, each firm focuses more on its “core” products. Thus, Firm 1 serves as the “S-provider” and may carry product D as a side-offering, while Firm 2 is the main “D-provider” and serves the low-end market. As we can see, while the increase in the size of the dedicated market leads to a higher degree of competition, an increase in the size of the flexible market has the opposite effect—each firm ends up occupying one end of the market and offering a different product. We illustrate this in Fig. 4(b), where we assume that $m = 30, M$ varies within [0, 180], $s = 4$, and $d = 2$ (which implies that $\gamma = 1, \bar{\gamma} = 5$, and $R = \frac{M}{s}$).

We next examine the impact of value factors, $s$ and $d$, on the equilibrium decisions. When $D$ is the only product offered in the market (that is, $R \leq \gamma$), each firm serves one third of the total market, $M + m$, and value factors do not have any effect on the capacities. Thus, we restrict our analysis to scenarios in which both products co-exist in the market. Our results follow directly from Theorem 1, and we omit the proofs.

**Proposition 4** (Impact of Value Factors on Capacities).

(i) (Product capacity) $y_S$ increases (resp., decreases) with $s$ (resp., $d$); $y_D$ decreases (resp., increases) with $s$ (resp., $d$); $y_{do}$ is not affected by changes in $s$ or $d$ when $R \leq \bar{\gamma}$ (the duopoly or semi-duopoly case) and decreases (resp., increases) with $s$ (resp., $d$) otherwise.

(ii) (Firm capacity) $y_1$ does not change with $s$ (resp., $d$) when $R < \bar{\gamma}$ (the duopoly or semi-duopoly case), and it increases (resp., decreases) with $s$ (resp., $d$) otherwise; $y_2$ is not affected by changes in either $s$ or $d$ when $R < \bar{\gamma}$ (the duopoly or semi-duopoly case), and it decreases (resp., increases) with $s$ (resp., $d$) otherwise.

It is natural that capacity for a product increases when the competing product is not popular. In addition, as mentioned at the beginning of this section, the value factors have no impact on the total capacity of either firm in semi-duopoly. Thus, for instance, Firm 1’s total capacity decreases with $d$ when it offers only product S (until it adds product D to its portfolio), and it increases with $s$ after it drops product D from its portfolio.

**Proposition 5** (Impact of Value Factors on Prices).

(i) $p_S$ (resp., $p_D$) increases with $s$ (resp., $d$).

(ii) Given that the product S is included in the portfolio, $p_S$ decreases with $d$, while $p_D$ decreases with $s$ for $R > \gamma$ and is not affected by $s$ when $R \leq \gamma$.

A higher value of $d$ makes product D more “threatening” to product S (i.e., reduces the advantage of Firm 1 over Firm 2), and hence Firm 1 reduces the price of product S in response to the change in market valuations (note that $p_S$ always remains higher than $p_D$, as shown in Proposition 1). When the market conditions cause $p_S = p_D$, Firm 1 benefits by removing product S from its portfolio, and we denote its price as $p_3 = 0$. A higher value of $s$, however, will not cause a reduction in the price of product D under semi-duopoly ($R \leq \bar{\gamma}$). To see this, assume that Firm 1 cannot manufacture product D. Then, an increase in $s$ may reduce $p_D$. When Firm 1 has the option to include product D into its portfolio, the competition in prices becomes less intense as Firm 1 wants to obtain a portion of the market for product D as well. However, one should not assume that Firm 2 becomes better off (because $p_D$ can remain unchanged) when Firm 1 can manufacture product D, because it will lose a part of its market share.

The discussion above implies that the development of disruptive technology increases competition more than the development of sustaining technology. This happens because any progress in sustaining technology only enhances the existing difference between the products, while progress in disruptive technology reduces this difference, which may eventually reverse the position of the two technologies. We also notice that Firm 1 is more sensitive to value factors than Firm 2, in both the capacity and the pricing decisions, because Firm 1 has the option to include product D in its portfolio or leave it out, while Firm 2 has no such choices in its product offering. We illustrate our results with a couple of examples.

