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# Technology Selection and Commitment in New Product Development: The Role of Uncertainty and Design Flexibility

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Selecting the right technologies to incorporate in new products is a particularly challenging aspect of new product definition and development. While newer advanced technologies may offer improved performance, they also make the product development process more risky and challenging. In this paper, we focus on the problem of technology selection and commitment under uncertainty, a major challenge to firms in turbulent environments. We argue that the "pizza-bin" approach of rejecting prospective technologies outright may not serve firms well when the pressure to differentiate products is enormous. After motivating the challenges and decisions facing firms using a real-life application from Dell Computer Corporation, we formulate a mathematical model of a firm that must define its products in the presence of technology uncertainty. Specifically, the firm faces two options: (i) a *proven* technology that is known to be viable and (ii) a *prospective* technology that offers superior price to performance results but whose viability is not a fully certain outcome. To minimize the impact of technology uncertainty, we consider two approaches to design flexibility, termed *parallel path* and *sufficient design*, which allow the firm to concurrently develop its products while the technology is being validated. Our analysis helps understand appropriateness of the different flexible design approaches. We illustrate our model with the Dell portable computer example and note the managerial implications of our analysis.
(*New Product Development; Design Flexibility; Technology Selection*)

## 1. Introduction

The increasing emphasis on market leadership and shareholder value creation have turned many a firm's attention to new product development as a source of growth, renewal, and competitive advantage. Product definition, the early phase of the product development process involving the determination of the key specifications of a product, has been shown to be critical to the success of a firm's new product (Cooper 1993, Bacon et al. 1994). While the crucial role played by product definition is increasingly recognized, how to define the product amidst customer and technology uncertainty remains largely an open question.

During the product definition phase, input data and information about customer needs and emerging technologies are used to finalize key specifications of the product such as its performance levels and features. These specifications are important inputs based on which subsequent downstream detailed design and prototyping activities are carried out. To minimize the adverse impact on these subsequent downstream activities, it is often recommended that the specifications be frozen early in the development process (Cooper 1993). However, Bhattacharya et al. (1998) studied the problem of product definition under customer preference uncertainty, and found that in dynamic environments it is necessary for the firm to tune its definition approach to the level of customer preference uncertainty.

In this paper, we address the related problem of product definition under *technology uncertainty*. One of the key decisions made during the product definition phase is the selection of component technology that offers the product its ability to perform at the level set in its specifications. Frequently, a development team is faced with the choice of more than one technological option. The team, in particular, may consider a *prospective technology* that is not yet fully proven but offers the potential of a superior level of performance at the same or lower cost than the best existing proven technological choice. Interestingly, the technology selection decision in product definition and development, despite its importance, has not attracted adequate research attention. Clark and Wheelwright (1993) describe an approach used at one of Hewlett-Packard's business units in the late 1980s, called the *pizza-bin approach*. Products are developed from "on-the-shelf" proven technologies, whose feasibility must be completely proven before product development commences. The pizza-bin approach aims to reduce the risk inherent in the Product Development (PD) process. However, by refusing to consider promising prospective technologies that are not yet fully proven, a firm may forego the chance to commercialize new technologies ahead of competitors and thereby differentiate its products.

Alternatively, the development team may choose to remain flexible and defer commitment to a specific technology, developing its products concurrently with the validation of the prospective technology. The "flexibility" required to pursue an approach may be obtained in one of the following ways. The team may choose to invest in parallel project paths, each of which develops the product for a certain technology. To bound development expenses, the company may decide to terminate the redundant paths as more information becomes available. A second approach involves overdesigning the product so that it would function with all of the technological options. Both these approaches involve additional costs that must be weighed against the benefits in deciding the proper course of action. The costs, benefits, and the decisions faced by a PD team are illustrated by the following real-life experience at Dell Computer Corporation.

### 1.1. Product Definition Under Technology Uncertainty at Dell

In Fall 1993, a small "core team" of Dell Computer's product developers embarked on the design of a new portable product to be launched to market in 12 months. The pressure on the team was intense because at that time Dell did not sell a portable computer. Its earlier product was discontinued because of "quality" problems. Dell's target customer-base—corporate customers—preferred to buy from vendors with a complete product line, so the lack of a portable product resulted in the loss of market share to competitors. Given the background of its prior portable product, the Dell development team felt that an undifferentiated "me-too" product was not enough to regain credibility and foothold in the intensely competitive marketplace. During the definition phase, the team was considering various options to differentiate its products. Market research showed that the top three features portable computer customers cared about were price, processor speed, and battery life. It was hard to differentiate based on processor speed, dictated largely by Intel and shared with all PC suppliers, and the company did not want to compete on price. So, the PD team considered using battery life as a differentiating feature.[1]

During this time-frame, the proven battery technology used by most PC firms was the nickel-metal-hydride (NiHi) battery technology, which lasted less than three hours and suffered from the "battery memory" problem (the battery would recharge only to a fraction of the full level). On the horizon was a new battery technology, called the lithium ion (LIon) technology being developed at Sony, which offered significantly higher battery density (or higher battery life per unit weight) than the NiHi batteries. However, the LIon technology was not yet completely proven for usage in portable computers. In exceptional cases, the battery was reported to be suffering from an "overcharging problem," in which lithium may separate

[1] More details of this case example are presented in the Harvard Business School case study, "Product Development at Dell Computer Corporation" (Thomke et al. 1998).

from the lithium ion if overcharged, potentially leading to an explosion. Sony had designed a workaround circuit to prevent the overcharging problem and was in the process of testing this new enhancement.

Dell had recently adopted a formal phase review approach to product development, which required a firm commitment to specifications at the end of the definition phase. However the new technology was not yet fully validated by the time of the definition phase review. At this point, the team could (a) stick with the proven NiHi technology, (b) commit to the LIon (prospective) technology despite its risks, or (c) decide to wait for more information and defer commitment until a later time. However, waiting for more information might delay the product launch beyond the target launch date. The development team could conceivably minimize/eliminate delays in launch by concurrently developing the product following two parallel paths or by overdesigning the product while waiting for the technology to be validated. The parallel path approach would mean additional development expenditure, and the more time the parallel paths are pursued, the greater the expense. (In particular, the money outflows in a typical product development project are back-loaded due to investment in tooling and dies, so as the firm delays terminating one of the development paths, the cost of the project grows at an ever-increasing rate.) A second option that would offer design flexibility would be to *overdesign* the product so that it could function with either battery technology. However, overdesign of the product could increase the unit variable cost of the product in production and cut into the product's gross margins.

### 1.2. Research Questions Addressed in this Paper

The above example illustrates some of the challenges in defining products amidst technology uncertainty. In this context, we seek to address the following questions:

1. When do prospective technologies deserve serious consideration in the PD process? When must a firm not strictly adhere to the pizza-bin approach (of rejecting unproven technology)?

2. If the firm chose to defer commitment to the technology, what are the implications of the parallel path and overdesign approaches for product development effectiveness?

3. What impact does the firm's risk aversion have on its product definition approach?

We begin answering these questions in §2 by formulating a simple model of product definition under technology uncertainty. Our stylized model is aimed more at generating insights than to serve as a decision support model. The model analyses in §§3 and 4 help characterize the appropriateness of the pizza-bin approach and the implications of deferring commitment. In §5, we relate our model back to the Dell example, summarize the managerial insights, and identify limitations and opportunities for further research.

