New Product Development: The Performance and Time-to-Market Tradeoff

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Reduction of new product development cycle time and improvements in product performance have become strategic objectives for many technology-driven firms. These goals may conflict, however, and firms must explicitly consider the tradeoff between them. In this paper we introduce a *multistage* model of new product development process which captures this tradeoff explicitly. We show that if product improvements are *additive* (over stages), it is optimal to allocate maximal time to the most productive development stage. We then indicate how optimal time-to-market and its implied product performance targets vary with exogenous factors such as the size of the potential market, the presence of existing and new products, profit margins, the length of the window of opportunity, the firm's speed of product improvement, and competitor product performance. We show that some new product development metrics employed in practice, such as minimizing break-even time, can be sub-optimal if firms are striving to maximize profits. We also determine the minimal speed of product improvement required for profitably undertaking new product development, and discuss the implications of product replacement which can occur whenever firms introduce successive generations of new products. Finally, we show that an improvement in the speed of product development does not necessarily lead to an earlier time-to-market, but always leads to enhanced products.
(*New Product Development; Time-to-market; New Product Performance*)

1. Introduction

Many technology-driven firms compete on new product development cycle time. Stalk (1988) coined the term *time-based competition* to highlight the importance of quick time-to-market in today's intensive competitive environment. Clark (1989) estimates that for a $10,000 car, each day of delay in introducing a new model represents a $1 million loss in profit. A recent McKinsey study reports that, on average, companies lose 33% of after-tax profit when they ship products six months late, as compared with losses of 3.5% when they overspend 50% on product development. In their book *Developing Products in Half the Time*, Smith and Reinertsen (1991) argue that it is necessary to adopt an incremental approach to product innovation in order to reduce time to market. This is because incremental product innovation reduces the amount of effort and learning that must be done and, consequently, the amount of time needed to invest in the new product prior to its launch. Such a perspective has led some companies (e.g., General Electric, Hewlett Packard) to adopt time-to-market as their principal product development metric.

There exists an alternative school of thought that emphasizes product performance. Several empirical studies have shown that a new product's success depends critically on its performance and its value to customers. Zirger and Maidique (1990), for example, examined 330 new products in the electronics industry and showed that these factors significantly affected product profitability. Cooper and Kleinschmidt (1987) demonstrated that product superiority in terms of unique features, innovativeness, and performance is a key factor that

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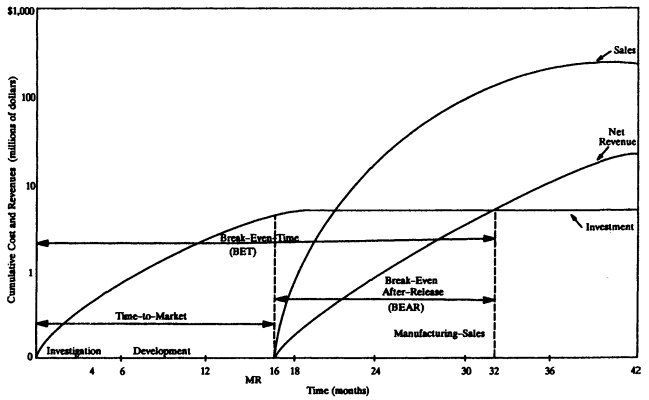
Figure 1 **The Return Map for HP Pocket Calculator (House and Price 1991)**



differentiates new product winners from losers. This perspective, for instance, has led Boeing to specify performance as the key metric for its new 777 aircraft. The highly successful Excel 3.0 software program is another case in point. It has 100 more new features than its predecessor and is considered to be a much friendlier and "smarter" system (Dyson 1991). New product performance is often the decisive factor in the purchase of technologically advanced products like software packages. Indeed, most consumer product guides give a heavy weight to the performance of a software package (Foster 1990). These observations provide support for a strategy of making significant improvements in new product performance over existing products. Unfortunately, such improvements often take more time to develop and can significantly delay the product launch (see Griffin 1992, and Yoon and Lilien 1985 for empirical evidence).

Clearly, there can be a tradeoff between the objectives of minimizing time-to-market and maximizing performance of the new product. Significant improvements in product performance have the potential to capture a larger market share from competing (or substitute) products, but they may take too long to accomplish, and, consequently, the company will miss the window of opportunity. An example of this is the Apple's Lisa-Macintosh development effort in the early 80s. The development project was extremely ambitious and aimed to make major leaps in both product performance (hardware and software) and manufacturing process development. The delay, by several quarters, of the product's introduction drove Apple's earnings down dramatically and caused the stock of the company to fall to less than half its early 1983 value (Hayes et al. 1988). Less ambitious improvements in product performance can be achieved quickly, but they may not attract too many customers. In fact, rushing to the market can be disastrous. General Electric's introduction of a new refrigerator with a rotary compressor which failed in the field has been retrospectively explained as a case where a product was launched too early. Over one million refrigerators had to be recalled and fixed (The Wall Street Journal 1990). Therefore, there are benefits as well costs involved in invoking each of these metrics. This suggests that employing integrative new product development metrics, which simultaneously capture time-to-market as well as product performance criteria, might be more advantageous.

This observation motivated Hewlett Packard's "BET/2" metric, which is directed toward reducing break-even time (BET) by one-half for its new products (House and Price 1991, Young 1991).

Figure 1 depicts the return map employed by Hewlett Packard (House and Price 1991) for managing a new pocket calculator development process. As shown, the break-even time (32 months) is the point at which total cumulative investment in the development project is equal to total cumulative net revenue. Reducing break-even time can motivate the product development team to address the crucial balance between a high product performance target and a short time-to-market. A significant improvement in the product performance target is likely to increase the slope of the sales (revenues) curve, at a cost of delaying the new product launch. Incremental product improvements, on the other hand, are likely to generate sale curves that are less steep, but which bring revenues to the firm earlier.

