Structuring the New Product Development Pipeline

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In many new product development (NPD) situations, the development process is characterized by uncertainty, and no single development approach will necessarily lead to a successful product. To increase the likelihood of having at least one successful product, multiple approaches may be simultaneously funded at the various NPD stages. The managerial challenge is to construct ex ante an appropriate NPD pipeline by choosing the right number of approaches to be funded at each stage. This so-called pipeline problem is also present in, among others, advertising copy selection and new products test markets problems. We describe here a normative model for structuring pipelines for such situations. The optimal structure of the pipeline is driven by the cost of the development approach, its probability of survival, and the expected profitability. We illustrate the workability and implications of the model by applying it to some real-world scenarios in the pharmaceutical industry, and by comparing its normative pipeline recommendations against actual pipelines. Our results suggest that, for the cases we studied, firms tend to use narrower pipelines for their new drug development than they should, and thereby they underspend on research and development. We also present general qualitative insights for one- and two-stage NPD optimal pipeline structures.
(*Marketing; New Products; Innovations Pipelines; R&D Projects; Pharmaceutical Industry*)

1. Introduction

In many situations, there is more than one way (approach) to develop a new product to satisfy some specific consumer needs and capture a business opportunity. In cases where no dominant approach can be identified a priori, managers must decide how many approaches should be supported in parallel. Consider the following problem as a case in point—the development of a preventive acquired immunodeficiency syndrome (AIDS) vaccine.

AIDS is caused by the human immunodeficiency virus (HIV) and "is now the leading cause of death among adults between the ages of 25 and 44—the age range of more than half the nation's 126 million workers" (Gerson 1997). The cumulative (national) costs of treating all people with HIV reached $10.3 billion in 1992 and has been increasing ever since (Hellinger 1992). The severity of this disease is further underscored by its infectious nature. This presents a significant business opportunity to the pharmaceuticals industry and, at the same time, an even bigger concern for public policy makers. As a result, substantial effort has been made, both by pharmaceutical/biotechnology industries and the U.S. government, to develop a preventive vaccine for HIV. May 18, 1998, was even designated the first HIV/AIDS Vaccine Awareness Day. To increase the probability of success, many prototype

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vaccines have been developed based on different mechanisms, including subunit vaccine, recombinant vector vaccine, peptide vaccine, virus-like particle vaccine, anti-idiotype vaccine, plasmid DNA vaccine, whole-inactivated virus vaccine, and live-attenuated virus vaccine. A number of prototype AIDS vaccines are being tested now in Phase 1 and Phase 2 human clinical trials, sponsored by various companies (e.g., Bristol-Meyers Squibb, British Biotech PLC, Chiron/BIOCINE, Genentech, and Pasteur Merieux Connaught), and organized by the National Institute for Allergy and Infectious Disease (NIAID; which has a branch specifically formed to organize AIDS vaccine clinical trials). By February 1998, NIAID had conducted 29 Phase 1 or Phase 2 clinical trials with 19 different vaccine candidates (see the NIAID website). While the goal is to obtain one successful preventive vaccine at the end, both companies and the public policy makers believe that more than one approach should be pursued concurrently (Henderson 1996). They, however, differ in their opinions about what is the right number of approaches that should be pursued simultaneously. The evidence suggests that while most of the companies mentioned previously have supported more than one prototype vaccine, they rarely pursue more than three simultaneously. They seem to believe this strategy is in their best interest. The public policy makers, on the other hand, seem to believe that even the combined number of known prototype vaccines (larger than 20) is not large enough. A government-sponsored review indicates, "the dilemma ... is related to the paucity of promising new AIDS vaccine candidates." To address this problem, new two-year innovation grants were awarded in FY1997 through NIAID to encourage new ideas of prototype AIDS vaccines (National Institutes of Health website 1997).

The AIDS vaccine example leads to the critical question faced by a pharmaceutical company: What is the optimal number of prototype AIDS vaccines that should be pursued simultaneously at each of the clinical trial phases? This is the essence of structuring an optimal pipeline. The general pipeline problem could be defined as: There exists a business opportunity (or payoff) that could be captured by launching an appropriate new product. Multiple development approaches may be chosen and funded to develop this new product, none of which guarantees a successful product at the end of the new product development (NPD) process. The NPD process is composed of multiples stages, and the managerial challenge is to determine whether single or multiple (if multiple, how many) approaches should be funded at each of these stages. This paper addresses this problem. The pipeline problem is highly relevant in many other contexts. For example, the development of an advertising campaign also involves the structuring of an optimal pipeline. To develop a successful advertising campaign, the ad agency usually creates multiple copies for the campaign. From this pool of potential ads, a subset is selected for copy testing. The copy testing itself may be done in a multistage fashion. For instance, focus groups could be used to do the first round screening, followed by second round screening in test markets. After reviewing the results, one final copy is selected for the campaign. Deciding on how many test markets to use prior to national rollout of a new product represents another pipeline-structuring business problem. The pipeline problem is critical in nonbusiness situations as well. One example is academic recruitment. The first stage of screening involves reviewing application packages (curriculum vitaes, recommendations, etc.). The second stage usually takes place in a conference. The fortunate ones will be invited to campus for the third stage of the process. Finally, schools need to decide how many offers to make, given that not everyone will accept the offer.

The remainder of this paper focuses our modeling and analyzing the pipeline structure problem in the context of multiple-stage NPD. We take an interdisciplinary perspective by incorporating research and development (R&D), marketing, and product development considerations. The paper is organized as follows. In §2, we review the literature that is most relevant to the problem. We then present (in §3) the model formulation and its analytical implications. In §4, we move from theory to practice, demonstrating the workability and implications of the model by implementing it in a number of real-world situations. Section 5 provides concluding remarks, discussion, and suggestions for further research.

2. Relevant Literature

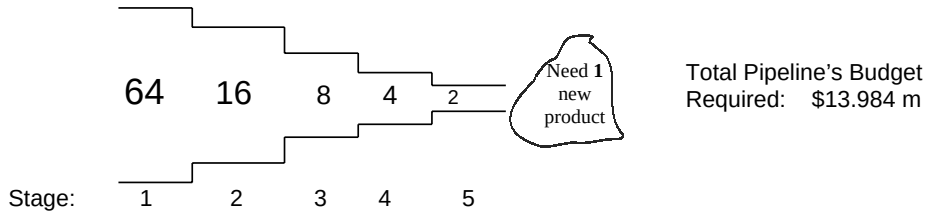
Two streams of literature have studied problems related to the one of concern in this paper—marketing and R&D. The marketing literature has examined issues related to pipeline structuring, mainly for one-stage processes, as well as issues related to managerial fallacies in pulling the plug to stop NPD projects. The R&D literature has focused mainly on resource allocation and portfolio models, using mainly static mathematical programming models.

Some simple heuristics for structuring pipelines for NPD, and their corresponding budgeting implications, can be found in marketing management (Kotler 1994) and NPD (Urban and Hauser 1993) textbooks. The guidelines given in these books, however, focus only on the pass ratios, and they consider the process deterministically. Figure 1 illustrates this line of thinking for a firm whose objective is to launch one successful new product. Although the pass ratios (also known as probability of survival) represent indeed a critical driver in structuring the NPD pipeline, they are not the only driver. Gross (1972) and Feinberg and Huber (1996), for instance, recognized it in their models of selecting advertising copies and the number of candidates to be invited for campus interviews in academic recruitment, respectively. Their models are, however, one-stage models. Srinivasan et al. (1997) focused on the concept selection stage of NPD and studied the question of "How many concepts should be carried forward?" This paper offers empirical support to the idea that more detailed design work should be performed on several concepts in parallel (before selecting the final concept) in some NPD situations. Similar to Gross (1972) and Feinberg and Huber (1996), this paper is framed as a one-stage problem. A recent working paper by Dahan (1998) examines a related problem. He also treats the entire NPD process as a single-stage problem, and asks the question of how many such stages (repeated development) should be considered by the firm, and within each repeat, how many approaches should be funded simultaneously. Relatedly, Bhattacharya et al. (1998) found that the traditional practice, recommended in the literature, of reaching a sharp definition for the new product early in the NPD process (i.e., support one prototype), may not be optimal, desirable, or even feasible in some dynamic situations. Boulding et al. (1997) demonstrate experimentally that the actual pipeline observed in practice may be suboptimal due to managerial misjudgment and/or fallacies. The authors suggested that a predetermined budgeting rule would alleviate such problems.