Our work adds to the growing body of literature focusing on the management of the product development process, reviewed recently by Krishnan and Ulrich (2001). In particular, the issues of uncertainty and development flexibility have been gaining increasing attention in recent years (Iansiti 1995, Ward et al. 1995, Kalyanaram and Krishnan 1997, Thomke 1997, Loch and Terweisch 1998). A few economists have studied the impact of parallel path research and development approaches, focusing more on the number of parallel efforts rather than their effect on product development decision making (Nelson 1961, Arditti and Levy 1980). In a related paper, McCardle (1985) has studied the adoption of uncertain technology, although more in the context of information acquisition costs than in the domain of new product development. Also related to our work is the paper by Srinivasan et al. (1997) who argue that with the new economics of product development (e.g., declining costs of prototyping), it may be optimal to select the best design later in the process. Our model presented below reinforces these findings.

## 2. Model Conceptualization and Formulation

Our attention is focused on a firm that develops a product for use by a set of customers who purchase the product primarily based on its performance and price. The product performance is due to one or more *core technologies* that underlie the product. (For example, in a portable computer, the core technologies include the microprocessor technology, battery technology, display technology, memory technology, etc.) Most firms that we have observed use minor variants of the development review approach in which the product is reviewed at periodic intervals prior to further investments in development (Cooper 1993). For the product being considered, let the firm's nominal product development cost be $C_{dev}$ and nominal development cycle length be $T_{dev}$ completed in $N$ periodic managerial reviews spaced at equal distances. We assume the development time and cost to be exogenously specified.

We also assume that the firm is operating in an industry with product life-cycle length $T_{Lf}$ exogenously determined by the market. However, we allow for dynamic demand by modeling the fraction of the product life-cycle demand sold by time $t$ during the life cycle ($0 \leq t \leq T_{Lf}$) to be described by the general distribution function $F(t)$, where $F(0) = 0$, and $F(T_{Lf}) = 1$. This helps us understand the impact of the life-cycle demand on the firm's technology selection decision. For instance, any delay in the launch of the product would mean a proportional loss in demand and revenues. If, for example, the firm introduces the product $t_{del}$ units of time into the life cycle, it would lose the proportion of gross revenues represented by $F(t_{del})$.

The firm seeks transient advantage by considering a more recent technology, which we call the prospective (*ps*) technology, for its new product. Its decision process differs from the pizza-bin process in the following manner. Instead of rejecting the *ps* technology outright (without giving it any consideration as in the pizza-bin approach), the firm deliberates its choice of technology at the beginning of its development process. To keep our attention focused on the insights, we assume the firm considers for comparison the best-existing proven technology option and only one *ps* technology option (our analysis could be extended to the case with multiple technologies). For the purposes of this paper, a proven technology (denoted by *pv*) is defined as one in which the firm has 100% confidence level about its viability, based on laboratory tests, manufacturing feasibility studies, or track record of the technology. A *ps* technology is, on the other hand, one in which the firm has a lower confidence level about its viability than the *pv* technology in the beginning of the development process. The *ps* technology, while offering better performance or price to performance capabilities, is in the process of being validated and is not yet a *pv* technology.

Suppose that the firm expects to sell $D_{pv}$ units of the product with *pv* technology during the product life cycle with a unit gross margin $m_{pv}$ (resulting in expected gross life cycle profit of $G_{pv} = D_{pv} * m_{pv}$). If the firm were to be successful in introducing a product with the *ps* technology at the beginning of the life cycle, it can expect to sell $D_{ps}$ units during the life cycle with a unit gross margin of $m_{ps}$ (resulting in expected gross life cycle profit of $G_{ps} = D_{ps} * m_{ps}$). Because of the higher performance potential associated with the *ps* technology, we assume it can fetch expected gross life-cycle profit that is higher than the *pv* technology ($G_{ps} > G_{pv}$), justifying the consideration of the *ps* technology despite its risks. We conduct our analysis with expected values of these parameters, later discussing sensitivity of our results to the case when there is uncertainty surrounding these parameters.

The development team's estimate of the viability of *ps* technology at time $T_n$ is described by the parameter $v_n$. At the beginning of the development process, the team's (prior) estimate of the viability of *ps* technology is given by $v_0$. As the process unfolds, more information arrives from the field tests of the *ps* technology that we assume helps the team update its priors in a Bayesian manner.

The sequence of events is as follows. At the beginning of the development process, the development team evaluates both the *pv* and *ps* technologies for their effect on expected profits based on its prior estimate of viability of the *ps* technology, $v_0$. Following this assessment, the team may decide to commit to one of the technologies. It may decide to commit to neither technology at this point, continue to collect more information about the *ps* technology, and defer the decision about commitment until the next development phase review. The new information helps the development team update its priors about the viability of the *ps* technology and form a posterior estimate that can be used to make the technology commitment decision. When the firm defers commitment, it tries to minimize the impact on its time to market by developing the product concurrently and by adopting a flexible approach as described in the next subsection. If the firm decides to commit to the *ps* technology at time $T_n$ ($<T_{dev}$), and finds closer to launch that the *ps* technology is not viable, there is a development cost and time penalty associated with reverting to the *pv* technology. We model that reverting to the *pv* technology results in a development cost penalty $C_{del}$ and time penalty $t_{del}$. For the analysis in §3, we model $C_{del}$ to be equal to $\gamma C_{dev}((T_{dev} - T_n)/T_{dev})$ and the launch time delay $t_{del}$ to be equal to $\beta(T_{dev} - T_n)$. Here $\beta$ represents the *coefficient of reversion to the pv technology* from the *ps* technology on the time dimension, and $\gamma$ represents the *coefficient of reversion to the pv technology* on the cost dimension, after commitment has been made at $T_n$ and the design tailored to the *ps* technology for the rest of the development cycle ($T_{dev} - T_n$). These coefficients of reversion capture the effect of learning from design iterations. It is to be expected that the coefficients of reversion are influenced by the product architecture—the more modular the product architecture, the smaller the coefficients of reversion. Our analysis can be easily extended to more general reversion time and cost delay functions. As stated before, the launch time delay $t_{del}$ results in the loss of sales in accordance with the dynamic demand function $F(t_{del})$.

We begin by assuming the firm is risk neutral, and consider the effect of risk aversion in §3. To stay focused on design flexibility issues, we also assume that the market segment considered is homogeneous in its preference and reservation prices for product performance.