In this paper we develop a modeling framework that allows explicit consideration and examination of this tradeoff for those product markets characterized by (1) a short and fixed window of opportunity, (2) a high rate of product obsolescence, and (3) customers who understand and respond to product performance improvements. Industries that exhibit these characteristics include packaged software, computer hardware and peripherials, and consumer electronics. Using Dolan's

(1993) terminology, such new products bring "low-medium" newness to the market. In addition, they have a "medium-high" opportunity cost and "medium" development costs.

The contribution of our modeling framework is based on the following three aspects. First, it recognizes the multi-stage nature of product performance improvement processes. This perspective allows us to study how development resources and time should be allocated across development stages. Second, it considers both the productivity and the return of development projects in producing product performance improvements. Prior research focused on either productivity or return, but not both together (see §2 for further details). Third, we adopt an integrative perspective over the new product development time horizon. This embeds development as well as marketing/production cycles. Both the cumulative costs and the revenues of the new product, over its entire life cycle, are considered. Our model yields the following policy insights:

(1) If product improvements are *additive* (over stages), it is optimal to allocate maximal time to the most productive development stage.

(2) Faster is not necessarily better if the new product market potential is large and if the existing product (to be replaced) has a high margin. In addition, it is better to take time to develop a superior product when the firm is faced with an intermediate level of rivalry.

(3) Minimizing break-even time may lead to premature new product introduction.

(4) The development capability hurdle needed to undertake profitably a new product development project increases with the total existing product performance (that of the developing firm as well as its competitors) in the market and decreases with the product category demand rate, the new product margin, competitors' market share, and the time window of opportunity.

(5) An improvement in the new product development capability does not necessarily lead to an earlier time to market, but it always leads to enhanced products.

These results are of interest since not all of them are intuitive. Moreover, the sensitivity of these conclusions to parametric/environment changes and the explicit representation of the tradeoffs in the model can further stimulate empirical and analytical research.

The paper is organized as follows. In the next section, we review the related literature. In §3, we provide a model formulation that captures explicitly the tradeoff between time-to-market and new product performance. The structure of the policies implied by the model is characterized in §4. Various insights are provided and stated in terms of testable propositions. Section 5 provides conclusions and suggestions for future research directions. The proofs of the formal results can be found in Cohen et al. (1995).

2. Literature Review

In §1 we discussed the relationship and tradeoff between time-to-market and new product performance. Time-to-market and product performance can also be affected by the overall level of development resources assigned to the project. Indeed, the economics/R&D race literature has often assumed a fixed target of product performance level and focused on the tradeoff between time-to-market and total development resources. This literature consists of two streams of research: the decision theoretic approach (for review, see Kamien and Schwartz 1982) and the game theoretic approach (for review, see Reinganum 1989). A standard assumption made here is that more severe compressions of development cycle ("crashing" the project) are achieved at increasingly high levels of total development cost; that is, the relationship between development cycle and total cost has been taken as strictly convex (see Scherer 1984 and Mansfield et al. 1977, for empirical evidence for this premise). Another assumption often made in this literature is that the firm that is first to the market wins the whole pie, the so-called "winner-takes-all" hypothesis. The winner-takes-all hypothesis and the fixed performance target assumption are reasonable under scenarios where firms compete on a patentable breakthrough technology. However, many firms spend a significant amount of their development resources competing against incumbents in terms of product improvements (Dolan 1993). More often than not, product development is assumed to be completed, and its development cost is not explicitly considered.

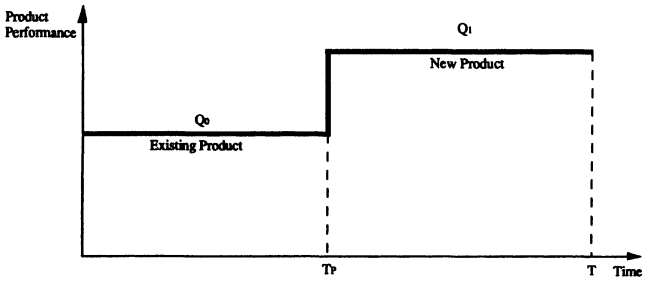
As noted earlier, our modeling framework considers both the productivity and the return of new product development over time. In this respect, our model

framework attempts to integrate the operations and marketing literatures. We focus on studying the tradeoff between time-to-market and product performance, given a specified level of total resource inputs, for three reasons. First, little or no attention has been devoted to studying this tradeoff analytically. To the best of our knowledge, this is the first model-based study of the issue. Second, the McKinsey study appears to suggest that the tradeoff between time-to-market and product performance is more critical than the tradeoff between time-to-market and level of development resources in those product markets that we are interested in modeling. Third, industry leaders are beginning to realize that new product development teams should be kept small, constant, and manageable. Large development teams involve expensive administrative coordination and communication and can delay the decision making process. For example, the size of the development team responsible for the successful IBM Laptop that was introduced in 1991 was only nineteen. This is about a tenth the normal size at IBM (The Wall Street Journal 1991). Hence, it is reasonable to assume that firms will fix the size of the product development team such that there is no opportunity to "crash" development programs. Consequently, incremental product innovations are necessarily accompanied by a short time-to-market, and significant improvements in product performance require a long time to market.