Suppose that $M = 120, m = 40$, and $s = 9$, which implies that $R = \frac{M}{s} = 3$ and $\gamma = \frac{1}{2}$. Fig. 5(a) and (b) show how the equilibrium capacity and price change when $d$ increases from 1 to 8. When $d$ is small, $\bar{\gamma} < R = 3$, and Firm 1 does not offer product D. As $d$...
increases, $\gamma < 3 < \gamma$. Firm 1 increases the capacity for product D. During this time, the price of product D increases with $d$, while the price of S decreases with $d$, until both of them reach $\$360$ (which happens at $\gamma = R = 3$). When $\gamma \geq 3$, both firms offer only product D.

Next, suppose that $M = 120$, $m = 40$, and $d = 3$, which implies that $R = \frac{M}{m} = 3$ and $\gamma = \frac{1}{3}$. Fig. 6(a) and (b) show how the equilibrium capacity and price change when $s$ increases from 3 to 15. Note that the graph in Fig. 6(a) represents (in general) a horizontal inverse of that in Fig. 5(a). The graph in Fig. 6(a), on the other hand, is quite different from that in Fig. 5(b). As we have discussed before, $p_D$ is not affected by changes in $s$ when $s < 12$ ($R < \gamma$). When $s \geq 12$, $p_D$ has an insignificant downward trend, which may not be captured in the current scale of the graph.

### 4.2.2. Effects of positive marginal capacity costs ($c_S$ and $c_D$)

Throughout this section, we have assumed zero marginal capacity costs, $c_S = c_D = 0$. The impact of positive capacity costs on capacity decision is obvious—Theorem 1 implies that we should replace $M$ with $M - c_S$ and $m$ with $m - c_D$ in our analysis. Thus, positive marginal cost of product $i$, $i \in \{S, D\}$, will have a negative impact on the capacity of product $i$. However, note that positive $c_S$ may have a positive impact on the capacity of product $D$.

The analysis of the impact of positive capacity costs on prices is less straightforward. Equilibrium unit prices for the a game with zero capacity costs and standardized market sizes ($M$ and $m$) represent the equilibrium marginal profit for the game with non-trivial capacity costs ($c_S$ and $c_D$) and original market sizes ($M$ and $m$). In other words, if the equilibrium prices in the zero-capacity-cost game are $p_S$ and $p_D$, then the equilibrium prices in the non-trivial-capacity-cost game should be $p_S + c_S$ and $p_D + c_D$. Thus, our observation that $p_S > p_D$ when the two products co-exist in the market should be revised, in scenarios with positive marginal costs, to “product S is more profitable than product D.”

### 4.3. Flexible capacity

In this subsection, we consider the problem in which Firm 1 uses flexible capacity instead of dedicated capacity; in other words, Firm 1 faces the same marginal cost $c_F$ for both products. This can also be viewed as having firm-based capacity costs, instead of product-based (as we did in the previous subsections). Note that in a deterministic setting, in which firms are certain about the market conditions, flexibility has little value. The main purpose of this analysis is to provide a benchmark case for the analysis of uncertain games, which are introduced in next section.

Denote $c = (2c_F - c_D)/s > 0$ and define

$$M = M - \tilde{c}, \; m = m - \tilde{c}/\gamma, \quad \text{and}$$

$$\tilde{M} + m = \tilde{M} + \tilde{m} + m - \frac{s}{3}\tilde{c}. \quad (4)$$

Then, under flexible capacity we would have the following equilibrium decisions.

**Theorem 2.** Consider the capacity-production game in which Firm 1 has flexible capacity, and assume $M > \tilde{c}$ and $m > \tilde{c}/\gamma$; then,

1. If $\frac{M}{M} < \gamma$, the established firm will only offer product D with

   $$y_1 = \frac{M + m - 2c_F/d + c_D}{3}, \quad y_2 = \frac{M + m + c_F/d - 2c_D}{3}.$$

   and the production quantities are $q_S = 0$, $q_D = q_1 = y_1$, and $q_2 = y_2$.

2. If $\gamma < \frac{M}{M} < \gamma$, the established firm will offer both product S and D. The equilibrium decisions are

   $$y_1 = \frac{M + m - 2c_F/d + c_D}{3}, \quad y_2 = \frac{M + m + c_F/d - 2c_D}{3},$$

   and the quantities are $q_S = \frac{M - m}{2}$, $q_{D_1} = y_1 - q_S$, and $q_2 = y_2$.  