Managers responsible for developing really new products often recognize that attempting to capture

Figure 1 An Example of Structuring the NPD Pipeline

Stage	Pass Ratio	Cost per approach
1. Idea screening	1:4	$1,000
2. Concept test	1:2	$20,000
3. Product development	1:2	$200,000
4. Test Marketing	1:2	$500,000
5. National launch	1:2	$5,000,000



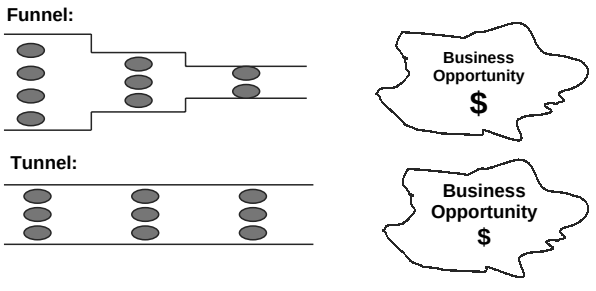
Note. Source: Kotler (1994), p. 319, Table 13-1.

the business opportunity with multiple approaches is inherently better (but more costly) than relying only on a single approach (This was indicated by executives we interviewed, who are responsible for resource allocation.) A recent article in *The Wall Street Journal* (Reid 1999) cited "Werner Schiebler, technology license director of Hoechst Marion Roussel, said … 'We need to … (be) doing things in parallel.' That means using more leads to develop a compound through phase I and II trials ...." This practice of funding multiple alternatives concurrently has been observed in the development of "really new products" in other industries as well. During the development of the videotape recorder technology, for example, Sony had pursued 10 major approaches where each approach had two to three subsystem alternatives (Rosenbloom and Cusumano 1987). AT&T and the major oil companies usually start several programs in parallel before finally selecting a technology for system wide usage (Quinn 1985). According to the Senior Vice President and Chief Technology Officer of Texas Instruments, the company had pursued several alternative approaches on the 16-megabit DRAM chip while simultaneously collaborating with Hitachi (Dreyfuss et al. 1990). During the development of Celcor (a honeycomb structure used to hold catalysts in a catalytic converter) at Corning Incorporated, six R&D teams had worked concurrently on the same problem using different approaches (Morone 1993). Pursuing multiple approaches (parallel NPD) is also common from a public policy standpoint. The Department of Defense of the U.S. government often supports multiple approaches simultaneously.

Firms that understand the importance of multiple approaches, may run, however, into the risk of funding too many (if not all) proposed alternative approaches for a single business opportunity and thus they may be running into the problem of overspending. That is, managers may not realize that sometimes they should only fund a subset of approaches and invest the saved money elsewhere. Sometimes, a strictly sequential NPD process would be appropriate. A sequential approach develops, tests, and launches one approach at a time until one alternative becomes successful (Chun 1994). It takes the same approach all the way through the process until the uncertainty surrounding its performance is completely resolved. By contrast, a parallel NPD procedure will pursue more than one approach at the same time. Because only one commercially successful product will be needed, there is potential waste of redundant NPD resources in the parallel approach. On the other hand, the parallel approach helps the company cope with uncertainties in development, motivates people through competition, and improves the amount and quality of information available for making final choices on scale-ups or introduction (Quinn 1996). The decision to adopt either sequential or parallel approach depends on several factors (Abernathy and Rosenbloom 1968, 1969): the probabilities of stage-wise success, the funding level for each research alternatives, the expected profit, and the constraint of new product development time. If the benefits of parallel approach outweigh the extra NPD investment, then the parallel approach should be used. The sequential approach should be used if the opposite is true.

The various pipelines observed in practice could thus be grouped into two categories (Figure 2). The first category is *funnel* structure in which the number of alternatives that a firm is committed to at each stage gradually decreases as the development process moves toward completion. According to the second category, *tunnel*, the firm makes a commitment to the same number of alternatives at each NPD stage. The two different pipelines (funnel vs. tunnel) have, of course, financial budgeting and organizational implications. A tunnel, for instance, may reflect management commitment to stable R&D personnel and their emotional attachment to the project they have been assigned to. The managerial challenge of determining the optimal pipeline structure for a specific situation,

Figure 2 Various Forms of Pipeline Structures Observed in Practice



however, has not been addressed adequately in the literature.

Another stream of literature that is somewhat related to the pipeline-structuring problem can be founded in the R&D literature. There is a copious collection of resource allocation models for observing evolutionary new products. Early development of the literature has been reviewed by Cetron et al. (1967) and Souder (1978). Reviews could be found in Jackson (1983), Souder and Mandakovic (1986), Steele (1988), Weber et al. (1990), and Schmidt and Freeland (1992). According to Souder and Mandakovic (1986), the population of project selections models could be categorized as classical methods, portfolio models, project evaluation techniques, and organizational decision methods. Classical methods try to prioritize available projects and fund the projects that are on top of the list. Some of the most common classical methods are profiles, checklists, scoring models, and economic indexes. Classical models are simple to use whenever the projects can be prioritized. On the other hand, they fail to reflect the dynamic decision-making process. Portfolio models are usually structured as an optimization problem; the goal of these models is usually to optimize an objective function under a given set of constraints (Schmidt and Freeland 1992). The most fundamental mathematical programming tool used is linear programming. Linear programming-based models have several weaknesses. They do not handle the interdependencies between NPD projects, and they are static. Project evaluation techniques are methods developed to evaluate individual NPD projects, including goal-contribution models, decision tree, utility theory, Monte Carlo simulation, and risk analysis models. To our knowledge, however, none of these methods has been used to address the pipeline-structuring problem of concern here. Although some existing studies have addressed the risk issue associated with developing new products, to our knowledge, no study/model has been conducted to investigate the optimality of parallel/sequential resource allocation for new products in a dynamic multistage decision-making framework and the extent to which companies over/underspend on the development of such new products. Under the (rather strong) assumption that every approach will eventually succeed, an optimal parallel approach problem has been investigated allowing managers to make either one intermediate decision (Nelson 1961) or multiple intermediate decisions (Marschak et al. 1967). However, these normative models could not be used for developing new products in which probability of ultimate success (p) is less than 1. Other researchers have considered this scenario ($p < 1$), but under fairly simplistic conditions. Abernathy and Rosenbloom (1968, 1969) formulated a model with two alternative approaches. Dean and Hauser (1967) formulated a model for the NPD planning of the Army Materiel Command with more than two alternative approaches. These studies, however, did not explicitly incorporate the multiple stages and the dynamic nature of decision making associated with the development of new products. Often, the process is considered exogenously as funnel, in which the number of options pursued becomes smaller as the project progresses toward launch.

3. Model Formulation and Its Implications

We begin by introducing the basic model that addresses the issues discussed earlier. Relaxation of the key assumptions, which leads to a refined model, is discussed in §5. Relaxation of other (nonkey) assumptions is discussed in this section.

Key Assumptions

Several assumptions, validated by interviews with executives in the pharmaceutical industry, have been made in developing the basic model:

1. Multiple approaches may be taken to develop the new product, and there is no dominant approach that guarantees success. Hence, initially we assume that the probabilities of success and the costs incurred within the various NPD stages are the same for all alternative approaches. They may vary, however, across stages.

2. The expected profit from the business opportunity can be captured if one successful product is launched. Profits generated by additional successful products are negligible.