3. Model Formulation

Figure 2 shows the firm's product performance in the marketplace over time for the situation we wish to capture here. It is assumed that there is a fixed window of opportunity T, beyond which the new product has no value. T can be interpreted as the demand window for the new product (Clark and Fujimoto 1990 and Dolan 1993). Such a demand window often exists for high-technology product markets where there is a high rate of product obsolescence. House and Price (1991) indicate that many of HP's products (e.g., calculators) exhibit such demand characteristics. Other industries that have such demand windows include packaged software, computer hardware and peripherals, and consumer electronics. Indeed, Krubasik (1988) suggests that a major risk in these product markets is one of missing the fast moving demand window. The firm of interest here has an existing product with performance Q_0. At time T_P, a new product with performance Q_1 is launched. We assume that the introduction of the new product makes the old product completely obsolete (e.g., the latest version of a software program often makes its predecessor completely obsolete). The strategic marketing decision is therefore to determine *when* to introduce the new product (i.e., replace it with the existing product) and what the target performance level should be for the new product. The strategic development decision is to determine the *allocation* of the development time and effort across development stages (to be discussed later). The objective of the firm is to maximize profits over the time window T.

Figure 2 **The Performance of the Firm's Product in the Marketplace over Time**



The development of the new product occurs in multiple steps. In particular, they include:[1]

(1) Concept Generation
(2) Product Design
(3) Engineering Analysis
(4) Process Analysis and Design
(5) Prototype Production and Testing

For the purpose of this paper we group these steps into two more aggregate stages of activities, i.e., *Design* and *Process*. The Design stage includes steps 1, 2, and 3 above. The Process stage includes steps 4 and 5. After the Process stage, the new product is launched in the market (Market stage). We note that there are many ways in which the activities embodied in these stages

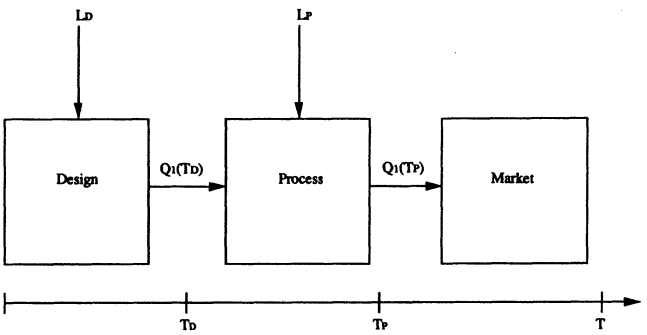
[1] Both the marketing literature (e.g., Urban and Hauser 1980) and the production literature (Hayes et al. 1988) have acknowledged the sequential nature of the new product development process.

can be organized. In particular, the recent movement toward Simultaneous Engineering (see Nevins and Whitney 1989) suggests that many of the activities involved in new product development should be carried out in a concurrent (as opposed to a sequential) manner. The impact of simultaneity is to reduce total development costs and time-to-market as well as to improve the manufacturability of the product. For the purpose of this paper, however, we will treat the two macro stages, defined above, in a sequential manner. Our interest is in understanding how the new product performance is affected by the time duration of each stage. We are especially concerned with how the new product performance is "transferred" between stages, i.e., the output of the new product performance at the end of the Design stage becomes the input at the beginning of the Process stage.

Figure 3 illustrates the overall structure of our model. As in previous papers (Clark and Fujimoto 1991, Adler et al. 1992), we focus on the engineering labor resource inputs. Mathematically, L_D and L_P denote the sizes of the development team (labor inputs measured in man-hour per unit time) for the Design and the Process stage, respectively. A more micro version of this model could consider more detailed classes of inputs (e.g., designers, technicians, draftsmen).[2] Under the model, a day spent in the Design or Process stage means a day lost in sales (i.e., a day lost in the Market stage). This premise allows us to capture explicitly the pressure to compress the development process of the new product in the product markets described above.

In Figure 3, T_D and T_P are completion times (calendar dates) for the Design and the Process stage, respectively. The cumulative product performance level at the end of a stage is determined by the following

Figure 3 A Multistage Product Development and Time Domain



variables: input performance level from the prior stage, the duration of the stage, and the size of the development team employed during that stage. Enhancements in performance are parameterized in terms of use of raw materials, innovative technology, manufacturing processes, ergonomics, etc. The firm is assumed to have numerous performance improvement opportunities so that the increase in the performance can be represented as a continuum, i.e., performance is captured by a real-valued index $Q(t)$.

The key factors in our model are the *speeds of improvement* for the Design and the Process stages. Specifically, we define the speed at which performance is being improved during each of the two development stages to be

$$\dot{Q}_D = K_D L_D^{\alpha_D}, \quad 0 \le t \le T_D, \tag{3.1}$$

$$\dot{Q}_P = K_P L_P^{\alpha_P}, \quad T_D \le t \le T_P, \quad \text{where} \tag{3.2}$$

$\dot{Q}_j$ = time derivative representing the speed of improvement during stage j [units of performance/time],

L_j = size of the development team for stage j [man-hour/time],

α_j = labor productivity parameter for stage j [units of performance/man-hour],

K_j = capital productivity parameter for stage j [units of performance/time],[3] and

$j = D$ (Design) or P (Process).

[2] The composition of the development team can be an important factor in the development of the new product. Moreover, it may be different across development stages. Our model captures this factor, albeit indirectly and aggregatively, via two exogenous parameters: α_D and α_P (see below). These labor productivity parameters are determined to a large extent by the composition of the team. A more explicit way to capture the composition of the team is to have detailed classes of labor resource inputs categorized by their expertise. We plan to pursue this as future research.

[3] $\dot{Q}_j$, L_j, and K_j are measured in logarithmic scales (see, for example, Walters 1963).