Fig. 5. Equilibrium in (a) capacity and (b) price when the value factor $d$ varies.

Fig. 6. Equilibrium in (a) capacity and (b) price when the value factor $s$ varies.
3. If $\gamma \leq \frac{4}{\sqrt{21}}$ the established firm will only offer product S and the equilibrium decisions are

$$
\begin{align*}
y_1 &= \frac{(2 - \gamma)m - 2c_F/s + c_D/R}{4 - d/s}, \\
y_2 &= \frac{M + 2m + c_F/s - 2c_D/d}{4 - d/s}, \\
p_S &= \frac{2sM - d(M + m) - 3c_0 + (2 - d/s)c_F}{4 - d/s}, \\
p_D &= \frac{d(M + 2m) + sM - 2c_0}{4 - d/s},
\end{align*}
$$

and $q_S = q_D = y_1$, $q_D = 0$, and $q_S = y_2$.

The equilibrium decisions are rather similar to those obtained in the model with dedicated capacity. However, a couple of differences should be noted that emerge due to the change in capacity-cost structure: first, the production limit of product S is higher than with dedicated capacity ($\frac{2sM}{4 - d/s} > \frac{3c_0}{4 - d/s}$); second, given that Firm 1 has the same product offerings with dedicated and flexible capacity, the total output and price at Firm 2 is higher under flexible capacity. These results can be explained by the fact that flexible capacity is more costly to both products, yet its “flexibility” option is not properly utilized in the deterministic game. Firm 2 then benefits from this cost inefficiency at its competitor, while Firm 1 offsets this effect by offering more of product S, which generates higher margin than product D.

5. Competition under uncertain disruptive technology

In Section 4 the problems are analyzed based on the exact value of $d$, which is assumed to be publicly known before any decision making. This assumption, however, may not hold in many instances, especially when: (1) the disruptive technology is new or (2) the development of disruptive technology is at the moment an onerous task (see, e.g., Anupindi and Jiang, 2008). In fact, depending on the probability of success ($\gamma$) of disruptive technology, there could be five different types of equilibria with regard to ex-ante capacity investment and ex-post capacity usage in our model; detailed discussion and analysis of these five cases can be found in the on-line technical appendix. In the reminder of this section, we will only discuss the most representative two equilibrium types; interested readers may refer to the appendix for a complete analysis.

**Proposition 6** (Low Uncertainty, High Cost). In a UBG in which uncertainty level is low ($\gamma$ close to 0 or 1) or marginal cost of technology is large, both firms in equilibrium produce up to their capacity, regardless of the realization of $d$. The equilibrium capacity decisions are

$$
\begin{align*}
y_3 &= \frac{M - x}{2} - \frac{E[d]\left(\frac{m + \frac{x}{2} - \frac{c_D}{d}}{2(s - E[d])}\right)}{2(s - E[d])}, \\
y_{D_1} &= \frac{s\left(\frac{m + \frac{x}{2} - \frac{c_D}{d}}{2(s - E[d])}\right)}{2(s - E[d])}, \\
y_2 &= \frac{M + m - \frac{c_0}{2}}{3}.
\end{align*}
$$

<table>
<thead>
<tr>
<th>Capacity Decision $(y_1, y_D, y_2)$</th>
<th>Realization of $d$</th>
<th>Pricing Decision $(p_S, p_D)$</th>
<th>Production Decision $(q_S, q_D, q_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firm 1 pays $c_Sy_S + c_Dy_D$</td>
<td>$y_1 = \frac{(2 - \gamma)m - 2c_F/s + c_D/R}{4 - d/s}$, $y_2 = \frac{M + 2m + c_F/s - 2c_D/d}{4 - d/s}$, $p_S = \frac{2sM - d(M + m) - 3c_0 + (2 - d/s)c_F}{4 - d/s}$, $p_D = \frac{d(M + 2m) + sM - 2c_0}{4 - d/s}$</td>
<td>$(y_S, y_D, y_2)$</td>
<td>$(q_S, q_D, q_2)$</td>
</tr>
</tbody>
</table>