3. The firm does not repeat any of the NPD stages, nor does it repeat the whole NPD process.

These three basic assumptions establish a useful framework. We observe that in practice Assumption 1 is used. One company we surveyed makes an even more restrictive assumption than Assumption 1 by not allowing for variations of probabilities of success and costs across stages. Assumption 2 is quite reasonable as judged by executives in the pharmaceutical industry we have interviewed. Assumption 3 may seem quite restrictive at first, but it is an accurate description of many really NPD scenarios, including drugs. For instance, in many situations, a firm can capture a large market share if it launches its product first (pioneer advantage) and thus becomes the market leader (Urban et al. 1986, Bond and Lean 1977, Parry and Bass 1990). Under this scenario, the potential profit of a late launch (due to repetition of certain NPD stages) is minuscule compared with launching the product first. To focus on the key drivers of the pipeline structure, we assume that all monetary terms have been transformed into present value based on the cost of capital and time. In analyzing the NPD process below, we move backward, that is from product launch to the early stages of the NPD process.

Stage 0 (Just Prior to Launch)

The expected degree of market success of any new product depends on two factors. First, whether the product is likely to meet consumers' needs. Second, how many other products it is likely to compete with. For the sake of exposition, we invoke, as an example, the assumption of no obvious product differentiation in the market. That is, all successfully launched products will divide the market equally among them. For example, a firm will capture the whole business opportunity if no competitor has successfully developed a similar product, whereas it will capture one third of the market if two of its competitors have launched simultaneously similar products. If there are m competitors in such market, each has probability p of developing at least one successful product. One way to express the expected profit of any firm, viewed just prior to launch, is

$$E[\pi_0(s_1)] = \begin{cases} 0 & \text{if } s_1 = 0 \\ \alpha R \sum_{i=0}^{m} \left[\frac{1}{1+i} \binom{m}{i} p^i (1-p)^{m-i} \right] & \text{if } s_1 \geq 1. \end{cases} \quad (1)$$

s_1	number of projects successfully passed the completion stage
$E[\pi_0(s_1)]$	expected cumulative profit when viewed from Stage 0
R	expected cumulative revenue for a business opportunity
α	average contribution rate (the pretax profit and development cost as a percentage of revenue)
i	number of competitors who have developed at least one successful product.

The probability of success (p) in the binomial distribution in Equation (1) represents the (equal) strength of each firm in capturing the business opportunity. Because the number of competing firms (m) is usually quite small, it should be fairly easy to modify Equation (1) and allow different probabilities of success for different firms. Of course, many other approaches can be taken to model $E[\pi_0(s_1)]$. An alternative method, based on trial-and-repeat behavior, could be used to estimate the magnitude of business opportunity for frequently purchased products (e.g., drugs treating chronic diseases). This method is described in §4. It has been applied in estimating the business opportunities faced by firms for seven new drug development situations.

Stage 1 (Last NPD Stage)

The probability of having a certain number of successful projects at the end of Stage 1 can be modeled as a binomial distribution

$$Pr(s_1|p_1, n_1) = \binom{n_1}{s_1} p_1^{s_1} (1-p_1)^{n_1 - s_1}. \quad (2)$$

n_i	number of approaches initiated in stage i
s_i	number of approaches that have successfully passed stage i
p_i	probability of success per approach at stage i
$\Pr(s_i\|p_i, n_i)$	probability of having s_i successful approaches at the end of stage i given p_i and n_i, modeled as a binomial distribution as in Stage 1.

The expected profit at this stage can be expressed as

$$\begin{aligned} E[\pi_1(n_1)] &= \Pr(s_1 = 0|p_1, n_1)E[\pi_0(s_1 = 0)] \\ &\quad + \Pr(s_1 > 0|p_1, n_1)E[\pi_0(s_1 > 0)] - n_1 c_1 \\ &= [1-(1-p_1)^{n_1}]E[\pi_0(s_1 > 0)] - n_1 c_1. \end{aligned} \quad (3)$$

c_i the cost of funding one approach at stage i.

It is straightforward to establish expressions for the variance and the probability of obtaining at least one successful product at this stage. They are, respectively,

$$V[\pi_1(n_1)] = (1-p_1)^{n_1}[1-(1-p_1)^{n_1}]\{E[\pi_0(s_1>0)]\}^2 \quad (4)$$

$$L_1(n_1) = 1-(1-p_1)^{n_1}. \quad (5)$$

Following similar arguments, we can also show that:

Stage k $(k \geq 2)$

The expected profit at this stage can be formulated (see Appendix A[1] for explanation) as

$$\begin{aligned} E[\pi_k(n_k)] &= \sum_{s_k=n^*_{k-1}}^{n_k} [\Pr(s_k|p_k, n_k)E[\pi_{k-1}(n^*_{k-1})]] \\ &\quad + \sum_{s_k=0}^{n^*_{k-1}-1} [\Pr(s_k|p_k, n_k)E[\pi_{k-1}(s_k)]] - n_k c_k. \end{aligned} \quad (6)$$

n^*_{k-1} is the optimal number of approaches to be supported at stage $k-1$; other parameters are defined as in Stages 0 and 1.

The variance for stage k and the probability of obtaining at least one successful product at the end of the NPD pipeline could be calculated, respectively, by

$$\begin{aligned} V[\pi_k(n_k)] &= \sum_{s_k=n^*_{k-1}}^{n_k} \{\Pr(s_k|p_k, n_k)[E[\pi_{k-1}(n^*_{k-1})]]^2\} \\ &\quad + \sum_{s_k=0}^{n^*_{k-1}-1} \{\Pr(s_k|p_k, n_k)[E[\pi_{k-1}(s_k)]]^2\} \\ &\quad - \left\{ \sum_{s_k=n^*_{k-1}}^{n_k} [\Pr(s_k|p_k, n_k)E[\pi_{k-1}(n^*_{k-1})]] \right. \\ &\quad \left. + \sum_{s_k=0}^{n^*_{k-1}-1} [\Pr(s_k|p_k, n_k)E[\pi_{k-1}(s_k)]] \right\}^2 \end{aligned} \quad (7)$$

[1] Appendices A and B are available on the *Management Science* website at ⟨mansci.pubs.informs.org/ecompanion.html⟩.

$$\begin{aligned} L_k(n_k) &= \sum_{s_k=n^*_{k-1}}^{n_k} [\Pr(s_k|p_k, n_k)L_{k-1}(n^*_{k-1})] \\ &\quad + \sum_{s_k=1}^{n^*_{k-1}} [\Pr(s_k|p_k, n_k)L_{k-1}(s_k)]. \end{aligned} \quad (8)$$

Having set up the model, it is now possible to investigate its implications. We begin with Equation (3).

PROPOSITION 1. *$E[\pi_1(n_1)]$ is a strictly concave function with a unique global maximum at n^*_1 that equals to*

$$n^*_1 = \frac{\ln\left(\frac{-c_1}{E[\pi_0(s_1>0)]\ln(1-p_1)}\right)}{\ln(1-p_1)}. \quad (9)$$

PROOF. Strict concavity can be shown by

$$\begin{aligned} \frac{\partial^2 E[\pi_1(n_1)]}{\partial n_1^2} &= -E[\pi_0(s_1 > 0)] \\ &\quad \times [\ln(1-p_1)]^2(1-p_1)^{n_1} < 0. \end{aligned} \quad (10)$$

The global maximum could be obtained by solving

$$\frac{\partial E[\pi_1(n_1)]}{\partial n_1} = 0. \quad (11)$$

Q.E.D.

COROLLARY 1.

- *n^*_1 in Equation (9) increases as the ratio between cost per approach and expected cumulative profit ($c_1/E[\pi_0(s_1 > 0)]$) decreases.*
- *n^*_1 in Equation (9) increases when p_1 increases from 0 to p^*_1, peaks at p^*_1, and decreases when p_1 decreases from p^*_1 to 1. p^*_1 is defined as:*

$$p^*_1 = 1 - e^{\frac{-c_1}{(1/e)*E[\pi_0(s_1>0)]}}.$$

The proof is straightforward.

Investigating Equation (6) for optimality becomes less tractable. However, it can be shown that:

LEMMA 1. *$E[\pi_k(n_k)]$ is a strictly concave function with a unique global maximum at n^*_k, in which n^*_k is implicitly defined by the following equation*

$$\begin{aligned} p_k \sum_{s_k=0}^{n^*_{k-1}-1} \{\Pr(s_k|p_k, n^*_k)[E[\pi_{k-1}(s_k+1)] \\ - E[\pi_{k-1}(s_k)]]\} - c_k = 0, \end{aligned} \quad (12)$$

in which k is a positive integer and $k \geq 2$.