Figure 4 shows graphically the evolution of the product performance over the total development time. It follows from (3.1)–(3.2) that the enhancements (i.e., the increments in product performance) during the Design and Process stages are $\dot{Q}_D T_D$ and $\dot{Q}_P(T_P - T_D)$, respectively. The multistage development process links the performance improvements in an *additive* manner. Improving product performance is like climbing up a performance ladder (Grossman and Helpman 1991). Thus, the performance level of the new product from the time it is launched until the end of T is

$$Q_1(T_D, T_P) = Q_0 + \dot{Q}_D T_D + \dot{Q}_P(T_P - T_D), \quad T_P \le t \le T. \tag{3.3}$$

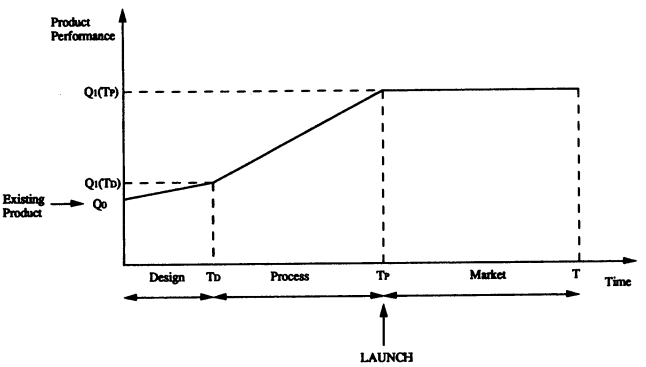
The total man-hours spent in the development project is

$$E(T_D, T_P) = L_D T_D + L_P(T_P - T_D). \tag{3.4}$$

The speed of improvement (Equations 3.1 and 3.2) is of the *Cobb-Douglas* form, and it is taken as analogous to a production function. The *Cobb-Douglas* forms are conceptually appealing. It is also worthwhile, however, to examine their empirical validity. Some empirical support for a *Cobb-Douglas* type of speed of improvement can be found in Kamien and Schwartz (1982, chapter 3) for hardware equipment and chemicals, and in Bohem (1982) for software. Additional evidence is discussed below.

Ho (1993) collected primary data from a major food processor and analyzed secondary data from the automobile industry to support the assertion that the *Cobb-Douglas* is a reasonable functional form. The primary data from a major food processor consisted of 51 new food development projects that were undertaken by the company from 1991 to 1993. For each food development project, more than 20 resource input variables and two performance measures of the new product were collected. Three resource inputs that could significantly predict the performance measures of the new product were total engineering hours spent in the project, average experience level of the design team, and the sample size of the focus groups used during product testing. Ho (1993) tried several functional forms in regressing the resource inputs against the performance measures and found that the *Cobb Douglas* form provided the best fit for both performance measures.

Figure 4 Improvements of Product Performance over Time



The secondary data involving the automobile industry were derived from Clark and Fujimoto's (1991) study. Clark and Fujimoto conducted a benchmarking study of new product developments by different firms for four strategic-regional groups (Japan, United States, Europe (high-end), Europe (Volume)). They measured the outcomes of the development process in terms of lead time (months), total product quality (units of performance, an index ranges from 1 to 100), and total engineering-hours spent in development for 31 different new car projects. By adjusting the above three measures relative to a reference point, which represented a standard car development project, the authors compared the projects' development efficiency. Ho (1993) divided the sample into three efficiency groups based on the speed of performance improvement (high productivity group, medium productivity group, and low productivity group) and found that in all three productivity groups, the *Cobb Douglas* form provided the best fit.

Returning to the model formulation, we assume that at each stage engineering resources are invested. Hence, the total development costs of the new product is

$$TC(T_D, T_P) = W_D L_D T_D + W_P L_P(T_P - T_D). \tag{3.5}$$

This development cost function assumes that engineering labor costs at each stage j ($j = D, P$) are charged at wage rate W_j measured as dollars per man-hour. For expository purposes, we ignore discounting.

Revenues from the new product can be realized only during the Market stage, $[T_P, T]$. A reasonable

market share function, frequently used in the marketing literature, is the logit model that was developed in discrete choice theory (McFadden 1980). The sales (demand) rate at time t for the firm that develops and introduces the new product is the product of the product category demand rate and the firm's market share:

$$D(Q(t)) = \begin{cases} M \dfrac{e^{U(Q_0)}}{e^{U(Q_0)} + e^{U(Q_c)}}, & 0 \le t < T_P, \\ M \dfrac{e^{U(Q_1(T_D,T_P))}}{e^{U(Q_1(T_D,T_P))} + e^{U(Q_c)}}, & T_P \le t < T, \end{cases} \tag{3.6}$$

where

$D(Q(t))$ = sales rate at t for the firm that develops the new product [units sold/time],

M = product category demand rate [units sold/time],[4]

Q_0 = performance level of the existing product [units of performance],

Q_c = competitive product performance level [units of performance].[5]

The logit model has received extensive empirical support. It has been employed widely in the marketing literature (Green and Krieger 1988, Lilien et al. 1992). It basically assumes that the customer's utility is the sum of two components—a deterministic component observable by the firm, and a random unobservable component. The deterministic part is a *monotonic* function of product performance and is represented by $U(Q(\cdot))$ in the expression above. The random part is assumed to have a double exponential probability distribution function. The probability that a randomly chosen consumer buys from the firm is simply the probability that the firm's product gives the highest utility to the customer (Luce and Suppes 1965). In this paper, we use a log utility function for performance. That is, $U(Q(\cdot)) = \ln(Q(\cdot))$.[6] Since $e^{\ln(x)} = x$, the sales rate for the firm which develops and introduces the new product is given by[7]

$$D(Q(t)) = \begin{cases} M \dfrac{Q_0}{Q_0 + Q_c}, & 0 \le t < T_P, \\ M \dfrac{Q_1(T_D, T_P)}{Q_1(T_D, T_P) + Q_c}, & T_P \le t < T. \end{cases} \tag{3.7}$$

The firm's cumulative profit is given by

$$T\Pi(T_D, T_P) = TR(T_D, T_P) - TC(T_D, T_P), \tag{3.8}$$

where $TR(T_D, T_P)$ and $TC(T_D, T_P)$ are total net revenues and costs (see Equation (3.5)), respectively. The total net revenues function is given by

$$TR(T_D, T_P) = Mr_0 \frac{Q_0}{Q_0 + Q_c} T_P + Mr_1 \frac{Q_1(T_D, T_P)}{Q_1(T_D, T_P) + Q_c} (T - T_P), \tag{3.9}$$

where r_0 = margin of the existing product, r_1 = margin of the new product.