### 2.1. Flexible Design Approach: Parallel Path

The first flexible design approach we consider is the *parallel path* approach in which the firm pursues multiple parallel paths to design the product with a specific technology choice in mind for a period $T_n$ ($<T_{dev}$). (For simplicity, we consider just two parallel paths here, but our analysis can be extended to more paths.) We assume that the development cost is increasing and convex in the time of development. The convex function is justified based on increasing tooling costs as the development delay increases, and has been used in prior research (Graves 1989, Bhattacharya et al. 1998).

$$C_{dev} = C(T_{dev}), \quad C' > 0, \quad C'' > 0. \tag{1}$$

The additional cost of investing in the second parallel path till time $T_n$ $C_n$ is given by:

$$C_n = C(T_n). \tag{2}$$

The second path is pursued in parallel, however we do not assume any economies of scale in pursuing it. If the firm pursues the parallel path approach until time $T_n$ and then decides to commit to either of the technologies with a posterior viability of $\nu_n$, its net profit of choosing proven (*pv*) and prospective (*ps*) technologies at time $T_n$ are given as follows.

$$\begin{aligned}\pi_n^{pv,PP}(v_n) &= \text{expected profit from choosing } pv \\ &\quad\ \text{technology at } T_n \text{ using parallel path} \\ &= G_{pv}F(T_{dev}) + v_n[G_{ps}(1-F(T_{dev})) - C_{dev}] \\ &\quad + (1-v_n)G_{pv}(1-F(T_{dev})) - C_{dev} - C(T_n) \\ &= G_{pv} - C_{dev} - C(T_n) \\ &\quad + v_n[(G_{ps} - G_{pv})(1-F(T_{dev})) - C_{dev}]. \end{aligned} \tag{3}$$

The above expression reflects the fact that even if the firm chose the *pv* technology at time $T_n$, it possesses the option to follow up after launch with a new product based on the *ps* technology (if it proves to be viable at the time of launch). For model tractability, we assume that (a) the firm waits to follow up with *ps* technology until launch after committing to *pv* technology, and (b) following up with a new product based on the *ps* technology takes the entire $T_{dev}$ units of time during which the firm sells the product based on *pv* technology and captures profit given by first term ($G_{pv}F(T_{dev})$). The second term, ($v_n(G_{ps}(1 - F(T_{dev})) - C_{dev})$), represents the net profit from launching the follow-up product with *ps* technology (which happens with a probability $v_n$), and the third term ($(1 - v_n)G_{pv}(1 - F(T_{dev}))$) depicts the profit from staying with the *pv* technology during the remainder of the life cycle. The final term ($C_{dev} + C(T_n)$) denotes the development cost incurred in the parallel path approach. However, the above expression is only for the case when the follow-up product is economically viable. This is the case when:

$$F(T_{dev}) < \left[1 - \frac{C_{dev}}{(G_{ps} - G_{pv})}\right].$$

We assume this condition is satisfied in the body of the paper. In an appendix available on the *Management Science* website,[2] we consider the simpler case when this condition is not satisfied and no follow-up product is launched.

The profit from choosing the prospective technology is as follows:

$$\begin{aligned}
\pi_n^{ps,\,PP}(v_n) &= \text{expected profit from choosing } ps \\
&\quad\ \text{technology at } T_n \text{ using parallel path} \\
&= v_n G_{ps} + (1 - v_n)(G_{pv}(1 - F(t_{del})) - C_{del}) \\
&\quad - (C_{dev} + C(T_n)) \\
&= G_{pv} - C_{dev} - C(T_n) - G_{pv}F(t_{del}) - C_{del} \\
&\quad + v_n(G_{ps} - G_{pv} + C_{del} + G_{pv}F(t_{del})). \qquad (4)
\end{aligned}$$

Again, the first term ($v_n G_{ps}$) denotes the profit from the *ps* technology, while the second term ($(1 - v_n)G_{pv}(1 - F(t_{del})) - C_{del}$) captures the chance that the firm may have to revert to the *pv* technology with the term $C_{del}$ depicting the reversion cost. In the linear case, the reversion costs $C_{del}$ are set to be equal to

$$C_{dev}(1 - v_n)\gamma \frac{T_{dev} - T_n}{T_{dev}}$$

to reflect the dependence on the time of commitment. If the firm delays commitment, the costs of reversion are lower because less work has to be reversed.

### 2.2. Flexible Design Approach: Sufficient Design (*SD*)

The second flexible development approach we model is termed sufficient design (*SD*) because the design is sufficient (adequate) for the product to function with both technologies. In this approach, the product is overdesigned in that the decision is made early on to define the architecture and the product package such that both technologies can fit in. The effect of this change is to reduce the gross margins because of the increased variable cost and/or decreased product attractiveness. The gross margins decrease from $G_{ps}$ to $\overline{G_{ps}}$ for the *ps* technology and from $G_{pv}$ to $\overline{G_{pv}}$ for the *pv* technology. *SD*'s advantage is that if the firm picks *ps* technology and finds that it is not viable at the time of launch, the cost of reversion is zero. However, it might require additional and more skilled development resources to identify a sufficient design, we model the development cost for *SD* to be $\overline{C}_{dev}$ (in general, $\overline{C}_{dev} > C_{dev}$). The profit expressions from following the *SD* approach are as follows.

$$\begin{aligned}
\pi_n^{pv,\,SD}(v_n) &= \text{expected profit from choosing } pv \\
&\quad\ \text{technology at } T_n \text{ using } SD \\
&= \overline{G_{pv}}F(T_{dev}) + v_n\left[\overline{G_{ps}}(1 - F(T_{dev}))\right] \\
&\quad + (1 - v_n)\overline{G_{pv}}(1 - F(T_{dev})) - \overline{C}_{dev} \\
&= \overline{G_{pv}} - \overline{C}_{dev} \\
&\quad + v_n\left[(\overline{G_{ps}} - \overline{G_{pv}})(1 - F(T_{dev}))\right]. \qquad (5)
\end{aligned}$$

With probability $v_n$, the firm will launch a follow-up product that can command a gross profit of $\overline{G_{ps}}$. Because of the effort invested in *SD*, the additional effort involved in launching a follow-up product is zero. The net profit earned by this follow-up product is $v_n[\overline{G_{ps}}(1 - F(T_{dev}))]$. The expected profit from choosing *ps* technology under *SD* equals the sum of the net profit from the *ps* technology ($v_n\overline{G_{ps}} - \overline{C}_{dev}$), and the profit from reversion to the *pv* technology ($(1 - v_n)\overline{G_{pv}}$).

$$\begin{aligned}
\pi_n^{ps,\,SD}(v_n) &= \text{expected profit from choosing } ps \\
&\quad\ \text{technology at } T_n \text{ using } SD \\
&= v_n\overline{G_{ps}} - \overline{C}_{dev} + (1 - v_n)\overline{G_{pv}} \\
&= \overline{G_{pv}} - \overline{C}_{dev} + v_n(\overline{G_{ps}} - \overline{G_{pv}}). \qquad (6)
\end{aligned}$$

## 3. Model Analysis

We now examine when a firm would consider a *ps* technology without rejecting it outright. Next, we compare the implications of the parallel path and *SD* approaches to design flexibility. Finally, we study how the firm's risk aversion influences its decisions under uncertainty.