PROOF. See Appendix A. □

The next proposition provides more insights into the nature of n_k^*:

PROPOSITION 2. *For Stage k* ($k \geq 2$):

n_k^* *in Equation* (12) *increases when* c_k *decreases*

n_k^* *in Equation* (12) *reaches maximum at an interior value of* p_k (*between* 0 *and* 1).

An approximation (*upper bound*) *for* n_k^* *in Equation* (12) *is given by*

$$n_k^* < \frac{\ln c_k - \ln(p_1 p_2 \cdots p_k E[\pi_0(s_1 > 0)])}{\ln(1 - p_1 p_2 \cdots p_k)}. \qquad (13)$$

PROOF. See Appendix A. □

PROPOSITION 3. *If, for all k* ($k \geq 2$),

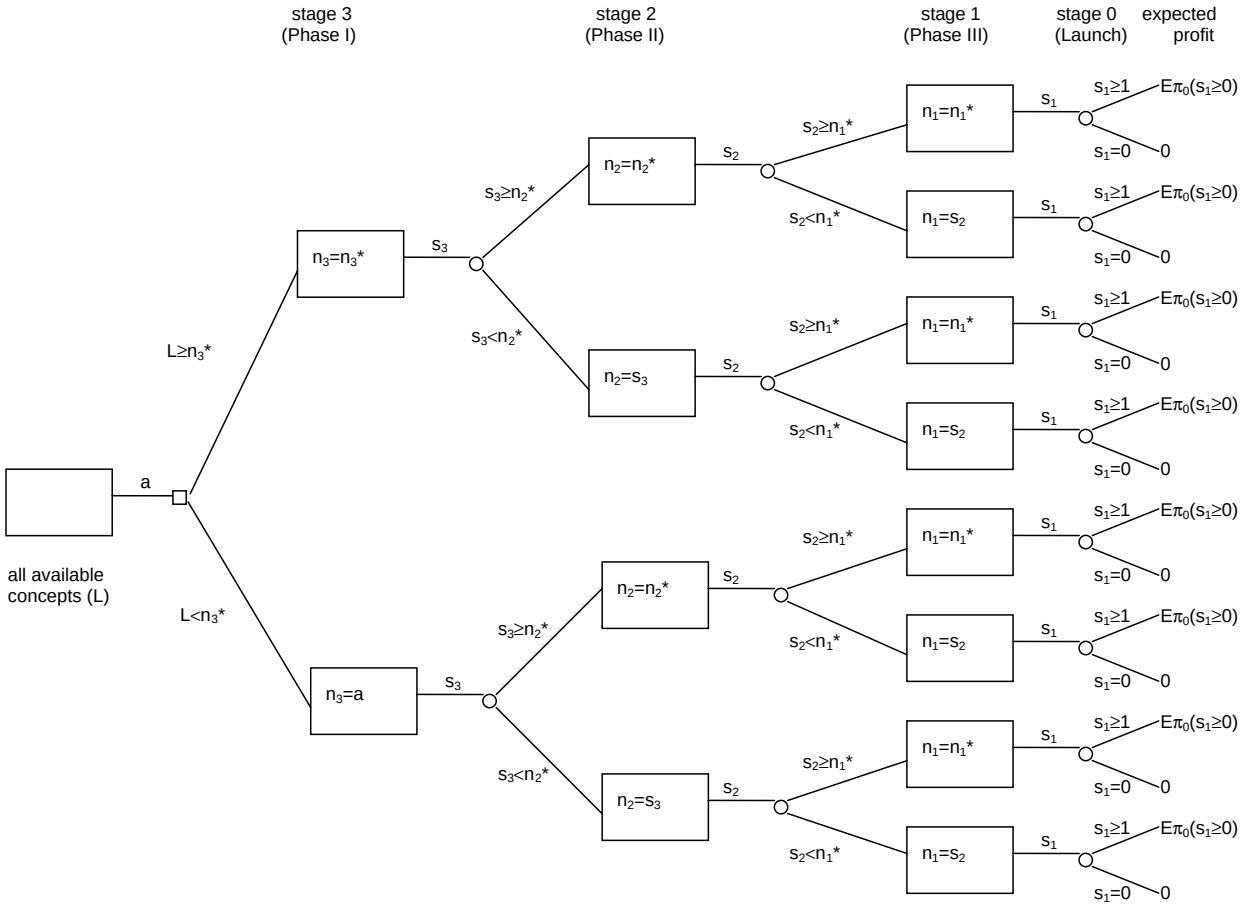
$$c_k < p_k \sum_{s_k=0}^{n_{k-1}^*-1} \{\Pr(s_k | p_k, n_{k-1}^*) \times [E[\pi_{k-1}(p_{k-1}, s_k + 1, c_{k-1}, E\pi_{k-2})] - E[\pi_{k-1}(p_{k-1}, s_k, c_{k-1}, E\pi_{k-2})]]\} = \bar{c}_k, \qquad (14)$$

then the NPD pipeline will take the shape of a funnel ($n_k^* > n_{k-1}^*$). *If the inequality in Equation* (14) *does not hold for any k, the pipeline will be a tunnel shape* ($n_k^* = n_{k-1}^*$). *If the inequality in Equation* (14) *holds only for some k, then the pipeline will have a mixed shape of funnel and tunnel.*

PROOF. See Appendix A.

Based on Propositions 1–3, the decision rules for structuring a three-stage optimal NPD pipeline are captured by a decision tree (see Figure 3). This

Figure 3 Decision Tree



decision tree could be easily extrapolated to k stages. When supplied with the required inputs (parameters) for a given NPD project, the model can then produce a specific decision tree to be used to construct the optimal pipeline by the managers.

Discussion

It is possible to represent geometrically the dependence of the optimal pipeline on the three key problem's drivers: expected profit, cost, and probability of success for a one-stage scenario. See Figure 4 (Appendix B provides the formal analysis).

Figure 4 represents a one-stage pipeline with some given $E[\pi_0(s_1 > 0)]$. Any point in the unit rectangle captures a combination of $(p_1, c_1/E[\pi_0(s_1 > 0)])$. The line and the curve shown in Figure 4 represent boundaries. Point E, for example, represents a pipeline situation characterized as $(p_{1E}, c_{1E}/E[\pi_0(s_1 > 0)])$, in which the normative number of development approaches is equal to 3. The numbers in the figure refer to the optimal numbers of approaches to be funded for various regions in the parameter space. Three key insights for the one-stage scenario are: (1) the managerial decision is reduced to a binary choice (fund a single approach or none) when the cost per approach (c_1) is larger than one fourth of the expected market potential ($E[\pi_0(s_1 > 0)]$); (2) for a fixed probability of success (e.g., p_{1E}), the optimal number (n_1^*) increases when the cost (c_1) decreases; and (3) for a fixed cost (e.g., c_{1E}), the optimal number (n_1^*) first increases then decreases as p_1 increases from 0 to 1. The intuition behind the last insight is that the marginal benefit of an additional approach is small under either small p_1 (this additional approach is less likely to be successful) or large p_1 (a successful product is likely to be developed by other approaches).

The story becomes more complex in a two-stage scenario (see Figure 5 and Appendix B[1] for formal analysis). There are essentially three types of normative pipelines that will emerge for the two-stage process, namely,

- M-M fund multiple approaches in both stages
- M-S fund multiple approaches in the initial NPD stage (e.g., concept screening) and focus on one approach in the second NPD stage (e.g., prototype testing)
- S-S fund a single approach in both stages.