We are now in a position to define the firm's profit as a function of the complete set of the new product development decisions. The decision set Δ, is defined as follows:

$$\Delta = \{T_D, T_P\}. \tag{3.10}$$

Note that decisions concerning T_D and T_P define the length of the Process stage ($T_P - T_D$). Combining Equations (3.1) through (3.10) it is straightforward to generate an explicit representation of the firm's cumulative profit as function of the decision variables. This substitution yields the following optimization problem:

[4] We have assumed that M is constant. The model structure can be extended to incorporate nonstationary demand for the category, i.e., $M(t)$.

[5] We assume a stationary competitive environment. Competitive actions and reactions can be studied using the above framework by allowing one or more competitors deciding Q_c. We plan to pursue this as future research.

[6] We assume a logarithmic utility function because it seems plausible to have utility as a log function of product performance (like utility as a log function of money payoff so commonly used in microeconomics analysis) (Kreps 1988). We tested the robustness of our results to the functional form of $U(Q)$ through numerical simulation. We experimented with the quadratic ($Q - aQ^2$) and power (Q^a) forms and found that most qualitative results remain unchanged.

[7] See Schmalensee (1978) for a related model which links advertising effort and quality to market share.

$$[\text{P1}]\quad T\Pi^*(\delta^*) = \max_{\delta\in\Delta}\Bigg[Mr_0 \frac{Q_0}{Q_0 + Q_c} T_P + Mr_1 \times \left\{\frac{Q_0 + K_D L_D^{\alpha_D} T_D + K_P L_P^{\alpha_P}(T_P - T_D)}{Q_0 + K_D L_D^{\alpha_D} T_D + K_P L_P^{\alpha_P}(T_P - T_D) + Q_c}\right\}(T - T_P) - (W_D L_D T_D + W_P L_P (T_P - T_D))\Bigg]. \quad (3.11)$$

Technological constraints may also be included for minimum time spent in the Design stage (τ_D) and Process stage (τ_P), i.e.,

$$0 < \tau_D \le T_D, \quad (3.12)$$

$$0 < \tau_P \le T_P - T_D. \quad (3.13)$$

This model structure is quite rich and can be employed to answer the following managerial questions:

(1) What should the launching timing and performance targets be?

(2) How should total developmental time be allocated across the two developmental stages?

(3) What are implications for break-even time (BET) reduction?

(4) Under what conditions should a new product development project be undertaken?

(5) What is the impact of technological and organizational improvements for the new product development process which will act to increase the speed of performance enhancement? How should improvement capabilities be exploited?

4. Analysis of the Optimal Policies

4.1. Optimal Design and Process Times

Our first proposition is concerned with the structure of the optimal solution of [P1] in terms of the relative time allocation between the Design and Process stages. It specifies circumstances under which it is optimal to concentrate on *either* the Design *or* the Process stage.

PROPOSITION 1. *If $K_D L_D^{\alpha_D} \neq K_P L_P^{\alpha_P}$, then either $T_D^* = \tau_D$ or $T_P^* - T_D^* = \tau_P$.*

PROOF. See [8]. □

Proposition 1 implies that the firm should identify its new product development strengths and concentrate its resource base on performance enhancements which are most productive. At the individual project level, this policy implies that life-cycle profits can be increased via a focused resource allocation strategy. This focused resource allocation strategy appears to have been practiced by Japanese automakers in the 1970s and 1980s when they channelled their development resources to improving product reliability (i.e., Process stage). Tandy computer adopted a similar strategy by subcontracting out its Process activities. Mansfield (1988) studied several industries in Japan and the United States and reported that Japanese companies allocated their development resources unevenly across the new product development stages. In particular, an unusually large proportion of resources was allocated to Process activities. American companies, on the other hand, spread their resources more evenly across the developmental stages. At the firm level, this result suggests that an increased specialization should be considered. Firms that focus and capitalize on their design strengths tend to hire outside suppliers for their less efficient activities. These subcontracting opportunities will make specialized design services viable and flourishing. It is interesting to note that the popular notion of core competence (Prahald and Hamel 1990) also appears to be consistent with above result. It is operationalized here as the firm's productivity in delivering product performance per unit time.

4.2. Optimal Time-to-market and Product Performance

Our next result expresses the optimal time-to-market as a function of the model's parameters. In particular, we wish to study the optimal time to market T_P^*, given that we know from Proposition 1 that mathematically, the optimal solution is a corner solution (i.e., focusing on only one of the two new product developmental stages). Without loss of generality, we assume that the Process stage is more productive than the Design stage (i.e., $T_D^* = \tau_D$). In the next proposition, we provide a closed-form solution for T_P^* and investigate its properties.