Fig. 7. Game Sequence in Uncertain Bertrand Game with Dedicated Capacity.
Proposition 6 implies that high marginal capacity costs have a counter-impact on the uncertainty level in \(d\); when the randomness in \(d\) is low, or when it can be “reduced” through high marginal costs, the capacity investment decision is the same as in the deterministic game in which the value factor of the disruptive technology is \(E[d]\). In addition, there is no idle capacity under either realization of \(d\). The reasons for these results can be two-fold. On the one hand, the need for installing extra capacity is eliminated by low uncertainty level; on the other hand, even if the randomness is high, the benefit of having extra capacity can be offset by the high costs associated with it. Thus, low uncertainty levels or high marginal capacity costs result in full capacity utilization. In another extreme, however, the opposite could happen:

**Proposition 7 (High Uncertainty, Low Cost).** In a UBG in which marginal capacity costs are small or uncertainty is high (\(\lambda\) close to 0.5), firms over-invest in capacity, which leads to over-production.

It is an interesting observation that when costs are small but strictly positive, firms may behave in a way that might be considered irrational; that is, they invest above the ex-post optimum. While both firms select capacity levels above those chosen in the deterministic case, Firm 1 will have idle capacity under either realization of \(d\) (albeit in one case for product \(S\), while in the other for product \(D\)), while Firm 2 has idle capacity only when disruptive technology achieves its lower valuation. Thus, both firms will over-invest in their capacity. As a result of this over-investment, firms also produce higher total quantity than in the deterministic case. This further implies that the prices can be below the ones charged under the deterministic scenario and that a larger market share can be served. Therefore, the customers benefit from uncertainty in disruptive technology when marginal capacity costs are low.

### 5.2. Uncertain Bertrand game with flexible capacity (UBGFC)

Now, consider an alternative problem, in which Firm 1 uses flexible capacity; this can happen, for instance, when Firm 1 adopts assembly line that can be used to produce either type of products, or when it uses experienced and cross-trained workers that can be re-tasked to work on different products. The marginal cost for such flexible capacity is then, naturally, higher than the cost for such capacity when the market a semi-duopoly. In this problem, both firms have to commit to a certain production quantities \((q_1, q_2)\) before \(d\) is realized, which are usually not optimal after the true \(d\) is revealed. We require the total quantity to be fixed for each firm; this may occur, for instance, when firms cannot strategically hold back production quantities after learning the market condition (e.g., the true \(d\)) and market clearing prices have to be applied, or when raw materials, labor, and other resources have already been contracted, and the contracted amount would be difficult to change. However, Firm 1 has some flexibility in the design of its portfolio—it can adjust its production allocation within the total quantity \(q_1\). Any reallocation of production quantities (by some amount \(A\)) incurs a unit cost \(c\). One can think of such cost as coming from capacity conversion, or as a compensation for a customer willing to buy a product with characteristics somewhat different from its original preferences. We note that Firm 1 again has a degree of flexibility in this case; however, unlike the first two cases (UBG and UBGFC) in which firms use responsive pricing (equivalently, ex-post production quantity) to hedge the uncertainties in \(d\), in UCG Firm 1 can only apply delayed product differentiation to achieve the same goal.

The timeline of the UCG is depicted in Fig. 9. We next analyze the problem in two steps: we first characterize the equilibrium quantity decisions of the firms before \(d\) is realized, and we then discuss the ex-post adjustment quantity for Firm 1 after \(d\) is revealed.

Equilibrium decisions in committed quantities are stated in **Proposition 9**. It can be verified that the total production in UCG corresponds to its counterpart obtained in the deterministic case. The initial selection of the committed quantity for product \(S\), \(q_s\) falls between the two ex-post optima, \(L_s\) and \(L_s\), where
\( L_a = \frac{M - \varepsilon_0 m}{2}, \ u \in \{ h, l \}, \) and \( M, m, \) and \( M + m \) are defined by (3). In addition, \( q_S \) will be close to at least one of the ex-post optima.

