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NEW PRODUCT DESIGN STRATEGY ANALYSIS: A MODELING FRAMEWORK*

Morris A. Cohen
Jehoshua Eliashberg
Teck H. Ho

The Wharton School
University of Pennsylvania
Philadelphia, PA 19104-6366

Abstract: The development of new products inevitably leads to tradeoffs among product performance, time to market, and development costs. In addition, the unit cost of the product, which is determined by the product performance, is also affected by the design process. In this paper, we present a model framework that examines the interaction of these factors. We derive several managerial insights that have important implications for new product strategy planning. The model framework is applied to evaluate five industry practices: 1) the traditional approach (iterative), 2) the target costing approach, 3) the target performance approach, 4) the target timing approach, and 5) an approach based on minimizing break-even time. Each practice is a restricted case of an optimal procedure which considers all factors simultaneously. Our model framework allows us to benchmark each practice against the 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.

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1. Introduction

Competitive pressures and the hastened pace of technology development have increased the strategic importance of new product development. Most companies have increased their product diversity and are placing greater emphasis on being responsive to diverse customer needs. Success in the market now depends on a firm's ability to deliver a high performance product, at a competitive price, in a timely fashion. These success factors (i.e. time to market, product performance, unit cost of the product, and development costs) may conflict, however, and firms must consider the tradeoffs among them. Indeed, many practitioners suggest that a framework that examines these tradeoffs explicitly is central to the strategic management of the new product development process (Smith and Reinertsen, 1991). In this paper, we introduce such a framework and discuss its implications for new product strategy planning. This modeling effort is part of a long-term project to develop models and procedures to facilitate strategic management of new product development.

Of the four success factors, product performance has no common definition among researchers. For example, the operations management (OM) researchers posit that "quality is free", implying that the unit cost of a product can be reduced by increasing the product's quality which is related to the conformance of the product to its expected design performance (Crosby, 1979; Juran and Gryna, 1980; Porteus, 1986). On the other hand, marketing scientists hypothesize that "product performance is costly" and that the unit cost of a product increases with its level of performance (Mussa and Rosen, 1978; Moorthy and Png, 1992). In this paper, we adopt a composite view of product performance by treating it as a random variable with mean (μ) and variance (V) (Karmarkar and Pitbladdo, 1992). This view of product performance integrates the two streams of literature. The OM's view of product performance is captured by the variance term with a low variance implying high product conformance. The marketing's view of product performance is gauged by the mean with a high mean indicating a high performance class. Therefore, the overall relationship between unit product cost and product performance is such that the cost increases with both the mean and variance of performance In addition, our definition of product performance is based on customer perception in the marketplace and thus can be influenced by advertising, brand name, and customer service practices even after the product is launched. Conformance can also be improved during this market stage by investment in continuous improvement of the manufacturing process.

Besides adopting a broader view of product performance, our framework is distinct in several aspects. First, it is the first formal framework that examines the six tradeoffs among the four success factors simultaneously. Previous work (e.g. Mansfield, 1988; Graves, 1989) examine only the tradeoff between time to market and development cost. Second, we model the new product development process as a *multi-stage* performance improvement process. This allows us to study how development and time resources should be allocated across development stages. Third, we adopt a *life-cycle* perspective to new product development process. Both the cumulative costs and revenues of the new product over its entire life cycle are considered. The framework develops in-depth insights on one of the three dimensions of a general framework for making an organization innovative proposed by Cohen and Dougherty (1992).

The paper is organized as follows. In section 2, we describe the framework. We use optimal control theory to characterize new product development policy in terms of time and resource allocations between development stages. We state several managerial insights derived from the framework as a set of testable hypotheses in section 3. In section 4, we show how the framework might be used to analyze the five design approaches which are used by companies in developing new products. The managerial implications of each design approach are discussed.

2. Model Framework

New product development is conceptualized here as a multi-stage product performance improvement process. Figure 1 shows the general structure of the modeling framework. The framework consists of three sets of variables and two sets of functional relationships.