Given that $E[\pi_2(n_2)]$ is concave with respect to n_2 (Lemma 1), the corresponding conditions under

Figure 4 One-Stage Process Analysis

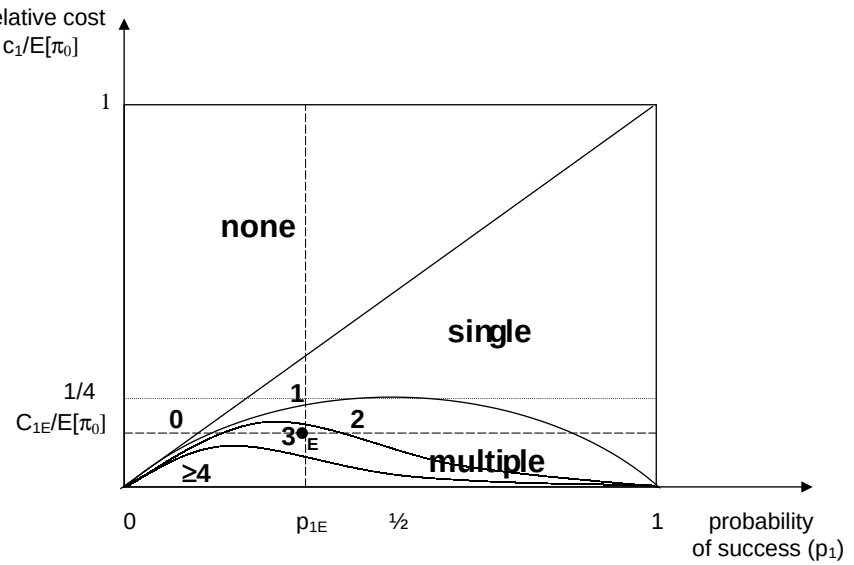
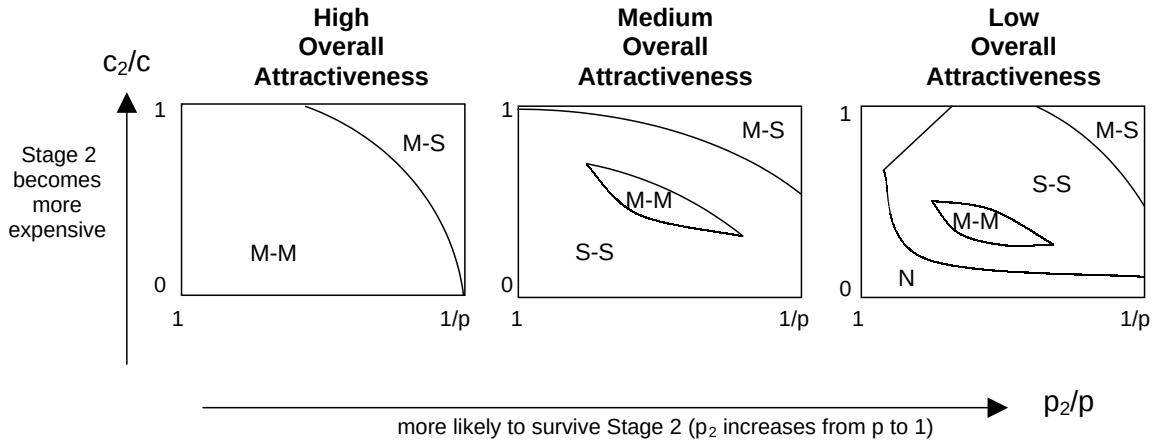


Figure 5 Two-Stage Process Analysis



Note. The abbreviations represent the optimal NPD strategy under various conditions: S-S, fund single ($n^* = 1$) approach at both stages: M-S, fund multiple ($n^* > 1$) in Stage 1, single ($n^* = 1$) in Stage 2 (last stage); M-M, fund multiple ($n^* > 1$) approaches at both stages; and *N*, none ($n^* = 0$) should be funded.

which each of the three scenarios is optimal could thus be simplified as

Scenario	First NPD Stage (e.g., concept screening)	Last NPD Stage (e.g., prototype development)
S-S	Given $n_1^* = 1$ $E[\pi_2(1)] > E[\pi_2(0)]$ and $E[\pi_2(1)] > E[\pi_2(2)]$	$E[\pi_1(1)] > E[\pi_1(0)]$ and $E[\pi_1(1)] > E[\pi_1(2)]$
M-S	Given $n_1^* = 1$ $E[\pi_2(2)] > E[\pi_2(1)]$	$E[\pi_1(1)] > E[\pi_1(0)]$ and $E[\pi_1(1)] > E[\pi_1(2)]$
S-M* (reduced to S-S)	Given $n_1^* > 1$ $E[\pi_2(1)] > E[\pi_2(0)]$ and $E[\pi_2(1)] > E[\pi_2(2)]$	$E[\pi_1(2)] > E[\pi_1(1)]$
M-M	Given $n_1^* > 1$ $E[\pi_2(2)] > E[\pi_2(1)]$	$E[\pi_1(2)] > E[\pi_1(1)]$

**Note.* It is possible to have a scenario in which the optimal pipeline is a reverse funnel [i.e., support one approach in the initial stage and multiple approaches in the second stage (S-M)]. Under the logical constraint that an approach, which is developed internally, must pass all earlier stages to be available for later development, this scenario is reduced to the S-S scenario in the analysis followed. This scenario is realistic, however, in the pharmaceutical industry in which pharmaceutical companies let external biotech firms do the initial development and then they acquire (or form an alliance with the biotech firms) a new compound that survived the earlier stages at the biotech firms.

Thus, there are two conceptually different determinants that affect the structure of the two-stage pipeline. One is the overall profile of the new product (the relationship among c, p, in which $c = c_1 + c_2$ and $p = p_1 * p_2$, and $E[\pi_0(s_1 > 0)]$). There are three regions, as defined below, that have very different effects,

$$\begin{aligned}&\text{Region 1 (high attractiveness)}\\&\quad c < (p - p^2)E[\pi_0(s_1 > 0)]\\&\text{Region 2 (medium attractiveness)}\\&\quad (p - p^2)E[\pi_0(s_1 > 0)] < c < pE[\pi_0(s_1 > 0)]\\&\text{Region 3 (low attractiveness)}\\&\quad c > pE[\pi_0(s_1 > 0)].\end{aligned} \tag{15}$$

The other is the distribution of the overall cost and probability of survival between the two stages (c_2/c and p_2/p), which are represented by the axes in Figure 5. The boundaries for different pipelines are shown in Figure 5, in which each rectangle represents the results for each overall attractiveness region.

For easier interpretation, we sum up the general insights with regard to the optimal pipeline structure under the two-stage scenario in Table 1. This table suggests that a firm should always cast a wide net (fund multiple approaches) in the first stage and focus on one approach in the second stage if the screening (first stage) is effective (remove most of the uncertainty) and cheap. This insight is fairly robust with respect to the overall profile of the project (similar across the three regions). It should be pointed out that the exact definition of effective and cheap screening (as other similar terms used here) is relative, and

Table 1 Summary Results for Two-Stage NPD Pipeline

		First NPD Stage (Screening Stage)*			
		Effective AND Cheap†	Semieffective AND Medium Cost‡	Ineffective OR Expensive§	In Between¶
Overall attractiveness	High#	Multiple (>1) First			
	Medium‖	Single (1) Later	Both	Both Single (1)	
	Low**	Later	Multiple (>1)	None (0)	

Notes.

*Relative to the second NPD stage's cost and probability of survival.

†Large p_2/p AND large c_2/c (small p_1/p AND small c_1/c).

‡Medium p_2/p AND medium c_2/c (medium p_1/p AND medium c_1/c).

§Small p_2/p OR small c_2/c (large p_1/p OR large c_1/c).

¶ All other situations.

#Corresponding to Region 1 in Equation (15).

‖Corresponding to Region 2 in Equation (15).

**Corresponding to Region 3 in Equation (15).

(the sizes of areas that fit this description) it may differ across the three groups of overall profiles. The optimal pipeline is also relatively straightforward for semieffective and medium cost screening and again fairly robust with respect to the overall profile of the project. Under this situation, the firm should fund multiple approaches at both stages. The pipeline-structuring strategy becomes complicated when the screening is ineffective or expensive. Under this condition, M-M strategy should be used when the overall attractiveness is high; S-S strategy should be used when the overall attractiveness is moderate; and the project should be abandoned (does not fund any approach) when the overall attractiveness is low. For all other screening conditions, S-S strategy should be used, except that a firm should adopt M-M when the overall cost is low.