**Proposition 9 (Committed Quantity Equilibrium under UCG).** In a UCG game with convertible capacity, if the established firm provides both products in the deterministic game under either realization of \( d, \) the equilibrium quantity decisions are \( q_1 = q_2 = \frac{M + m}{2} \) and

1. If \( L_l - L_h \leq c_l, \) then
   \( q_S = \frac{M - m + \varepsilon_0 m}{2}; \)
2. If \( c_l < L_l - L_h < c_l + c_h, \) then there exist \( 0 < x_1 < x_2 < 1 \) s.t.
   \[ q_S = \begin{cases} L_l - \frac{\varepsilon_0}{2}c_l & \text{if } \alpha \in [0, x_1), \\ L_h + \frac{\varepsilon_0}{2}c_h & \text{if } \alpha \in (x_2, 1], \\ \frac{M + m}{2} & \text{if } \alpha \in [x_1, x_2); \end{cases} \]
3. If \( c_l + c_h \leq L_l - L_h, \) then
   \[ q_S = \begin{cases} L_l - \frac{\varepsilon_0}{2}c_l & \text{if } \alpha < \frac{1}{2}, \\ L_h + \frac{\varepsilon_0}{2}c_h & \text{if } \alpha > \frac{1}{2}; \end{cases} \]
where \( \varepsilon = \frac{M}{\varepsilon_0 m}. \)

The first instance occurs when \( d_h \) and \( d_l \) are close—the selection of \( q_S \) only uses the expectation of \( d, \) and Firm 1 does not perform any conversion regardless of the realization of \( d. \) The last instance occurs when \( q_S \) and \( q_S \) are far apart—the committed quantity in \( S \) is selected closer to the ex-post optimum with higher probability of occurrence. Finally, the second instance depicts the case in which \( d_h \) and \( d_l \) are moderately different. When one of the outcomes occurs with a much higher probability, \( q_S \) is set closer to the corresponding ex-post optimum. However, when \( x \) is somewhere in the middle (that is, uncertainty in \( d \) is high), \( q_S \) will be set closer to the “middle”, which is similar to the deterministic case in which \( d \) takes the value of its expectation.

Given the initial quantity decisions as in Proposition 9, the results regarding ex-post product type adjustment are summarized in **Proposition 10**. The basic idea is that for any ex-post optimum quantity of product \( S, \) say \( L, \) we can find a “buffer-zone”—a continuous interval centered at \( L \) (see Fig. 10)—such that if the initial quantity decision \( q_S \) is within the “buffer-zone,” then no adjustment will take place ex-post; otherwise, some adjustment \( A \) will be made to the original \( q_S \) so that the new quantity for \( S, q_S + A, \) is moved to the closest border of the “buffer-zone.”

**Proposition 10 (Ex-Post Adjustment Quantity).** In a UCG with convertible capacity, if the established firm provides both products in the deterministic game under either realization of \( d, \) the ex-post adjustment quantities are

1. If \( L_l - L_h \leq c_l, \) then
   \[ (A_1, A_h) = (0, 0); \]
2. If \( c_l < L_l - L_h < c_l + c_h, \) then
   \[ (A_1, A_h) = \begin{cases} (L_l - L_h - \frac{\varepsilon_0}{2}c_l, 0) & \text{if } \alpha \in [0, x_1), \\ (L_h - L_l - \frac{\varepsilon_0}{2}c_h, 0) & \text{if } \alpha \in [x_2, 1], \\ (0, 0) & \text{if } \alpha \in [x_1, x_2]; \end{cases} \]
3. If \( c_l + c_h \leq L_l - L_h, \) then
   \[ (A_1, A_h) = \begin{cases} (0, L_l - L_h - \frac{\varepsilon_0}{2}c_l - c_h) & \text{if } \alpha \leq \frac{1}{2}, \\ (L_h - L_l - \frac{\varepsilon_0}{2}c_h, 0) & \text{if } \alpha > \frac{1}{2}; \end{cases} \]
where \( \varepsilon = \frac{M}{\varepsilon_0 m}. \)