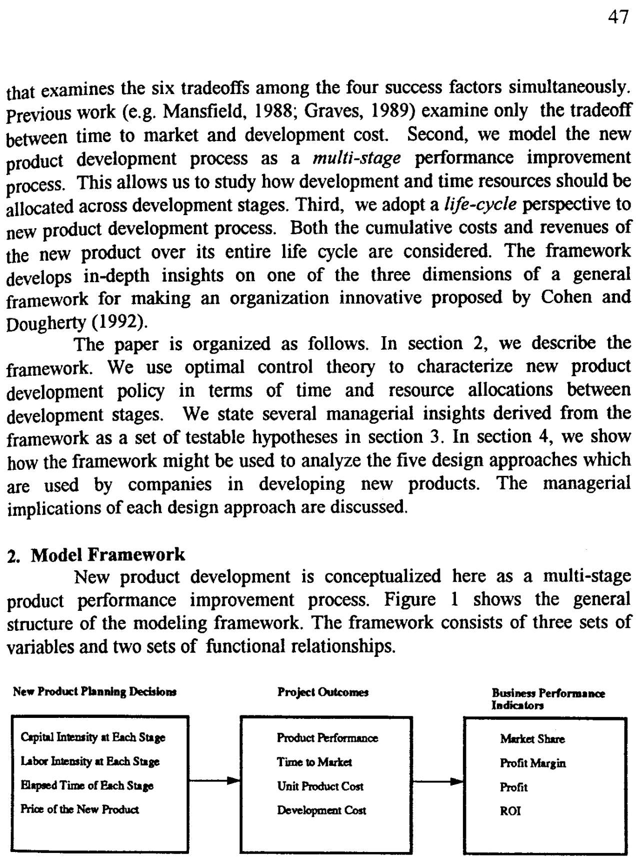

Figure 1: General Structure of the Modeling Framework

For a particular new product development project, one needs to consider:

- New Product Planning Decisions

Intensity level of capital utilized at each developmental stage, K_i.

Intensity level of labor (engineering or sales) utilized at each developmental stage, $L_i(t)$, over time

Elapsed time for each developmental stage, τ_i

Price of the product at time t, p(t)[1]

• Project Outcomes

Product performance in the market at time t, denoted by the random variable Q(t) with mean and variance, $\mu(t)$ and V(t)

Time to market, T_p

Unit product cost at time t, c(t)

Cumulative development cost at time t, TC(t)

• Business Performance Indicators

Market share at time t, S(t)

Profit margin of the product at time t, r(t)

Cumulative profit at time t, $T_\pi(t)$

Return on investment at time t, ROI(t)

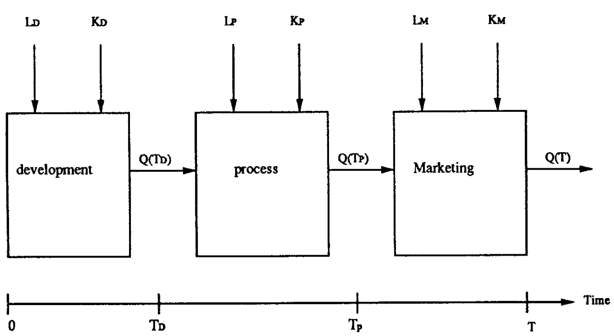

Figure 2: A Three-stage New Product Development Process

Figure 2 illustrates how resource inputs are transformed into product performance via a three-stage product performance improvement process. The Development stage includes concept generation, product design, and engineering analysis. The Process stage consists of process analysis and design, and prototype production and testing. The Marketing stage encompasses activities associated with volume production, advertising, and selling of the product. Labor and capital inputs, $L_i(t)$ and K_i, to each stage represent various resources required to carry out the development activities. A more detailed version of this model could consider more detailed classes of inputs (e.g. engineering, designer, production, and marketing labor). Since the window of opportunity is finite, a day spent in the Development or Process stage means a delay of one day in the Marketing stage.

[1] In many cases firms are pure price takers in competitive markets and hence we assume that price is exogenously determined.