PROPOSITION 2. *Let $\hat{Q}_0 = Q_0 + (K_D L_D^{\alpha_D} - K_P L_P^{\alpha_P})\tau_D$. If the consumer's utility function is logarithmic, then the profit-maximizing time to market T_P^* is*

$$T_P^* = \frac{\sqrt{\dfrac{Mr_1 Q_c(\hat{Q}_0 + K_P L_P^{\alpha_P} T + Q_c)}{Mr_1 + W_P L_P - Mr_0 Q_0/(Q_0 + Q_c)}} - (Q_c + \hat{Q}_0)}{K_P L_P^{\alpha_P}}. \quad (4.1)$$

PROOF. See [8]. □

Proposition 2 has several implications that can be obtained via standard comparative statistical analytical procedures (presented in the appendix). First, it implies that the compression of the Design and Process stages (T_P^*) is less sensitive than the time window compression (T). This is true because T_P^* is a square-root function of T. We illustrate it with a numerical example. If, for instance, $Mr_1 = 1.0$, $W_P L_P = 0.01$, $Q_0 = 0.0$, $Q_c = 1.0$, $\tau_D = \tau_P = 0$, $K_P L_P^{\alpha_P} = 0.2$, and $T = 10$, then $T_P^* = 3.7$. If T is compressed by 100% to 5, then $T_P^* = 2.1$. While the time window of opportunity drops by 100%, the optimal time-to-market of the new product only drops by 76% (3.7 → 2.1). Second, it is better to develop a superior new product rather than to move fast to the market when the margins of the new and existing products (r_1 and r_0) are high and the product category demand rate (M) is large. Thus, the conventional wisdom that "faster is better" may not hold under these scenarios. Third, the firm should introduce a greater leap in product performance when it faces an intermediate level of rivalry (Q_c). Again, it is suboptimal to rush a product too quickly to the market. On the other hand, developing an ambitious new product and thus delaying the time-to-market too long is suboptimal if the competitive performance level is very low or very high.[8]

The optimal level of the new product performance during its Market stage is $Q_1(T_D^*, T_P^*) = \hat{Q}_0 + K_P L_P^{\alpha_P} T_P^*$. It can be readily shown that the optimal product performance level increases with K_P and α_P. Thus, with a higher values for the parameters characterizing the speed of performance improvement, the firm should strive to increase its performance level target. That is, better performance always pays. We shall show, however, that it is not necessarily optimal to reduce the time-to-market with higher values of K_P and α_P.

4.3. Break-even Time Reduction

It is interesting to compare T_P^* (given in Equation 4.1) with T_P^{**}, the market release time that minimizes the break-even time (discussed in §1 and illustrated in Figure 1). Break-even time has been employed as a practical guideline for new product launching (see, for example, House and Price 1991). The break-even time as a function of T_D and T_P can be obtained by replacing T with T_{BET} in Equation (3.11) and setting $T\Pi$ equal to zero. In doing so, we obtain

$$T_{\text{BET}}(T_D, T_P) = T_P + \frac{W_D L_D T_D + W_P L_P (T_P - T_D) - Mr_0 \dfrac{Q_0}{Q_0 + Q_c} T_P}{Mr_1 \dfrac{Q_0 + K_D L_D^{\alpha_D} T_D + K_P L_P^{\alpha_P} (T_P - T_D)}{Q_0 + K_D L_D^{\alpha_D} T_D + K_P L_P^{\alpha_P} (T_P - T_D) + Q_c}}. \quad (4.2)$$

Note that the break-even time is simply the sum of the time-to-market (i.e., T_P) and the elapsed time taken to recoup the cumulative net investment (i.e., cumulative development cost minus cumulative net revenue from the existing product). The latter time is simply the ratio of the cumulative investment and the net revenue rate from the new product (i.e., the second term in the right-hand side of (4.2)).

PROPOSITION 3. *Minimizing BET leads to premature product introduction.*[9] *In particular,* $T_P^{**} < T_P^*$.

PROOF. See [8]. □

The above proposition suggests that using BET alone as a metric for new product performance leads to suboptimized profits in new product launching under the scenarios captured by our model. In particular, new products launched under minimizing the BET metric will tend to be incremental types

[8] Consider if Q_c is allowed to prevail at some time t_c, ($t_c > 0$) during the time window of opportunity (presently we have $t_c = 0$). We checked via numerical simulation how T_P^* might be affected if this was indeed the case. It was found that if t_c is less than the original T_P^*, the optimal time-to-market remains unchanged and is greater than t_c (this is the case where the firm is the follower). If t_c is marginally greater than the original T_P^*, the revised T_P^* is greater than the original time-to-market and is identical to t_c (this is the case where firms launch their products simultaneously). If t_c is significantly higher than the original T_P^*, the revised time-to-market is greater than the original time to market but is less than t_c (this is the case where the firm is the leader). Only if t_c is very large would the revised time-to-market be smaller than the original time-to-market. Thus, the overall impact of an Q_c which prevails at some time $t_c > 0$ is to make the firm more aggressive by delaying and launching a higher performance product.

[9] Our model does not include a fixed cost, such as overhead and sale costs, associated with the launching of the new product. Including a fixed cost will not affect T_P^* as long as it remains profitable to undertake new product development. Including a fixed cost will delay the break-even related release time, T_P^{**}.

rather than quantum leaps because the firm does not spend enough time to fully "bake" them. This is akin to the old saying "no wine before its time." The gap between T_P^{**} and T_P^* is smaller, however, when T is shorter. Since the BET metric is simple and helps functional coordination, it seems plausible that the metric be used along with other metrics, especially those that capture explicitly the life-cycle profits of the new product. It has been our observation that firms adopt time-based metrics (minimizing T_P or BET) without considering life-cycle profits because of their ease of measurement.