[2] ⟨mansci.pubs.informs.org⟩

### 3.1. Prospective Technology (*ps*): To Consider or Not to Consider

To find when the *ps* technology deserves consideration, we simply compare the profit expressions from the *pv* and *ps* technology at the beginning of the development process. At this point, the firm has not chosen the *PP* or the *SD* schemes, so the cost of development is essentially $C_{dev}$. However, if the firm picks the *ps* technology, with a probability of $(1-v_0)$ it will incur an additional cost and time penalty to revert to the *pv* technology. Setting the cost of reversion to be $C_{dev}\gamma$ and the development time delay to be $\beta T_{dev}$, the profit expressions are as follows.

$$\begin{aligned}\pi_0^{pv}(v_0) &= \text{expected profit from choosing } pv \text{ technology at the beginning}\\ &= G_{pv}F(T_{dev}) + v_0[G_{pv}(1-F(T_{dev})) - C_{dev}]\\ &\quad +(1-v_0)G_{pv}(1-F(T_{dev})) - C_{dev}\\ &= G_{pv} - C_{dev}\\ &\quad + v_0[(G_{ps}-G_{pv})(1-F(T_{dev})) - C_{dev}]. \qquad (7)\end{aligned}$$

$$\begin{aligned}\pi_0^{ps}(v_0) &= \text{expected profit from choosing } ps \text{ technology at the beginning}\\ &= v_0G_{ps} + (1-v_0)[G_{pv}(1-F(\beta T_{dev}))]\\ &\quad - C_{dev}(1+(1-v_0)\gamma)\\ &= G_{pv} - C_{dev} - G_{pv}F(\beta T_{dev}) - C_{dev}\gamma\\ &\quad + v_0(G_{ps} - G_{pv} + C_{dev}\gamma + G_{pv}F(\beta T_{dev})). \qquad (8)\end{aligned}$$

Comparing the expected profit expressions above, we obtain a condition for the firm to consider the *ps* technology by setting $\pi_0^{ps}(v_0) \geq \pi_0^{pv}(v_0)$ or if:

$$\begin{aligned} v_0 &\geq v_{thr}\\ &= \frac{C_{dev}\gamma + G_{pv}F(\beta T_{dev})}{(G_{ps}-G_{pv})F(T_{dev}) + C_{dev} + C_{dev}\gamma + G_{pv}F(\beta T_{dev})}. \qquad (9)\end{aligned}$$

While the expression above is neither necessary nor sufficient for the firm to consider the *ps* technology, it could be argued that a rational firm giving serious consideration to the *ps* technology would, at a minimum, expect the profits from the *ps* technology at the outset to exceed the profit from the *pv* technology. In that sense, the above expression is a surrogate for necessary and sufficient conditions (that depend on subsequent information received as modeled in the next section), and provides a "threshold" value of viability above which the prospective technology is likely to be considered. On the basis of this threshold, the firm would consider the *ps* technology, when the gross profit of the *ps* technology $G_{ps}$ is higher and when the gross profit of the *pv* technology $G_{pv}$ is lower. Also, $v_{thr}$ in (9) is increasing in the coefficients of reversion $\gamma$ and $\beta$. As the reversion penalties get increasingly expensive, the firm is less likely to consider the *ps* technology to minimize reversion costs (confirming intuition). Interpreting the relationship of $v_{thr}$ to the demand life cycle represented by $F(T_{dev})$, $T_{dev}$, and the cost of development $C_{dev}$ is more involved, and depends on the relative values of profitability of the *pv* and *ps* technologies as seen below. For the cost of development, $C_{dev}$, we can state the following.

Result 1a. When

$$\frac{G_{ps}-G_{pv}}{G_{pv}} < \frac{F(\beta T_{dev})}{\gamma F(T_{dev})},$$

the threshold viability $v_{thr}$ is monotone decreasing in $C_{dev}$.

Result 1b. When

$$\frac{G_{ps}-G_{pv}}{G_{pv}} > \frac{F(\beta T_{dev})}{\gamma F(T_{dev})},$$

the threshold viability $v_{thr}$ is monotone increasing in $C_{dev}$.

For the demand life cycle represented by $F(T_{dev})$, we can state the following:

Result 1c. When

$$\frac{G_{ps}-G_{pv}}{G_{pv}} < \left[\frac{1}{v_{thr}} - 1\right]\frac{\partial F(\beta T_{dev})}{\partial F(T_{dev})},$$

the threshold viability $v_{thr}$ is monotone increasing in $F(T_{dev})$.

Result 1d. When

$$\frac{G_{ps}-G_{pv}}{G_{pv}} > \left[\frac{1}{v_{thr}} - 1\right]\frac{\partial F(\beta T_{dev})}{\partial F(T_{dev})}, \qquad (10)$$

the threshold viability $v_{thr}$ is monotone decreasing in $F(T_{dev})$.

In other words, when the relative difference in profitability between the two technologies is smaller than the effect of the ratio of the coefficients of reversion

$$\left(\frac{G_{ps}-G_{pv}}{G_{pv}} < \frac{F(\beta T_{dev})}{\gamma F(T_{dev})}\right),$$

a smaller nominal cost of development ($C_{dev}$) leads to a smaller region of consideration for the *ps* technology. However, the opposite is the case when the relative difference in profitability between the two technologies is large

$$\left(\frac{G_{ps-G_{pv}}}{G_{pv}} < \frac{F(\beta T_{dev})}{\gamma F(T_{dev})}\right)$$

the firm increases its consideration of *ps* technology when the cost of development is small.

The physical interpretation of this result is somewhat involved and is as follows. When the relative difference in profitability between the *pv* and *ps* technologies is small, the cost of development weighs heavily on the firm. Higher cost of development favors reversion activities more than follow up (which involves doubling of the development costs), prompting the firm to more seriously consider the *ps* technology. However, when the relative difference in profitability between the *pv* and *ps* technologies is large, the firm opts to follow up with a product offering the *ps* technology, and hence, the firm favors considering the *pv* technology at the outset, increasing the value of the threshold viability.

Similarly, in the case of the life-cycle demand, the decision to choose between the *pv* and *ps* technologies at the beginning of the deliberation process is governed by the trade-off between net benefits of reversion and follow-up activities (done to follow a product based on *pv* technology with a product made of the *ps* technology). If the net gains from reversion exceed the net benefit from follow up, the firm is likely to consider at the outset the *ps* technology for a greater range of the threshold viability values.

When the demand gets more front-loaded in the life cycle, the net benefits from both reversion as well as follow up are reduced because of the loss of revenues. However, the ratio of this reduction in net benefit from reversion to follow up is inversely proportional to $((G_{ps}-G_{pv})/G_{pv})$. When the fractional improvement in gross profitability due to the *ps* technology $((G_{ps}-G_{pv})/G_{pv})$ is small, the reduction in net benefit from reversion exceeds the reduction in net benefit from follow up, causing the firm to gravitate towards the *pv* technology (and use the follow-up approach in case the *ps* technology is available at launch time). The *ps* technology in this case is not attractive enough to incur the costs of reversion. However, when the ratio $((G_{ps}-G_{pv})/G_{pv})$ is high, the follow-up approach suffers more than reversion from front-loaded demand, leading the firm to increase the region of consideration of the *ps* technology. Now, the *ps* technology is attractive enough to overcome the costs of reversion.

From the chain rule, we can see that the length of the development cycle affects the choice of technologies in a fashion similar to that of $F(T_{dev})$. Thus, when the relative difference in profitability between the two technologies is small, a shorter development cycle increases the region of consideration of the *ps* technology, because the costs of reversion are lowered by the shorter development cycle (and follow-up costs cannot be justified for the marginally profitable *ps* technology). However, when the relative difference in profitability between the two technologies is large, a shorter development cycle decreases the region of consideration of the *ps* technology, because the demand lost during the follow-up period is reduced due to the shortness of the length of the development cycle.