We make some assumptions about two sets of functional relationships. First we assume that the rate of performance improvement at each stage i is a *Cobb-Douglas* production function (see Bohem, 1982; Griliches, 1984). That is, the rates at which the mean and variance of product performance are enhanced are proportional to $L_i^{\alpha_i} K_i^{\beta_i}$ where α_i and β_i are labor and capital productivity parameters. We assume diminishing returns to both the labor and capital investments so that α_i and β_i are both less than 1. Second, we assume that the multi-stage development process links the performance improvement functions in an *additive* manner. Improving product performance is analogous to climbing up a performance ladder (Grossman and Helpman, 1991). The firm is also assumed to have an infinite number of improvement opportunities so that the increase in the product performance can be represented as a continuum. Based on the two assumptions, mean and variance of the product performance at time t in $[T_{i-1}, T_i)$ are given by:

$$\mu(t) = \mu(T_{i-1}) + \int_{T_{i-1}}^{t} \delta_i \, L_i^{\alpha_i} \, K_i^{\beta_i} ,$$

$$V(t) = V(T_{i-1}) - \int_{T_{i-1}}^{t} \eta_i \, L_i^{\alpha_i} \, K_i^{\beta_i} ,$$

where δ_i and η_i are proportionality constants[2]. Third, we assume that there is industry price leadership or the industry is regulated such that product performance is the main competitive tool. We use the attraction model to determine the market share of the new product (see Bell, Keeney, and Little, 1975; Lilien, Kotler, and Moorthy, 1992):

$$S(t) = \frac{A(t)}{A(t) + Ac(t)}$$

[2] Note that the units of performance are in terms of a consumer performance index which can be assessed at the various stages of the design process.

where A(t) and Ac(t) are attraction levels of the firm's and competitors' products in the marketplace, respectively. The attraction of the new product, A(t), is assumed to increase linearly with the mean product performance and decrease linearly with the variance of the product performance. That is:

$$A(t) = \mu(t) - \rho V(t)$$

where ρ is a proportionality constant. Fourth, the unit cost of a product is increasing and linear in mean and variance of the product performance at the time of product launch (c.f. Porteus, 1986; Moorthy and Png, 1992).

$$c(\mu(t), V(t)) = \theta_m \mu(t) + \theta_v V(t)$$

where θ_m and θ_v are marginal costs of the mean and variance of product performance.

Revenue from new product sales can only be realized in the Marketing phase, $[T_p, T]$. During $[0, T_p)$ we allow for a revenue stream from an existing product. We assume that upon introduction, the new product makes the old product completely obsolete (e.g. the 1992 Toyota Camry makes the 1991 model completely obsolete and the latest version of a software program often makes its predecessor completely obsolete). The firm's cumulative profit is determined as follows,

$$T_\pi(t) = TR(t) - TC(t)$$

where TR(t) and TC(t) are net revenues and costs at time t, respectively. The net revenues function is given by

$$TR(t) = \int_0^t [\, p(s) - c(\mu(s), V(s))\,]\, M(s)\, S(A(s))\, ds$$

where $c(\mu(.), V(.))$ = unit production cost determined at the beginning of the Marketing stage and M(.) is the total market size at time t[3]. We note that the production cost includes direct costs (material, labor), indirect and overhead costs, exclusive of the costs of product and process design and marketing effort. The total cost function is given by:

$$TC(t) = TC(T_{i-1}) + C_i K_i + \int_{T_{i-1}}^t W_i(s)\, L_i(s)\, ds$$

This total cost function assumes that labor costs at stage i are charged at wage rate $W_i(t)$, at time t. Capital inputs are lumpy and are charged at unit cost C_i. It is straightforward to discount all costs to time 0. For expository purposes, we ignore discounting.

The objective is to maximize the life-cycle (i.e. cumulative) profits $T_\pi(T)$[4], where T is the end of the window of opportunity available to the product. This objective is attained by optimally choosing labor resource and time allocation policies before the Marketing stage (i.e. $L_D(t)$, $L_P(t)$, τ_D, τ_P; for t in $[0, T_p)$). The optimization problem can be formulated as a multi-stage optimal control problem with labor intensity as the control variable and attraction and unit cost of the product as the state variables (see Cohen, Eliashberg, and Ho 1992b). This model structure is quite rich and can also be used to explore a number of interesting managerial issues. It also forms the basis for more extensive analyses involving multiple products, dynamic learning, and product generations. In the next section, we shall focus on the interpretations of the derived analytical results.