There are some exceptions to the insights summarized in Table 1. First, even though we have stated that a cheap *and* effective screening is required for the M-S strategy to be optimal, this requirement is relaxed to include expensive but very effective screening for highly attractive projects and very cheap but ineffective screening for moderately attractive projects (see Figure 5). The second major exception is that the areas in Figure 5 with M-M as its optimal strategy may not exist under some situations (e.g., when the overall attractiveness approaches the high end within each profile group).

So far, we discussed optimal structures for one- and two-stage processes; separately, some insights can also be obtained by examining and comparing the economic implications of multiple vis-à-vis single-stage development processes. The following simple example sheds some light onto such comparison (see Figure 6). Note that in both cases the probability of ultimate success is 0.36, and the total funding required is \$10 million. The best decision in the single-stage case is to GO if $X > 10/0.36$ (see Decision Tree 1, Figure 7). The best decisions in the two-stage case is to GO with Stage 2 if $X > 6/0.6$ *and* to GO with

Figure 6 An Illustrative Example

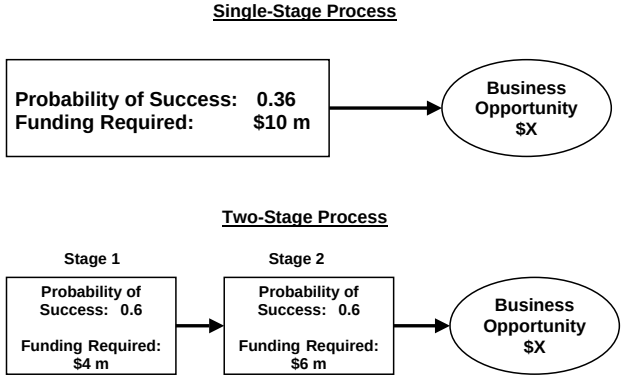
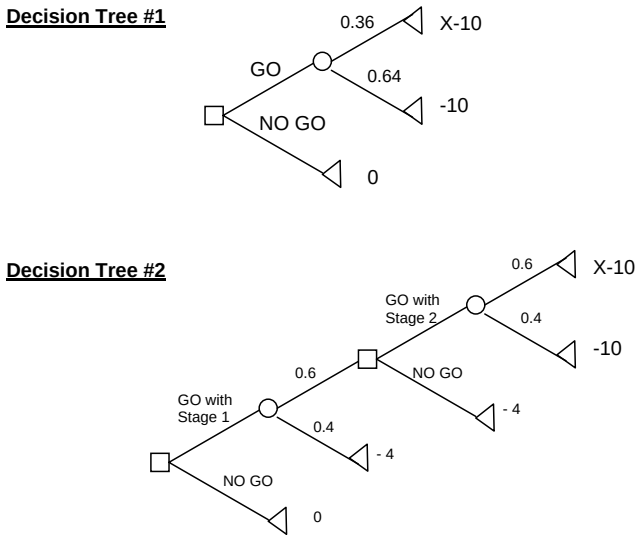


Figure 7 Decision Trees for the Illustrative Example



Stage 1 if $X > 7.6/0.36$ (see Decision Tree 2, Figure 7). This implies that the firm should fund *both* Stages 1 and 2 if $X > 7.6/0.36$. Because $7.6/0.36 < 10/0.36$, this simple example illustrates that multiple (two)-stage development processes can lead to pursuing smaller business opportunities.

4. From Theory to Practice

In this section, we will demonstrate the implementability of the model and its implications by studying first the motivating example discussed in §1: the HIV vaccine. Next, we analyze seven other new drug development cases. We will compare the models' (normative) recommendations to actual data. We will also demonstrate how the model can be used as a simulation tool to provide managers with a confidence region for its recommendations in the face of uncertainty. This is achieved by varying systematically the key parameter values.

The expected profit (Equation 1) of an AIDS vaccine for any firm engaged in developing it can be calculated following the method used by Grabowski and Vernon (1990) with some modifications. The return to the firm from treating a person infected with AIDS is estimated to be \$102,000 (Hellinger 1992). The number of people infected with HIV every year is estimated to be at least 40,000 (Office of AIDS Research, National Institutes of Health). Within one year of introducing a successful AIDS vaccine, the entire U.S. population (280 million) will be inoculated. The number of firms currently engaged in active development of preventive AIDS vaccines with NIAID is 12. Assuming each firm starts with three prototype vaccines, given the various phase-wise survival probabilities (see Table 2), the expected probability of success for each firm will then be $1-(1-0.75\times 0.48\times 0.63)^3 = 0.5$. Thus the expected profit for any one firm, given that it succeeds in developing a vaccine, will be the expected market share (0.17) times the total business opportunity (Equation 1). The cumulative cash flow (profit plus R&D costs) can be obtained using an average contribution rate of 40%, which is then adjusted for a 36% tax rate and discounted using 10% cost of capital assuming a 10-year development cycle prior to product launch. Finally, this domestic cumulative cash flow can be extrapolated to worldwide cumulative cash flow using a multiplier of 1.9 following Grabowski and Vernon (1990). The worldwide firm's expected profit will be

$$E[\pi_0(s_1>0)] = \left(\$102{,}000\times\frac{40{,}000}{280{,}000{,}000}\right) \times 280{,}000{,}000\times 0.17\times 40\%\times 64\% \times 1.1^{-10}\times 1.9 = \$130\,m. \quad (16)$$

The expected benefit for the public policy makers, however, is quite different. In this analysis, we use the amount of national costs associated with treating AIDS over a long time horizon (the resources that may be saved by using an AIDS vaccine) as the benefits for public policy makers. The cumulative (national) costs of treating all people with HIV are estimated to be \$10.3 billion in 1992 (Hellinger 1992). Based on the average infection rate and the same cost of capital, we may calculate the present value of the benefits to public policy makers

$$E[\pi_0(s_1>0)] = \sum_{i=0}^{\infty}\frac{(\$10.3\text{ billion})\times(1+\frac{40{,}000}{280{,}000{,}000})^i}{1.1^i} = \$113.5\text{ billion}. \quad (17)$$

The estimated cost for each prototype vaccine at any one of the three clinical trials should be same

Table 2 AIDS Vaccine Pipeline

Clinical Trial Stages	Cost Per Prototype Vaccine ($m)	Probability of Success	Actual Pipeline for a Firm	Optimal Pipeline of Prototype Vaccines Recommended by the Model for: A Firm ($130m)	Optimal Pipeline of Prototype Vaccines Recommended by the Model for: Public Policy Maker ($113.5b)
Phase 1	2	0.75	<3	5	34
Phase 2	4	0.48	<3	5	25
Phase 3	13	0.63	N/A	2	9

for both companies and public policy makers. In our initial analysis, we will adopt the industrial averages from DiMasi et al. (1991). Later, we will vary the values of these parameters. Table 2 shows the cost and probability of success at each clinical trial stage, and the model's pipeline recommendations for a private firm and public policy makers. We have also included the currently known actual pipelines for developing AIDS vaccines by firms. From Table 2, it is clear that a parallel approach is desirable for developing the AIDS vaccine, from both a for-profit firm's standpoint and a public policy makers' standpoint. The numbers of optimal parallel approaches at each stage, according to our model, are quite different for these two parties. Although our model recommends that a firm should support about five prototype projects in Phase 1, public policy makers would like to see up to 34 *different* prototype projects being supported in Phase 1. Similar differences in magnitude can also be seen for the other two development stages. The actual pipeline of the firm is more narrow than what the model recommends.

Two additional observations are noteworthy.[2] First, the difference in the returns for private firms and public policy makers is much larger in scale relative to the difference in their optimal pipeline structures. This suggests that results from this model will be robust in situations in which estimated returns may have a wide margin of error. Second, the total number of approaches funded by all private firms is actually comparable with that of a policy maker. Thus, excluding the case where the research approaches are identical across firms, increased competition among private firms could effectively replace the need for a centralized research program organized by a public policy maker.

The probabilities of obtaining a return within any given range for either firm or the public policy makers can also be calculated, based on Equations (5) and (8), for different NPD stages as shown in Table 3.