In the above analysis, we assumed that some of the variables, like the payoffs $G_{ps}$ and $G_{pv}$ are known and deterministic. These assumptions can be relaxed in the model, however, it is difficult to obtain analytical solutions for problems with two stochastic variables. Numerically, we can show that if a firm is risk averse, it will have a higher threshold value to consider the *ps* technology, as the payoff from the *pv* technology can be estimated with a much higher degree of accuracy. Since the payoff from the *ps* technology ($G_{ps}$) has a higher degree of uncertainty, a risk-averse firm will discount this payoff to a larger extent. Similarly, if the cost of development for the *ps* technology is uncertain, the firm will have a higher threshold value compared to the case when the cost of development is known and deterministic, this result also has a similar intuition. We now turn our attention to the comparison of the two flexible approaches.

## 4. Analysis of the Different Design Flexibility Approaches

The technology deliberation process benefits from the real time information available about the *ps* technology from laboratory and field tests. We model that the firm begins with a prior estimate $v_0$ of the viability of the *ps* technology, and updates its prior information with signals from the field tests in a Bayesian manner. Let the firm's posterior estimate of the viability of *ps* technology at time $t_n$ be denoted by $v_n$. It is common in literature to assume that the prior and signals form a conjugate prior, so that the posterior is of the same distribution as the prior (McCardle 1985). Due to the nature of the parameters, we assume that the prior estimate $v_0$ of the viability of the *ps* technology is from a Beta distribution (between 0 and 1 with parameters $\alpha$ and $\delta$), and the signals are taken from a Bernoulli distribution—a favorable (unfavorable) signal indicating the success (failure) of the technology in field tests.

At any point in the development process, if the team makes the decision to commit to one type of technology, it will commit to that technology which fetches the greater amount of expected profit. However, the team also has the option to continue to collect more information from the technology supplier and defer the commitment decision as late as possible or at least until the next review. It is possible that the new information might increase the certainty of available information thereby increasing the expected profit. However, continuing to collect more information also means that the development team spends more time pursuing a parallel path or an *SD* approach, increasing either the fixed cost of development or reducing its margins. Whichever flexible approach the team follows, the optimal course of action for a team at review $n$ with posterior probability $v_n$ of the viability of the *ps* technology can be formulated as a dynamic program as follows. Let:

$\pi_n(v_n)$ = return from commitment to the most profitable technology at review $n$,

$\overline{R}_{n+1}(v_n)$ = return from optimal policy at review $(n+1)$ given $v_n$ at review $n$, (11)

$R_n(v_n)$ = return from following the optimal policy at review $n = \text{Max}[\pi_n(v_n), \overline{R}_{n+1}(v_n)]$,

where $\overline{R}_{n+1}(v_n) = v_n \cdot R_{n+1}(v_n^+) + (1-v_n) \cdot R_{n+1}(v_n^-)$.

Here, $v_n^+$ denotes the updated value of $v_n$ when a positive signal arrives, and $v_n^-$ denotes the updated value of $v_n$ when a negative signal arrives. This is because $v_n$ is also the probability the firm expects to receive a positive signal about the viability of *ps* technology at stage $n$. For a Beta-Bernoulli conjugate pair with parameters $\alpha$ and $\delta$, they simplify to:

$$v_n^+ = \frac{v_n \cdot (\alpha+\delta+n)+1}{(\alpha+\delta+n+1)}; \quad v_n^- = \frac{v_n \cdot (\alpha+\delta+n)}{(\alpha+\delta+n+1)}.$$

When the firm chose to follow the *SD* approach, we have:

$$R_n^{SD}(v_n) = \text{Max}\big(\pi_n^{pv,SD}(v_n), \pi_n^{ps,SD}(v_n), \overline{R}_{n+1}^{SD}(v_n)\big). \tag{12}$$

The expression for parallel path (*PP*) can be written in a similar fashion by substituting *PP* for *SD*. The optimal course of action at review $n$ depends on which alternative provides the greatest expected profit: commitment to *pv* technology, commitment to *ps* technology, or continuation of the deliberation and information collection process. Accordingly, the expression for $R_n(v_n)$ compares these three profit terms, with the last term $\overline{R}_{n+1}(v_n)$ denoting the benefit of continuing to collect more information. Given $v_n$ at review $n$, the next piece of information will be favorable with probability $v_n$ (indicating that the *ps* technology functions to specifications in market conditions), and with probability $(1-v_n)$, the next signal will be unfavorable. Implicit in the above formulation is the modeling assumption that once the firm picks one of the flexible design approaches, it sticks to the approach. At the beginning the firm must choose between outright commitment to the *pv* or *ps* technology and the *PP* or *SD* approaches. The dynamic programming equation for the initial decision (on whether to commit or continue) is as follows.

$$R_0(v_0) = \text{Max}\big(\pi_0^{pv}(v_0), \pi_0^{ps}(v_0), \overline{R}_1^{SD}(v_0), \overline{R}_1^{PP}(v_0)\big). \tag{13}$$

### 4.1. Analysis of Sufficient Design

Among the two approaches to design flexibility, *SD* is the easier one to analyze. It is interesting to note that the marginal value of new information collected under *SD* is increasing in time, due to which commitment will happen as late as possible (see Result 2 below). However, after the choice is made to pursue the *SD* option, the marginal cost of collecting new information is zero under *SD*, so the firm need not worry about delaying commitment. In theory, the firm may fit either technology into its product, and can even offer more than one version of the product in a diverse market using the same product design.

RESULT 2. The marginal value of positive information in the *SD* approach is positive until the point of launch, making it optimal to delay the point of commitment as much as possible. The proof of the result follows directly from Expressions (5) and (6) in §2.2. It is clear that the profit is monotone increasing in the team's viability estimate, and a positive signal increases the viability estimate. Although the marginal increase in expected profit is decreasing in time, a positive signal does contribute to an increase in expected profit until the point of launch. This is due to the fact that there is no marginal cost associated with the *SD* approach. The firm may therefore commit at the point of launch or, if possible, even beyond. Unlike the *SD* approach, the parallel path approach, which we now consider, involves a marginal cost of pursuit.

### 4.2. Analysis of Parallel Path (*PP*)

If the firm follows the parallel path (*PP*) approach, the profits when it commits to either the *pv* or *ps* technology are as in Expressions (3) and (4). They are of the form $F^{PP} - C(T_n) + A^{PP} v_n$ where $F^{PP}$ and $A^{PP}$ are time invariant for the *pv* technology, and time variant for the *ps* technology. For the *pv* technology (see Expression (3)), $F^{PP}$ and $A^{PP}$ are given by:

$$F^{pv,PP} = G_{pv} - C_{dev}$$

and

$$A^{pv,PP} = [(G_{ps} - G_{pv})(1 - F(T_{dev})) - C_{dev}].$$

For the *ps* technology (see Expression (4)), $F^{pp}$ and $A^{pp}$ are given by:

$$F^{ps,PP} = G_{pv} - C_{dev} - G_{pv}F(t_{del}) - C_{del},$$

and

$$A^{ps,PP} = (G_{ps} - G_{pv} + C_{del} + G_{pv}F(t_{del})).$$

Let

$$\Delta A^{PP} = A^{ps,PP} - A^{pv,PP} = ((G_{ps} - G_{pv})F(T_{dev}) + C_{dev} + C_{del} + G_{pv}F(t_{del})).$$

We have left the terms $t_{del}$ and $C_{del}$ generally, but the linear forms assumed in §2 can be substituted for them to achieve simplicity.