Thus, when the degree of uncertainty is not very high or when capacity conversion is rather costly, no adjustment will be made under either realization of \( d \) (case 1 in Proposition 10 and case 2 when \( x \) is close to 0.5). On the other extreme, when the disruptive technology is facing high uncertainty or when converting capacity is affordable (case 3 and 2 when \( x \) is close to 0 or 1), the initial quantity decision will place \( q_S \) close to the ex-post optimum that is more-likely to happen (actually, \( q_S \) will be within the “buffer-zone” of this more-likely ex-post optimum) such that the ex-post adjustment will be made only when the less-likely \( d \) is realized. In general, ex-post quantity adjustment will happen under at most one of the possible two realizations, \( d_h \) or \( d_l. \)

6. Concluding remarks

Disruptive-vs.-sustaining-technology based competition has been long observed in many industries, from consumer electronics, telecommunications, to automobile industry and healthcare (Chris-tensen et al., 2000). As customers’ needs become more diversified—sometimes even conflicting with each other (say, the need for both full functionality and compact size)—technology evolutions do not always go vertically up trying to fulfill every aspect of customers’ demand. Rather, disruptive technology strives to make some reasonable trade-offs between those needs (say, instead of “faster, stronger and smaller,” it may provide products that are “slower but smaller;” or “lower-performance but more mobile.”)

Such incomplete substitution between products could be looked upon as multi-dimensional vertical differentiation, which has been studied, for instance, by Moorthy (1988) and Vandenbosch and Weinberg (1995). However, this type of research generally imposes rather generic market assumptions that may not fully capture the challenge imposed on the mature sustaining technology by the emerging disruptive technology. In order to better capture competitions between these two technologies, a model has to accommodate the following characteristics: (1) disruptive technology has a larger customer base than the sustaining technology, and may steal some...
existing customers from the latter; (2) established firms have more flexibility in choosing which technology (or technologies) to adopt.

In this paper, we use a framework in which both of these conditions are met in our effort to understand the impact that disruptive technology may have on the industry, as well as on the established sustaining technology. We characterize equilibrium outcomes in various competition types between these two technologies. Unlike the existing literature, our results suggest that the established firm may adopt disruptive technology along with the entrant, and that the two will price the new products at the same level. Our model also helps the established firm to evaluate if at a given moment it should enter the market for the new product (by analyzing the valuation of the new product and market conditions), and if it should abandon the old product (when its price is high, rather than engaging in a price war with the new product). Incorrect identification of these conditions may help to explain numerous failures of companies facing disruptive technologies mentioned in Christensen (2003).

For many innovative products, the most critical issue is the chance of success. We model this uncertainty by assuming that the value factor of disruptive technology is random. This part of our analysis highlights the impact that the degree of uncertainty and marginal investment costs may have on investment, production, and marketing decisions. In contrast to the deterministic game in which firms always fully utilize their capacity, over-investment, over-production, and low capacity usage might occur when the new technology exhibits high uncertainty and/or low marginal costs. This result can be particularly useful for industries with high fixed costs and low marginal costs (e.g., telecommunications or publishing). We have examined the cases with uncertain market sizes as well, and arrived to similar conclusions when the highest valuation stays the same; when the overall valuation is positively correlated with the market size, the price competition is less intense and firms produce up to capacity. The paper also sheds a light on how decision makings would be different under flexible capacity option (which is more costly than dedicated ones); in general, our results suggest that equilibrium capacity usage increases and more sustaining-technology based products may be manufactured.

There are many ways in which our analysis could be extended. On the supply side, one might allow for the possibility of multiple established/entrant firms and analyze whether cooperation/collusion could take place between the established and/or entrant firms. On the demand side, one might allow the customers to have two products at the same time, or introduce a dedicated market for the sustaining technology and analyze whether it changes current results. The model could also be modified to include the "brand effect" for the established firms, which would lead to differentiated pricing of products based on the same technology. We are also aware that there are many other alternatives to model the preference heterogeneity among customers; one may refer to Adner and Zemsky (2005) for an example with discrete market segments. We conjecture that extended model which allows heterogenous vertical differentiation (different slopes of valuation function) within the same segment may lead to additional insights (e.g., such as incumbent offering both products). Finally, the game can be extended to a multi-period setting such that time-based strategies could be derived for both firms.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ejor.2010.04.033.

References


Engadget.com. 2007. Asus exceeds expectations, ships 350 k Eee PCs in one quarter.


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