To test the sensitivity of our analyses, the value of the parameters was varied one at a time. The results are shown in Table 4. Based on Table 4, it appears that, in general, our model's normative recommendations for structuring pipelines for developing AIDS vaccines are quite robust with respect to variations in the parameter estimates.

To analyze further the current practice in the area of new drug development, we have analyzed seven additional new drug development categories. Given that there is only one paper (DiMasi et al. 1995) that has estimated therapeutic-category specific cost and probability of survival, we have selected seven chronic diseases for which these parameter values are available. These include three from the cardiovascular class, namely, arrhythmia, hypertension, high cholesterol; three from the neuropharmacological class, namely, depression, Alzheimer's disease, and migraines; and one from nonsteroidal anti-inflammatory drugs, COX-2 drugs treating arthritis. Moreover, we know that different firms are engaged in developing drugs for each of these categories, and they are at different stages in the development cycle. Our analyses below focus on the most advanced firm in each category.

The expected gross profit for such firms is calculated using a two-step procedure. First, the gross profit is estimated for a given competitive scenario.

[2] We thank the area editor for pointing out these two important observations.

Table 3 Probabilities of Returns: AIDS Vaccine Pipeline

		Probabilities	
	Specified Range of Returns	Firm $73–187m	Public $113.5b
Condition under which the probabilities are assessed	Start with optimal number at Phase 1	39%	99.97%
	Start with optimal number at Phase 2	44%	99.98%
	Start with optimal number at Phase 3	48%	99.99%
	Have at least one successful vaccine for launch	56%	100%

Table 4 Sensitivity Analysis for AIDS Vaccine Pipelines

	Optimal Number of Prototype Vaccines Recommended by Our Model					
	Firm			Public Policy Maker		
Clinical trial stage	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Base case	5	5	2	34	25	9
Vary the number of competitors (m)						
2	11	9	4	34	25	9
20	3	3	2	34	25	9
Vary the strength of competitors (probability of success p)						
0.78	3	3	2	34	25	9
0.23	8	7	3	34	25	9
Vary probability of success, Phase 3 (p_1)						
0.3	4	4	4	65	50	23
0.8	5	5	2	27	19	6
Vary probability of success, Phase 2 (p_2)						
0.2	6	6	2	77	60	9
0.7	4	3	2	23	16	9
Vary probability of success, Phase 1 (p_3)						
0.5	7	5	2	52	25	9
0.9	4	4	2	27	25	9
Vary cost, Phase 3 (c_1)						
8 m	6	5	3	34	25	10
20 m	5	4	2	33	25	9
Vary cost, Phase 2 (c_2)						
2 m	6	6	2	34	27	9
8 m	4	3	2	33	23	9
Vary cost, Phase 1 (c_3)						
1 m	6	5	2	35	25	9
4 m	4	4	2	32	25	9
Varying expected profit (firm)						
100 m	4	4	2	34	25	9
200 m	7	6	3	34	25	9
Varying expected benefit (public policy)						
100,000 m	5	5	2	33	24	9
200,000 m	5	5	2	36	26	10

Second, the expected gross profit is obtained by weighing the gross profit for each scenario using the probability of occurrence for that scenario. Under each scenario, defined by a specific combination of the R&D outcomes for all firms involved (e.g., one scenario might be: Firm 1 launches its new drug in Year 1, Firm 2 fails in its product development efforts, and Firm 3 launches its new drug 2 years after Firm 1, ...), the revenue of the new drug at each period is calculated by summing the trial and repeat prescriptions for the pioneering firm. We assume that a patient has a given probability of trying a new generation of drugs during each office visit, and the physician does not discriminate among similar (me-too) drugs in deciding which drug to prescribe to the patient. Thus, trial prescriptions at each period could be easily calculated if we know the market size and the probability of trial. We also assume that there is a given probability that a patient will respond well to the trial and will thus repeatedly use the same drug and will not switch to other me-too drugs. As a result, the repeat sales could also be easily obtained. Once the prescriptions at all periods have been obtained, the expected revenues and gross profit can then be calculated based on the following equations:

$$E[\pi] = \sum_{o=1}^{O} q_o \pi_o$$

in which

$$\pi_o = \sum_{t=1}^{T} \frac{s(t) \times (1-\alpha) \times C}{(1+\beta)^t} \tag{18}$$

- $E\pi$ expected gross profit
- π_o gross profit under scenario o
- O total number of possible competitive scenarios (vary from each other depending on which one of the competing firms' NPDs are successful)
- q_o probability of having a particular competitive scenario o
- T product life (e.g., 12 years)
- C contribution rate (e.g., 40%)
- α tax rate (e.g., 36%)
- β cost of capital (e.g., 9%)
- $s(t)$ revenues from the drug during period t.

After the trial-repeat purchase structure used in pretest market models (e.g., ASSESSOR; Silk and Urban 1978), we have developed a formulation that captures the unique context in drug prescriptions. The revenues for a given drug during period t, $s(t)$, can be obtained as following:

$$\begin{aligned} s(t) &= Trial\_Sale(t) + Repeat\_Sale(t) \\ &= MSize(t) \times [1 - CTC(t-1)] \times \frac{t_r}{n(t)} + MSize(t) \\ &\quad \times CT(t-1) \times r_r \end{aligned} \tag{19}$$

- *Trial Sale*(t) revenue during period t generated by first-time users
- R*epeat Sale*(t) revenue during period t generated by repeat users
- *Msize*(t) market size (\$) during period t
- $CTC(t-1)$ (cumulative) proportion of the market that has tried any new drugs up to period $t-1$
- $CT(t-1)$ (cumulative) proportion of the market that has tried the drug of interest up to period $t-1$
- t_r probability of trying the new drugs for the first time in one period
- r_r probability of getting a repeat prescription for the same drug after trial
- $n(t)$ number of new drugs available during period t.

For the seven cases studied here, we have estimated the most conservative gross profit, assuming that all competing firms will eventually succeed in their NPD effort; but their introductions of the new drugs will be sequential, based on their current development stages. The 1998 market size and growth rate for each disease have been obtained from "Pharmaceutical Therapeutic Categories Outlook" by SG Cowen (March 1999). The actual pipelines of all competing firms have also been obtained from the same source. The contribution rate, tax rate, and cost of capital have been obtained from the literature (Grabowski and Vernon 1994).

The trial (t_r) and repeat (r_r) probabilities for each new drug/compound have been obtained by surveying eight experts (two clinicians, two pharmacists

who are also professors in pharmacy schools, two marketing/forecasting managers in two major pharmaceutical companies, and two pharmaceutical marketing consultants). The cover letter of the survey informed the respondents that they would be asked to estimate two parameters for seven new drugs/compounds based on their experience/intuition:

Percentage 1	What percentage of targeted patients is likely to be prescribed the new drug (get an least one prescription) within two years of the new drug launch?
Percentage 2	What percentage of the above patients is likely to be repeat users of the drug after using the drug for the first time?

The survey used a list of relevant information for the seven new drugs/compounds, namely, Indication Targeted (e.g., arthritis), the name of New Drug/Compound and the leading firm that is developing it (e.g., Celebrex by Monsanto), and the novel mechanism used by the new drug/compound (compared with existing therapies, e.g., selective nonsteroidal anti-inflammatory drug, COX-2 only). The averages (across respondents) of the percentage values are used to estimate the trial (t_r) and repeat (r_r) probabilities in the following manner: for each drug/compound, the average of estimates for percentage 2 is used directly as the probability of repeat prescriptions (r_r). The trial rate is recovered from the average value of percentage 1 under the premise that there will be approximately eight office visits during the two-year period (an average prescription covers 30 days, with two refills for another 60 days). Thus,

$$P_1 = 1 - (1 - t_r)^8 \tag{20}$$

in which P_1 is the average value of percentage 1 for a drug (probability of trial within two years of the drug launch), and t_r is the first trial probability per office visit for the drug (the probability of receiving a prescription for the new drug per office visit, if a patient has not used the drug before).