4.4. Product Replacement

Product replacement is an important factor in new product strategy whenever firms introduce successive generations of new products that completely replace existing versions via improvements and enhancements. To analyze its effect on the optimal time to market, we need to obtain the optimal time-to-market under no replacement. That is, we wish to analyze the difference in time-to-market of a successive generation (T_P^*) vis-a-vis first generation of new products (T_P^{**}). This can be done in our model by setting $r_0 = 0$ or $Q_0 = 0$ in (3.11) and solving for the new optimal T_P^{**}. This yields

$$T_P^{**} = \frac{\sqrt{\dfrac{Mr_1 Q_c(\hat{Q}_0 + K_P L_P^{\alpha_P} T + Q_c)}{Mr_1 + W_P L_P}} - Q_c - \hat{Q}_0}{K_P L_P^{\alpha_P}}. \tag{4.3}$$

PROPOSITION 4. *Product replacement always increases the time to market (i.e., $T_P^{**} < T_P^*$). The amount of delay, $\Delta T_P = T_P^* - T_P^{**}$, increases with T and Q_0 and decreases with $K_P L_P^{\alpha_P}$.*

PROOF. See [8]. □

This proposition shows that a firm should delay launching the successive generation of a new product if it already has a superior existing product. The superior existing product (high Q_0) allows the firm to earn significant revenues during the development of the new product and thus reduces the "pressure" to launch a new product quickly. The proposition also suggests that if the firm has a superior new product development capability (i.e., high value of $K_P L_P^{\alpha_P}$), then the amount of delay due to product replacement can be reduced. This is so because a significantly better new product can be developed within a shorter time frame with a superior development capability. If the time window of opportunity is short, the delay due to product replacement will become less significant because the pressure to catch the window becomes the firm's dominant concern.

4.5. The Minimally Required Speed of Improvement

The model also allows us to investigate the minimal speed of performance improvement which is required for a profitable undertaking of the new product development project. This minimal speed is useful because it indicates to the firm whether it has the development capability needed to undertake a new product development for a given market situation. The firm will undertake a new product development only if the optimal cumulative profit associated with new product development is greater than the cumulative profit when there is no new product development. That is,

$$T\Pi(T_D^*, T_P^*) > Mr_0 \frac{Q_0}{Q_0 + Q_c} T. \tag{4.4}$$

Note that the right-hand side of inequality (4.4) is not zero. This is because when there is no new product development, the firm still enjoys some profits from the existing product. To find the minimal speed of improvement required for undertaking the new product development challenge, we need only to identify the conditions which guarantee the validity of (4.4). We find that it is necessary that the speed of improvement ($K_P L_P^{\alpha_P}$) be greater than some lower bound. For a fixed development team size, this lower bound on the speed of development imposes minimal values for the parameters α and K that the firm must possess in order to undertake profitably the new product development project. This insight is summarized in the following proposition.

PROPOSITION 5. *If $\tau_D = \tau_P = 0$, then the speed of improvement has to satisfy the following condition for undertaking profitably new product development:*

$$\dot{Q}_P = K_P L_P^{\alpha_P} \geq \frac{Q_c + Q_0}{T} \times \left[\frac{W_P L_P}{(M r_1 Q_c)/(Q_0 + Q_c)} + \frac{(r_1 - r_0)Q_0)}{r_1 Q_c} \right]. \quad (4.5)$$

In particular, if $r_1 = r_0$, *then*

$$\dot{Q}_P = K_P L_P^{\alpha_P} \geq \frac{Q_c + Q_0}{T} \frac{W_P L_P}{(M r_1 Q_c)/(Q_0 + Q_c)} = \underline{\dot{Q}}_P. \quad (4.6)$$

PROOF. See [8]. □

The form of the minimal speed of improvement required for a profitable undertaking of a new product development shown in (4.6) is interesting. It increases with total existing product performance in the market $(Q_0 + Q_c)$ (while keeping $Q_c/(Q_c + Q_0)$ fixed). Thus, a product market that is flooded with many superior products is difficult to enter. The minimal required speed is also higher when the time window is shorter. These implications appear to support the notion that many Japanese firms employ their fast development capability as a competitive weapon to raise entry barriers. Firms that have slow development capability will not be able to catch up with the fast and effective new product developers. Hence, the rapid developers can use the RHS of (4.6) as a strategic barrier. The minimal required speed of improvement decreases, however, with increases in the product category demand rate (M), the new product profit margin (r_1), and the competitor's market share $(Q_c/(Q_0 + Q_c))$ (while keeping $Q_c + Q_0$ fixed). The last point suggests that a firm that already has a higher market share has a bigger challenge and thus a higher hurdle speed of improvement than a firm with a lower existing market share.

It can be readily shown that $\underline{\dot{Q}}_P$ is convex in Q_c and that for $Q_c > (<) Q_0$, $\underline{\dot{Q}}_P$ increases (decreases) with Q_c. If we think of the firm as a follower given that some pioneer has already introduced a product of performance level $Q_c > Q_0$, then the inequality (4.6) can also be used by the pioneer to determine the *preemptive* product performance Q_c, above which it is not profitable for the follower to introduce a new product since to do so would require a minimum new product development speed of improvement capability—which is either unattainable or prohibitively expensive.

4.6. Exploitation of Improved Speed of Performance Enhancement Capability

Our next proposition shows that it is not necessarily optimal to reduce the time-to-market, even with better speed of performance enhancement capability.