Note that although the firm does not pay an explicit cost for the information collected in our model, it does incur the cost of pursuing an additional path for one more phase. As mentioned earlier, the development cost function is convex due to the increased investments later in the development process. This additional development cost of pursuing the second path for one more period is denoted as $C_n^{PP}$ and is given by: $C_n^{PP} = C(T_{n+1}) - C(T_n)$.

Suppose that the firm's nominal development process is made up of $N$ equally spaced managerial reviews. We now examine if one of the *PP* can be terminated before all $N$ reviews are completed with a beta distribution for the prior and a Bernoulli distribution for incoming information.

RESULT 3. Under the *PP* development approach, the firm will terminate one of the paths at the first point where the

$$\frac{\text{variance}(v_n)}{\text{mean}(v_n)} \leq \text{ a critical value } \Psi, \tag{14}$$

or at review $n$ if $\exists\, n\; 1 \leq n \leq N$ for which

$$\begin{aligned}(C_{del} + G_{pv}F(t_{del}))\left(\frac{\delta + N - 1}{(\alpha + \delta + N - 1)}\right) &< C_n^{PP} + \frac{\alpha}{(\alpha + \delta + N)} \cdot \{C_{dev} + (G_{ps} - G_{pv})F(T_{dev})\} \\ &\quad + \frac{\alpha}{(\alpha + \delta + N - 1) \cdot (\alpha + \delta + N)} \cdot \{G_{ps} - G_{pv}\},\end{aligned} \tag{15}$$

where

$$\Psi = \frac{(C_n^{PP} - \frac{\alpha + N}{(\alpha + \delta + N)} \cdot \{C_{dev} + (G_{ps} - G_{pv})F(T_{dev})\} + \frac{\delta}{(\alpha + \delta + N)} C_{del})}{A^{pv,PP}}. \tag{16}$$

The proof proceeds as follows. We show first that the net benefit of new information is either decreasing in time or always negative beyond a certain point if the condition above is satisfied while following the *PP* development approach. In the former case, if the net benefit of the *PP* approach becomes negative at some point in time *during* the product development process, the firm should immediately converge to one of the technologies, because all future information cannot improve the expected profit from the current levels. Similarly, in the latter case, the firm should commit at the point the net benefit of information turns negative.

To determine the net value of new information, we must consider both positive and negative information. It can be intuitively seen (and also shown mathematically quite easily) that the value of the new information that does not cause the firm to change its decision from one type of technology to the other is decreasing in time (McCardle 1985). Even if such information increases or decreases the value of the firm's estimate of viability, the marginal change in the estimate due to new information decreases with time, and the firm incurs the additional cost of the *PP*, which is increasing in time. However, the value of new information that causes a change in the decision is more involved. There are two possibilities:

(a) Negative information may cause the firm to choose the *pv* technology without which the firm would have chosen the *ps* technology.

(b) Positive information may cause the firm to choose the *ps* technology without which the firm would have chosen the *pv* technology.

Consider Case (a). The value of the new information $\Delta\pi$ is given by:

$$\begin{aligned}\Delta\pi &= F^{pv,PP} - F^{ps,PP} + v_n^- A^{pv,PP} - v_n A^{ps,PP} \\ &\quad - \big(C(T_{n+1}) - C(T_n)\big) \\ &= \Delta F^{PP} - C_n^{PP} + (v_n^- - v_n)A^{ps,PP} - v_n^-(\Delta A^{PP}),\end{aligned}$$

where $\Delta F^{PP} = F^{pv,PP} - F^{ps,PP}$ and $\Delta A^{PP} = A^{ps,PP} - A^{pv,PP}$. In the above expression, $\Delta F^{PP}$ equal to $C_{del} + G_{pv}F(t_{del})$ is decreasing in time (later the time of commitment smaller the reversion penalty), and $C_n^{pp}$ is increasing in time at a convex rate. Notice that the last two terms in the above expression $((v_n^- - v_n)A^{ps,PP}, -v_n^-(\Delta A^{PP}))$ are increasing in time, but they are always negative, since $A^{ps,PP}$ and $\Delta A^{pp}$ are always positive. Commitment is guaranteed through new information not adding positive value when the following condition is satisfied:

$$\begin{aligned}&\Delta F^{PP} - [C(T_{n+1}) - C(T_n)] + (v_n^- - v_n)A^{ps,PP} \\ &\quad - v_n^-(\Delta A^{PP}) < 0, \\ &\Delta F^{PP} < [C(T_{n+1}) - C(T_n)] + (v_n - v_n^-)A^{ps,PP} \\ &\quad + v_n^-(\Delta A^{PP}), \\ &C_{del} + G_{pv}F(t_{del}) < C_n^{PP} + v_n^-\{C_{del} + G_{pv}F(t_{del}) + C_{dev} \\ &\qquad + (G_{ps} - G_{pv})F(T_{dev})\} \\ &\qquad + \frac{v_n}{\alpha+\delta+n+1}\{G_{ps} - G_{pv} + C_{del} + G_{pv}F(t_{del})\}.\end{aligned}$$

The left-hand side of the above equation decreases in $n$. We can get a sufficient condition by substituting the right-hand side with a minimum value for all stages. (If this condition is satisfied for a particular $n$, it is satisfied for all future phases.) The minimum value of $v_n^-$ is achieved when all the signals received are negative, which corresponds to

$$v_n^- = \frac{\alpha}{(\alpha+\delta+N)}.$$

Under these circumstances, the minimum value of

$$\frac{v_n}{\alpha+\delta+n+1} = \frac{\alpha}{(\alpha+\delta+N-1)\cdot(\alpha+\delta+N)}.$$

We get:

$$\begin{aligned}&C_{del} + G_{pv}F(t_{del}) \\ &\quad < \Bigg(C_n^{PP} + \frac{\alpha}{(\alpha+\delta+N)} \\ &\qquad \times \{C_{del} + G_{pv}F(t_{del}) + C_{dev} + (G_{ps} - G_{pv})F(T_{dev})\} \\ &\qquad + \frac{\alpha}{(\alpha+\delta+N-1)\cdot(\alpha+\delta+N)} \\ &\qquad \times \{G_{ps} - G_{pv} + C_{del} + G_{pv}F(t_{del})\}\Bigg). \\ &(C_{del} + G_{pv}F(t_{del}))\left(\frac{\delta+N-1}{(\alpha+\delta+N-1)}\right) \\ &\quad < \Bigg(C_n^{PP} + \frac{\alpha}{(\alpha+\delta+N)}\cdot\{C_{dev} + (G_{ps} - G_{pv})F(T_{dev})\} \\ &\qquad + \frac{\alpha}{(\alpha+\delta+N-1)\cdot(\alpha+\delta+N)}\cdot\{G_{ps} - G_{pv}\}\Bigg).\end{aligned}$$

Now consider Case (b). The value of the new information $\Delta\pi$ is given by:

$$\begin{aligned}\Delta\pi &= F^{ps,PP} - F^{pv,PP} + v_n^+ A^{ps,PP} - v_n A^{pv,PP} \\ &\quad - \left[C(T_{n+1}) - C(T_n)\right] \\ &= -\left[C(T_{n+1}) - C(T_n)\right] + (v_n^+ - v_n) A^{pv,PP} \\ &\quad + v_n^+ (\Delta A^{PP}) - \Delta F^{PP}.\end{aligned}$$