[3] Note that before the new product is launched, $c(\mu(s), V(s)) = c_0$ which is the unit cost of the existing product. Also the attraction level of the firm's existing product in the marketplace is A_0.

3. Testable Hypotheses

Based on few stationarity assumptions (see Cohen, Eliashberg, and Ho, 1992b), we obtain results 3.1 and 3.2. If, in addition, the size of the development team is fixed and there is no opportunity to enhance the perceived product performance in the Marketing stage, closed-form solutions for optimal time to market and product performance can be derived. These closed-form solutions lead to stronger results given in 3.3 to 3.5 (see Cohen, Eliashberg, and Ho 1992a for details).

3.1. Resource Allocation Across Developmental Stages. The optimal new product development policy is such that under certain circumstances it is optimal to focus development and time resources on the most productive developmental stage. At the individual project level, this policy implies that life-cycle profits can be increased via a focused resource strategy. This focused resource strategy appears to be practiced by Japanese automakers in the 70s and 80s when they channelled their development resources to improving the reliability of the car (i.e. Process stage). Tandy computer adopted the same strategy and subcontracted out its Process activities. Mansfield (1988) studied several industries in Japan and U.S. and reported that Japanese companies allocated their development resources unevenly across development stage. In particularly, an unusually large proportion of resources was allocated to Process

[4] Other objectives such as return on investment or a weighted average of profit and market share are possible under the framework.

activities. American companies, on the other hand, spread their resources more evenly across development stages.

At the firm level, this policy suggests that the firm should consider an increased specialization and less vertical integration of design activities. Firms will focus and capitalize on their design strengths and hire outside suppliers for their less efficient activities. These subcontract opportunities will make specialized design services viable and flourish. It is interesting to note that the popular notion of core competency is consistent with these findings and is operationalized here as the firm's productivity in delivering product performance per unit time.

3.2. Development Team Size. The structure of the optimal policy is such that it is best to have a fixed labor input throughout the development period. This result stems from the assumed diminishing return to labor investment in the performance improvement process. Since the diminishing return assumption is quite reasonable in practice, this result suggests that firms should strive for stability in the size of the development team throughout the development process. Having greatly varying team size over time is suboptimal.

3.3. Time to Market and Product Performance. The optimal time to launch a new product increases with both the margins of the existing and the new products. In addition, it increases with the total market size. These results suggest that in a high-margin or large size market, better life-cycle profits could be obtained if the firm would develop a "superior product" rather than adopt a "quick and dirty" strategy associated with rapid introduction of a lower performance product.

The time to market is an increasing concave function of the product life cycle. That is, the first derivative of time to market with respect to product life cycle decreases with the product life cycle. Thus, the tension to compress time to market will be even greater when product life cycle is shortened. As a consequence, time to market becomes an increasing fraction of the life cycle as the life cycle contracts.

3.4. Design Capability Hurdle. The design capability hurdle indicates the threshold level of design technology the firm must possess in order to profitably undertake the development project. The model predicts that the threshold will be higher if the total product performance in the market is high; will be lower if the total market size is high, the product life cycle is longer, and the competitor has most of the market shares. The result that design capability hurdle is lower if the firm has a lower market share is interesting because it

suggests that an incumbent has a higher design capability hurdle than a potential entrant in undertaking a new product development project.

3.5. Cannibalization. The model predicts that it is optimal to delay product launch if the new product cannibalizes an existing product. The amount of delay is larger if the product life cycle is longer and if the performance level of the existing product is high; and is smaller if the firm has an efficient design technology.