PROPOSITION 6. *Whenever the speed of improvement is within certain bounds, it is optimal to increase the time to market with a more effective speed of performance enhancement. Specifically, whenever* $K_P L_P^{\alpha_P}$ *is between* $\dot{Q}_{P1}$ *and* $\dot{Q}_{P2}$, *then* $\partial T_P^*/\partial(K_P L_P^{\alpha_P}) > 0$, *where*

$$\dot{Q}_{P1} = \underline{\dot{Q}}_P, \quad (4.7)$$

$$\dot{Q}_{P2} = 2\left[\underline{\dot{Q}}_P + \frac{(Q_0 + Q_c)(r_1 - r_0)Q_0}{r_1 Q_c T} + \underline{\dot{Q}}_P \sqrt{1 + \gamma} \right], \quad \textit{and} \quad (4.8)$$

$$\gamma = \frac{M r_1 Q_c + 2M(r_1 - r_0)Q_0}{(Q_0 + Q_c) W_p L_P} + \frac{M^2 r_1 Q_c (r_1 - r_0) Q_0 + M^2 (r_1 - r_0)^2 Q_0^2}{[(Q_0 + Q_c) W_p L_P]^2}. \quad (4.9)$$

PROOF. See [8]. □

It is worth noting that, mathematically, $\dot{Q}_{P1} < \dot{Q}_{P2}$ (see Equations 4.7 and 4.8). Proposition 6 shows that improvements in the firm's speed of performance capability may lead to a *longer* time-to-market rather than a *shorter* time-to-market. Lilien and Yoon (1990) have studied timing of entry and have shown empirically that if the performance of a follower's new product can be readily improved relative to that of the existing products, then delaying the market entry timing may lead to better market performance (Proposition 10 in their paper). If we assume that some pioneer has already introduced a new product of performance Q_c, and our firm is the follower, then our results become consistent with Lilien and Yoon's empirical evidence if the firm has a speed of improvement capability bounded from above and below, between $\dot{Q}_{P1}$ and $\dot{Q}_{P2}$. Thus, an improvement in the speed of product improvement does not necessarily lead to an earlier time-to-market, but always

leads to enhanced products (see also the discussion on Proposition 2).

5. Conclusion and Further Research

In this paper, we have focused on the tradeoff between target performance and the time-to-market a new product. Under an additive multistage model of the performance "improvement" process, we have shown that it is optimal to concentrate efforts on the most productive stage. In addition, it is possible to determine the optimal time-to-market and the product performance target, both of which are functions of the parameters relating to the firm's cost structure and to the market characteristics. We have also derived the minimal speed of improvement capability required for undertaking profitably new product development projects and shown that this lower bound is a fairly complex function of the firm's rate of development labor expense, current performance in the market, product category demand rate, the new product profit margin, competitor's market share, and time window of opportunity. Finally, we have shown that *replacing* existing products always delays the time-to-market and product performance target for the new product vis-à-vis introducing the first generation of products. Moreover, *product replacement* should be delayed further when the existing product has a high performance. It should, on the other hand, be introduced faster when the time window is short or when the firm has a fast development capability. Sensitivity analyses of the optimal time-to-market indicate that an incremental improvement from the minimal speed of improvement may lead to *delayed* rather than *quicker* times-to-market; i.e., the optimal strategy is to use the faster speed of improvement to develop a better product rather than to develop a product faster. These results, in general, contradict some conventional wisdom concerning the dominance of incremental over significant improvements in product enhancements.

Like any analytical model, our modeling framework relies on certain assumptions. In particular, we assume that product performance is *additive* over the new product developmental stages. The additive assumption is reasonable if the new product can be structured into modules and if teams are well coordinated. Proposition 1 is driven mainly by this assumption. Invoking this assumption facilitates studying the relative allocation of development time across stages. Since Proposition 1 appears to have received some empirical support, we conjecture that the additivity assumption is a good approximation in certain industries under certain situations. Proposition 1 is quite robust structurally, however. It is not affected by several model extensions. For example, the proposition remains true even if the labor inputs L_D and L_P are taken to be time-varying decision variables.

Other model assumptions, such as stationary product category demand rate (M), competitive product performance (Q_c), and fixed size of development teams (L_D and L_P) can be relaxed easily. Relaxing these assumptions would allow us to pursue other managerial issues. For example, allowing product category demand rate to be a function of price would enable the analysis of pricing the new product. If the market for the product varies over time, then it is possible to study the revised optimal timing by allowing M to be a function of time. Competition among firms can also be analyzed if a game theoretic approach is adopted and Q_c is expressed as a function of the competitor's time-to-market. By letting L_D and L_P be (possibly dynamic) decision variables, we can study how the firm may choose to compress the time to market by employing over time more resources in the new product development process, i.e., by "crashing" the project.

Another possible extension of our modeling framework might be to allow the firm to enhance its product performance in the Marketing stage via advertising. Our current model assumes that there is little opportunity for the firm to do that. Such an assumption is reasonable in industrial products or products whose performance can be verified easily by the consumer. In experience goods, where product performance is not easily verified, firms can influence the consumers' perception of the product performance by investing in advertising. Our modeling framework can be easily extended to incorporate this phenomenon (see Ho 1993).

Propositions 2–6 generate several interesting propositions which may be subject to empirical scrutiny. For example, Proposition 2 suggests that optimal time-to-market is a square-root function of time window T. A cross-sectional study can be conducted to test whether this is true. Specifically, it is possible to collect data on new product development times and their time win-

dows of opportunities across relevant industries and test the proposition. Another proposition which may be examined empirically in a fairly straightforward manner is Proposition 5. Factors that determine the firm's decision to undertake a new product development project can be collected and analyzed. Proposition 5 predicts that these factors include the total existing product performance, the competitor's market share, the length of the time window, the product category demand rate, and the margin of the new product.

Our modeling framework can also be used to evaluate various industry practices such as the target timing approach, target performance, and target costing. Each of those practices can be constructed as a restricted case of a globally optimal procedure based on our modeling framework. Comparisons of each practice against the global optimal procedure with respect to the size of the development team, time-to-market, new product performance level target, and unit cost of the product can then be made (see Cohen et al. 1993 and forthcoming). We have also used our modeling framework as the basis for a real-world implementation and development of a support system (see Cohen et al. 1994).

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Accepted by Abraham Seidmann; received December 1994. *This paper has been with the authors* 1 *month for* 1 *revision.*