The first three terms of the right-hand side of the above expression are decreasing in $n$. $\Delta\pi$ is negative in the following case:

$$\begin{aligned}&(v_n^+ - v_n) \\ &\quad < \frac{(C(T_{n+1}) - C(T_n) - v_n^+(\Delta A^{PP})) + \Delta F^{PP}}{A^{pv,PP}} \\ &\quad < C_n^{PP} - \frac{\alpha + N}{(\alpha+\delta+N)} \\ &\qquad \cdot \left\{C_{dev} + (G_{ps} - G_{pv}) F(T_{dev}) + C_{del} + G_{pv} F(t_{del})\right\} \\ &\qquad + C_{del} + G_{pv} F(t_{del}) / A^{pv,PP}.\end{aligned}$$

Let $S_n$ denote the number of positive signals that have arrived until review $n$. Then

$$\begin{aligned}(v_n^+ - v_n) &= \frac{\alpha + S_n + 1}{\alpha + \delta + n + 1} - \frac{\alpha + S_n}{\alpha + \delta + n} \\ &= \frac{(\delta + n - S_n)}{(\alpha + \delta + n + 1)(\alpha + \delta + n)} = \frac{\text{var}(v_n)}{\text{mean}(v_n)}.\end{aligned}$$

Because for a Beta distribution

$$\text{var}(v_n) = \frac{(\alpha + S_n)(\delta + n - S_n)}{(\alpha + \delta + n + 1)(\alpha + \delta + n)^2}$$

and

$$\text{mean}(v_n) = \frac{(\alpha + S_n)}{(\alpha + \delta + n)}.$$

By taking the minimum value of $t_{del}$, the point of convergence is thus bounded by:

$$\frac{\text{var}(v_n)}{\text{mean}(v_n)} \le \Psi, \quad \text{where}$$

$$\Psi = \frac{C_n^{PP} - \frac{\alpha+N}{(\alpha+\delta+N)}\{C_{dev} + (G_{ps} - G_{pv}) F(T_{dev})\} + \frac{\delta}{(\alpha+\delta+N)} C_{del}}{A^{pv,PP}}.$$

Given the above result, how should the firm decide at the beginning of the development process between *PP* and *SD* approaches? It can be shown that the ratio of variance to mean at review $n$ is related directly to the ratio of variance to mean at review 0 (beginning of the development process).

$$\frac{\text{var}(v_n)}{\text{mean}(v_n)} = \frac{\text{var}(v_0)}{\text{mean}(v_0)} \frac{1}{1 + (\frac{n}{\alpha+\beta+1})},$$

so the firm can make the decision based on the ratio of the variance to mean at the beginning of the development process. In particular, if the ratio of variance to mean is low, the firm is better off picking the *PP* approach, otherwise it would prefer to choose the *SD* approach (which entails no marginal cost of deliberation). Clearly, the exact decision would depend on the value of other parameters.

### 4.3. Effect of Firm's Risk Aversion

The above analysis has assumed a risk-neutral firm. In practice, firms are risk averse due to which they may be more reluctant to consider unproven technology. What is the effect of the firm's risk aversion on product definition under technology uncertainty? Since the *SD* approach does not involve a marginal cost of pursuit once the approach has been chosen, we consider the impact of risk aversion on the parallel path approach. For tractability, we assume that the firm has an absolute risk aversion of the quadratic form, i.e., we assume that the payoff of $w$ to the firm is of the form of $U(w) = -(a - w)^2$ (Pratt et al. 1995). The risk-averse firm's objective is to maximize the certainty equivalent of its expected profit, which would be lower than the profit anticipated by the risk-neutral firm. The effect of risk aversion is, in general, to lead the firm to choose the *pv* technology because of its lower uncertainty. But risk aversion also has implications for when the firm terminates the *PP* approach, as in Result 4 below (the proof is available as an appendix from the authors).

Result 4. Under *PP*, the risk-averse firm will converge *earlier* (later) than a risk-neutral firm, when the viability of the *ps* technology is above (below) a critical value.

We now consider the managerial implications of our analysis.

## 5. Model Implications and Managerial Insights

The first finding from our analytical results is that a firm should not always reject a *ps* technology outright, given the ability to differentiate the product and increase gross margins. Clearly, the more profitable the *ps* technology or the smaller the coefficient of reversion, the more likely the firm would be to consider the *ps* technology. The impact of the demand intensity function, cost of development and the length of the development cycle on the region of consideration of the *ps* technology are quite interesting. As explained in §3.1, the exact relationship depends on the difference in profitability between the *pv* and *ps* technologies. When the relative difference in profitability between the two technologies is small, front-loaded demand during the product life cycle and smaller nominal cost of development lead the firm to a smaller region of consideration of the *ps* technology. However, the opposite is the case when the relative difference in profitability between the two technologies is large. This is due to the trade-off between net benefits of reversion and follow-up activities. If the net gains from reversion exceed the net benefit from follow up, the firm increases consideration of *ps* technology. When the demand gets more front-loaded in the life cycle, the net benefits from both reversion as well as follow up are reduced because of the loss of revenues. When the improvement in gross profitability due to the *ps* technology is small, the reduction in net benefit from reversion exceeds the reduction in net benefit from follow up, causing the firm to gravitate towards the *pv* technology. However, when the improvement in gross profitability due to the *ps* technology is large, the follow-up approach suffers more than reversion from front-loaded demand, leading the firm to increase the region of consideration of the *ps* technology.

The analytical result on the effect of the different approaches to design flexibility, although based on a Beta prior, offers useful insights. We find that despite the fact that the *SD* approach involves an added cost of development, there is no marginal cost associated with collecting information, so the optimal point of commitment occurs as late as possible. On the other hand, the *PP* approach has a significant marginal cost associated with deliberating—the cost can increase at an increasing rate with time due to the investments in tooling made later in the development process. It is important to reach convergence (terminate one of the *PP*) earlier in the development process. Our results show that, under the modeling assumptions, when the ratio of variance to mean of viability falls before a critical value, one of the *PP* is likely to terminate soon.

Our analysis suggests that when the firm's initial variance as well as the initial mean viability are both low, pizza-bin would be the logical choice. When the firm's initial estimate of viability is high, however, the *ps* technology deserves more serious consideration through a flexible design approach. When the initial variance of viability is also high, *SD* is more appropriate because the time taken to achieve convergence would be expensive under the *PP* approach but *SD* does not involve a marginal cost of deliberation. When the initial variance of viability is low, *PP* may be appropriate because of the lower time required to reach convergence. These are, however, general directional guidelines, and the exact approach pursued depends on a number of parameters including the length of the development and life cycles, profitability of the *pv* and *ps* technologies, and the coefficients of reversion.

### 5.1. Illustration: Product Definition Under Technology Uncertainty at Dell

We now revisit the Dell laptop situation described in §1. It is noteworthy that the development team chose to commit to the lithium-ion technology right away. The battery supplier was eventually able to control the lithium-ion overcharging problem, so the decision to go with lithium-ion technology led to a successful product that brought Dell back into the portable market in the 1990s. In retrospect, the decision served them well, but the decision was fraught with risks and Dell could have achieved the upside from the lithium-ion battery *without* the significant downside risk of up-front commitment by adopting the *PP* or *SD* approach. Based on data collected from Dell and other industry sources, we also examine the profit from the two flexible approaches to see which would have been more appropriate to the Dell context.