3.6. Exploitation of Improved Design Technology. The model suggests that different product developers should invest and exploit technology which improves the design process (e.g. CAD/CAM) differently. More efficient product developers should use the improved technology to both increase product performance and decrease time to market simultaneously. Less efficient firms, on the other hand, should only use the improved technology to enhance the product performance. It is not optimal for the less efficient firms to use the improved technology to shorten time to market. This result challenges the conventional wisdom that it is always optimal to use improved design technology to compress development cycle.

4. Evaluation of Industry Practices

Our normative framework represents the best possible policy to which several reported industry practices are to be compared. These industry practices simplify the product development process by either imposing one or more constraints on the optimization problem or by ignoring some interactions among the success factors. An evaluation of these industry practices based on a preliminary numerical simulation experiment[5] is conducted. The results are reported below:

4.1. Traditional Approach. The traditional approach ignores the interaction between unit cost of the product and the product performance. In terms of optimal control terminology, the kinematic equation for the unit product cost is ignored in the optimization problem. The approach starts with an initial estimate for the unit product cost and checks the resulting unit product cost at

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[5] The experiment manipulated four exogenous parameters: 1) the length of the window of opportunity, T, 2) total market size, M, 3) price, p, and 4) competitive product attraction, Ac, Each of these parameters has three levels. Thus, the numerical experiment consists of 81 examples.

the conclusion of the design process. If the resulting cost is too high, then the firm must go back and repeat the design process (see Figure 3)[6].

Our numerical simulation results show that the approach often results in a grossly suboptimal new product development policy. In particular, the approach leads to over-sized development teams, too ambitious product change levels, inflated time to market, and resulting unit product costs which are too high. These results suggest that the interaction between unit product cost and product performance is highly relevant for the management of the new product development process.

4.2. Target Costing Approach. It has been suggested that the secret weapon for Japanese success lies in its use of target costing approach to design (Fortune, 1991). The approach is similar to the optimal policies except that there is a constraint imposed on the unit cost of the product (See Figure 3). Our analysis predicts that if the target cost is not too far away from the optimal unit product cost, then the deviation from the optimal solution is small. This result is interesting because it implies that target costing approach might be a good approximation for best policy if the firm has a reasonable estimate of what the optimal unit product cost is. It can be shown that the size of the development team, product performance, and time to market are lower (higher) than the corresponding optimal value of the best practice if the target cost is lower (higher) than its optimal value.

Compared to the traditional approach, the target costing approach has a shorter time to market even if the target cost is set much higher than its optimal value. The approach also has a smaller development team size and makes a less revolutionary product innovation than the traditional approach. These results are consistent with the empirical observation that American companies which adopt the traditional approach to design often introduce more revolutionary products but at a lower frequency. Compared to the traditional approach, the target costing approach makes significantly higher profits.

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[6] In the numerical simulation experiment, the resulting unit product cost is always less than the price and we assume that no iteration is necessary. In practice, the firm might have a target unit cost. If the resulting unit cost is higher than the target cost, the firm will go back and repeat the design process. Our framework, in its present form, is open-loop and does not have a mechanism to capture this iterative process. The framework is currently being extended so that it can capture this dynamic aspect of the traditional design process.

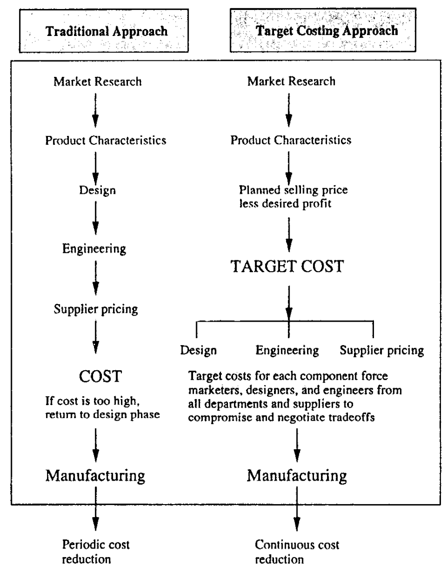

Figure 3: Two Design Approaches for New Product Development (Fortune, 1990)

4.3. Target Performance Approach. As the name implies, the approach imposes a constraint on the product performance target to simplify the product development process. The approach can be used by followers in a product market to catch up with the leader. Some innovators use this design approach to ensure that their new products are always at a fixed percentage superior to the best product in the market. In other cases, firms are designing to meet a current or anticipated industry standard. Like the target costing approach, the approach considers all interactions among the success factors.