Dell enjoyed a sizeable 2.5% of the market of worldwide portable market before the product fiasco discussed in §1 which brought down the market share (to 1%). The team expected that if it developed a quality product with *pv* technologies, it could recapture a share of the market ($m_{pv}$) equal to 2.5%. Additionally, if the team were able to launch a product that is differentiated along a differentiating feature (such as battery life), it could hope to recapture a greater share of the worldwide market ($m_{pp}$) equal to 3%. The market size ($M$) was expected to be about 33 million units for the time period 1995–1997 (from IDC data). The product development cycle length ($T_{dev}$) was 18 months, and the life-cycle length $T_{Lf}$ was estimated to be 36 months. The estimated cost of developing a new product at Dell is $10 million with six reviews/gates to approve further investments. If the team picked the LIon technology and later discovered that it had to revert to the *pv* NiHi technology, we found from our interviews that it would have to rework about 30% portion of the work ($\beta = \gamma = 0.3$). We roughly estimated the team's confidence level ($v_0$) associated with the viability of the lithium-ion technology to be about 0.6, because three of the five battery-savvy developers in the team believed LIon technology would be viable at launch, while two viewed it to be not viable.

The average gross margin for the new product during its three-year life cycle (1995–1997) was expected to be $600. The Dell team wanted to grow the demand and its share of the market with the new product keeping same margins. So, gross margin associated with the LIon product was also $600 (average), but Dell's market share was expected to increase from 2.5% to 3%. Using the above data, the gross profit associated with the NiHi product for the three-year life cycle = 33 million units $*$ 600 margin/unit $*$ 2.5% = $495 million. The gross profit associated with the LIon product for the three-year life cycle 33 million units $*$ 600 margin/unit $*$ 2.5% = $594 million.

*Case* (a). The development team uses the pizza-bin approach (rejects LIon outright and goes with NiHi battery technology. With the NiHi product alone, the team can make a net profit of $485 million (gross profit of $495 million—$10 million development cost). However, if LIon technology proves to be viable at launch, the team can develop and launch a follow-up product with LIon 18 months (one cycle) after the first product is launched. In this case (which occurs with a probability of 0.6), the total expected net profit = $509 million (using (7) in §3).

*Case* (b). The development team can pick LIon technology outright (as it eventually did). Using expression (8), the net profit from this choice comes out to be $513.5 million. Note the significant downside associated with this approach. There is a 40% chance the firm will be late to market with a NiHi product, damaging its reputation and significantly lowering profits.

*Case* (c). Instead of committing at the beginning, the team could decide to be flexible and try the *PP* option. While we could apply the analysis of §4 to this case, it is interesting to note that the gross profits in this case are significantly larger than the cost of development. Even if the team pursues the parallel path for the entire duration, the net profit would equal $0.6 * 574 + 0.4 * 475 = \$534$ million. If the team terminates the *PP* earlier, the profit could be even higher. Also, the downside risk is significantly reduced.

*Case* (d). The team could overdesign the product so that it could function with either technology. The engineers estimated the increase in unit variable cost and the resulting increase in size would reduce the gross margins by about $12 (or 2%). The net expected profit from this case is given by $0.6 * 0.98 * \$584$ million + $0.4 * 0.98 * \$485$ million = $533.5 million.

Both the *SD* and the *PP* approach achieve nearly the same expected profit assuming the *PP* do not terminate until the very end of the development process. *PP* would be more attractive if the team could terminate the alternate path earlier. However, *PP* cannot be shown to converge earlier using (14) because the critical value $\Psi$ (from (16)) is negative. Dell was also severely cash-constrained at this time, so sufficient design might have been more appropriate as it does not require immediate cash outlays. Either way, the flexible design approaches would have significantly reduced the downside risk while offering an attractive return compared to outright commitment.

### 5.2. Limitations and Future Work

Our model in this paper was deliberately stylized to keep the attention focused on obtaining insights. We made a number of modeling assumptions that need to be relaxed in future work, so we review some of the key assumptions here. First, we assumed for tractability that the firm faced the choice of one *pv* and one *ps* technology. Second, we have considered demand dynamics during the life cycle, but have ignored the effects of demand uncertainty, which must be considered in future research. Also, the cumulative demand distributions for both the *pv* and *ps* technology are assumed to be the same for tractability reasons, which may not be the case in practice. We also did not consider the flexibility offered by the *SD* option for upgrading the product with the *pv* technology to the *ps* technology in the next generation.

In performing the analysis of convergence, we have assumed that the firm did not incur the cost of collecting information (which was borne by a supplier), and the prior information and market signals formed a conjugate pair so that posterior information is of the same distribution as the prior information. In particular, we assumed a particular form (Beta-Bernoulli pair) for the prior and the signal. Also, the firm being modeled was essentially a monopolist, so future work should consider the effects of competition as well as market diversity in studying technology selection and product definition under technology uncertainty.

## References

Arditti, F. D., H. Levy. 1980. A model of the parallel team strategy in product development. *Amer. Econom. Rev.* **70** (December) 1089–1097.

Bacon, G., S. Beckman, D. Mowery, E. Wilson. 1994. Managing product definition in high technology industries: A pilot study. *California Management Rev.* **36** (Spring) 32–56.

Bhattacharya, S., V. Krishnan, V. Mahajan. 1998. Managing new product definition in highly dynamic environments. *Management Sci.* **44** (11, Part 2 of 2) S50–S64.

Clark, K., S. Wheelwright. 1993. *Managing Product and Process Development*. The Free Press, New York.

Cooper, R. 1993. *Winning at New Products*. Addison-Wesley Publishing Company, Reading, MA.

Graves, Steven B. 1989. The time-cost tradeoff in research and development: A review. *Engnrg. Costs Production Econom.* **16** 1–9.

Iansiti, Marco. 1995. Shooting the rapids: Managing product development in turbulent environments. *California Management Rev.* **38**(1) 37–58.

Kalyanaram, G., V. Krishnan. 1997. Deliberate product definition: Customizing the product definition process. *J. Marketing Res.* **34** (May) 276–285.

Krishnan, V., K. Ulrich. 2001. Product development decisions: A review of the literature. *Management Sci.* **47** (January) 1–21.

Loch, C., C. Terwiesch. 1998. Communication and uncertainty in concurrent engineering. *Management Sci.* **44** (August) 1032–1048.

McCardle, K. F. 1985. Information acquisition and the adoption of new technology. *Management Sci.* **31** (November) 1372–1389.

Nelson, R. R. 1961. Uncertainty, learning, and the economics of parallel research and development efforts. *Rev. Econom. Statist.* **43** (November) 351–364.

Pratt, J. W., H. Raiffa, R. Schlaifer. 1995. *Introduction to Statistical Decision Theory*. MIT Press, Cambridge, MA.

Srinivasan, V., W. S. Lovejoy, D. Beach. 1997. Integrated product design for marketability and manufacturing. *J. Marketing Res.* **34** (February) 154–163.

Thomke, S. H. 1997. The role of flexibility in the development of new products: An empirical study. *Res. Policy* **26** (March) 105–119.

——, V. Krishnan, A. Nimgade. 1998. Product development at Dell Computer Corporation. Harvard Business School Case, Boston, MA.

Ward, A., J. K. Liker, J. J. Cristiano, D. K. Sobek. 1995. The second Toyota paradox—How delaying decisions can make better cars faster. *Sloan Management Rev.* **36** (Spring) 43–61.

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