The framework indicates that setting a higher than optimal product performance level target leads to longer time to market, larger development team size, and higher unit product cost. A lower than optimal product performance level target has reverse effects. In both cases, the loss in life-cycle profits are less severe than the traditional approach if the target performance is reasonably close to its optimal value.

4.4. Target Timing Approach. The target timing approach is particularly relevant in industries where there are natural product introduction times (model year and season). Examples include automobiles (beginning of the year), toys (Christmas season), and wearing apparel (fashion season). The approach considers the interactions among all success factors but imposes a constraint on the time to market.

The framework predicts that if the time to market is set higher than the optimal time to market, the size of the development team is smaller, the product performance is higher, and the unit product cost is higher than their corresponding optimal values. Imposing a lower than optimal time to market has reverse effects. Again, the loss in life-cycle profits is as not severe as that of the traditional approach.

Table 1 provides a summary of the results. The optimal values of development team size, time to market, product performance, and unit product cost of each design practice are compared to those of the best practice under two scenarios. Timing, performance or unit cost targets (or in the traditional approach initial cost estimates) which are lower or higher than the optimal values of best policy are chosen. The numerical values are percentage deviations from the optimal values of the best policy. It is interesting to note that the loss in profits resulting from imposing a constraint on time to market, product performance level target, or unit product cost is not as severe as that of ignoring the interactions between the success factors. Thus, firms should invest in acquiring know-how of the underlying relationships among the success factors by analyzing their design capabilities and the tradeoffs inherent in the process. The target costing, performance or timing approaches are good alternatives to the best practice (optimal solution) since they simplify the new product development process considerably with a small profit penalty (as long as these targets are in the neighborhood of the optimal value).

4.5. Minimize Break-even Time. We can also analyze the impact of minimizing break-even time (BET). Hewlett Packard has announced that one of its corporate strategies for the 90s is to reduce product break-even time by one half of all its new product (House and Price, 1991). Our framework shows

Design Practice	Development Team Size	Time to Market	Product Performance	Unit Product Cost	Profits
1. Traditional					
0.95 c*	+48.3%	+51.3%	+84.5%	+16.0%	- 25.4%
1.05 c*	+23.3%	+56.1%	+73.5%	+13.9%	-19.8%
2. Target Costing					
0.95 c*	- 7.2%	-24.1%	-26.9%	- 5.0%	- 4.1%
1.05 c*	+ 7.1%	+22.7%	+26.9%	+ 5.0%	- 3.3%
3. Target Performance					
0.80 A*	- 3.8%	-18.4%	-20.0%	- 3.7%	- 1.9%
1.20 A*	+ 6.5%	+16.3%	+20.0%	+ 3.7%	- 2.1%
4. Target Timing					
0.80 Tp*	+42.5%	-20.0%	- 4.5%	- 0.8%	- 0.5%
1.20 Tp*	-25.7%	+20.0%	+ 3.4%	+ 0.7%	- 0.4%

Note: x* is the optimal value for variable x of the best policy generated by the model framework

Table 1: An Evaluation of Four Industry Practices vis-a-vis the Best Policy Generated by the Model Framework

that minimizing BET often leads to premature product introductions that exhibit conservative bias in product performance change. Thus, BET alone might be too simplistic a metric for managing new product development process (Cohen, Eliashberg, and Ho, 1992a). It is interesting to note, however, that depending on the current value of BET, the decision to achieve BET/2 could move a company closer to the optimal value for BET.

5. Conclusions

In this paper, we develop an analytical framework for generating managerial insights for new product strategy. The insights are stated as testable hypotheses so that they can be subject to empirical scrutiny. We also apply the model framework to evaluate several industry practices and benchmark each practice against the best policy generated by the framework. Each practice is a restricted case of the optimal solution generated by the model framework and thus is sub-optimal if all practices have identical costs of implementation.

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