The expected market returns and the normative/actual pipelines for the seven new drug development problems are presented in Table 5.

Two interesting insights emerge from this analysis. First, the leading firm in each case seems to underspend on their corresponding new drug development throughout the clinical trials compared with the model's normative recommendations. These gaps, however, must be interpreted with caution. Managers may be under internal budget constraints, whereas the model has assumed the financial market is efficient. The budget constraint, if presented as a minimum Internal Rate of Return, could be easily incorporated into the model. Managers may also face creativity limitation. The observed underspending could be due to the lack of suitable new drug candidates. Different assessment of the market opportunity may also partially explain the gap. Another possible explanation is that the probabilities of survival of the alternative approaches/candidates are not independent of each other. As shown in the next section, the normative pipeline should indeed become narrower if there is correlation among alternative approaches. We also note from the analyses that *different* NPD pipelines are needed for *different* new drug development problems. In addition to different optimal numbers of approaches at each stage, the shapes of the pipelines are also quite distinctive for different cases. For instance, for all three cases in the neuropharmacological class, the optimal first two stages should have a tunnel structure (similar or same optimal numbers), and the firm should exhibit more focus (decrease the alternative approaches funded dramatically) only in the last stage. For the remaining cases (except arrhythmia), the optimal pipelines all exhibit a funnel structure (gradually decreased optimal numbers as the development progresses). In light of this observation, it is interesting to note that pharmaceutical firms, at least the ones studied here, adopt a one-size-fit-all funding strategy (either 1-1-1 or 2-2-2) for various new drug development cases.

Table 5 Seven NPD Challenges in the Pharmaceutical Industry

Indication	Expected Market Return (firm), $E[\pi]$ ($m)	Actual Pipeline (leading firm)*	Model Recommendation (leading firm)*
Cardiovascular Class (3)			
Arrhythmia	191	1 → 1 → N/A	2 → 2 → 2
High cholesterol	7,858	1 → 1 → N/A	16 → 10 → 4
Hypertension	10,334	1 → 1 → 1	17 → 11 → 5
	Phase 1	Phase 2	Phase 3
Cost (capitalized), c ($m)	8.47	13.48	33.38
Probability of survival, p	0.639	0.566	0.724
Neuropharmacological Class (3)			
Alzheimer's disease	8,021	1 → 1 → N/A	20 → 19 → 7
Migraine headache	1,099	1 → 1 → 1	11 → 11 → 4
Depression	5,238	2 → 2 → 1	18 → 17 → 7
	Phase 1	Phase 2	Phase 3
Cost (capitalized), c ($m)	4.31	8.05	33.94
Probability of survival, p	0.898	0.442	0.511
NSAID Class (1)			
Arthritis (COX-2)	3,059	2 → 2 → 2	12 → 10 → 3
	Phase 1	Phase 2	Phase 3
Cost (capitalized), c ($m)	11.53	18.15	68.34
Probability of survival, p	0.750	0.417	0.709

*The three numbers corresponding to Phases 1, 2, and 3, respectively.

Note. N/A, no data available; NSAID, nonsteriodal anti-inflammatory drug.

5. Conclusions, Discussion, and Further Research

In this paper, we developed a parsimonious model that recommends optimal pipeline structures for multiple-stage product development processes. When supplied with its key inputs—magnitude of the business opportunity, cost per development approach, and survival probabilities—the model can shed insights into under (over) spending in NPD. Such results can force managers to engage in systematic thinking and examination of their product development pipelines and budgeting decisions. As a decision support tool, the model developed here can also be used to simulate the uncertainty associated with really new products and provide a comprehensive understanding and internal analysis. In the real world, some mergers and acquisition decisions are motivated by reviewing pipelines of new products for their appropriateness. "Most of the mergers we have seen have been made out of weakness (in their pipelines)," as declared by Pfizer chairman William Steere when Pfizer launched its hostile-takeover bid for Warner-Lambert, in an effort to pre-empt a merger between Warner-Lambert and American

Home Products. However, "Some folks on Wall Street ... argue that Pfizer's own bid could be no different from other drug mergers in its aim" (McGough and Deogun 1999). Wall Street analysts also rely on pipeline conditions in their valuation of firms' stocks.

As demonstrated in the AIDS vaccine case, our model should also be of interest to public policy decision makers who are responsible for allocating tax money to biomedical research related to human diseases. There are always more fundable grant applications and more diseases than could be possibly supported. Furthermore, multiple approaches are often available to investigate the mechanism of a single disease. To cope with these problems, decision makers, in general, often try to divide the research budget among various diseases and support multiple (and different) laboratories for each disease. Unfortunately, instead of maximizing social welfare as public funding should do (which could be easily achieved by models such as ours once profit is replaced by a measure of social welfare), these decisions are sometimes influenced by other factors. The allocation of resources to different diseases is often influenced by political and social pressures (e.g., the case of breast cancer), and the allocation of resources for different projects related to the same disease is determined by scientific merit and budget constraint. These decision rules may result in less than optimal welfare. The absolute magnitude of improvement, if systems such as our model are used, is signified by the sheer size of public funds in question. For instance, the National Cancer Institute, one of the 24 institutes and centers that is collectively known as the National Institute of Health, had a budget of $2.4 billion in fiscal year 1997 for the sole purpose of supporting research related to cancers.

This paper also contributes to the literature by filling the research gap regarding optimal resource allocation in parallel multistage NPD processes. As a marketing–R&D interface model, we have demonstrated how market inputs (size of the market, number and strength of competitors, and the proportion of the target market that can be addressed by each successful product) could be used to optimize resource allocation decisions during R&D and NPD.

The model proposed in this paper, although realistic for industries such as the pharmaceuticals, can, like any other model, be potentially expanded in several directions to incorporate additional considerations by relaxing its assumptions. Below, we discuss a number of possible extensions; some of these have already been undertaken.

Extension 1: Nonidentical Success Probability and Cost in Each NPD Stage

The basic model assumes that all available approaches have the same probability of success and cost at each stage (different across stages). This essentially captures the situation where there is no a priori advantages of any one development approach. In other situations, however, alternative approaches have different probabilities of success and cost, and it is possible to rank the alternative approaches based on their probabilities of success, costs at each stage, or a composite measure of both probability and cost (e.g., probabilities of success per cost). The mathematical analysis is again based on the basic concept of comparing the marginal value of an additional project with the associated cost of supporting it. The actual analysis is straightforward, but rather lengthy (each approach now has two parameters at each stage). We found that the propositions still hold with regard to the existence of a unique maximum at each NPD stage, and the actual optimal number of approaches at each stage can also be identified. Furthermore, we found the entire pipeline implications hold in spirit as well. Another promising avenue for further research is to represent the probabilities of success as a function of spending for that particular approach.

Extension 2: Modeling the Correlated Development Approaches

The basic model assumes explicitly that the alternative development approaches at each stage are probabilistically independent of each other. In other words, there is no commonality across different development approaches. This may not be true in all applications. It is possible that one or more common obstacles may exist across different development approaches, and that those need to be resolved before any approach could be successful. As a result,

the outcomes of alternative development approaches will be positively correlated. One extreme example of such scenarios is the simultaneous support of multiple development teams using basically the same technology. One way to address this aspect is to model the probability of success p_1 as p_1/p_c, in which p_c is the probability of overcoming a common obstacle presented in all approaches (see Appendix A[1]). We found that the insights from the basic model still hold in this more general environment. Furthermore, we have also examined the impact of the correlated approaches on the pipeline structure. The optimal number of approaches at Stage 1 will decrease as the (positive) correlation becomes stronger. The above result holds, at least when the correlation is high, for any stage k ($k \geq 2$). Of course, other possibilities exist to model the scenario in which the development approaches are correlated.

Extension 3: Products Are Not Identical (Differentiation)

The basic model assumes products are identical, and the business opportunity will be captured by a single successful product. In other situations, the final products may not be identical, and the actual outcome may be more complicated. For example, more than one successful product may be launched by a firm to capture multiple niche markets. Alternatively, a firm may still launch a single product, but each successful product may have different market potentials (different side effects of a drug, for example) that become clear only after the last NPD stage, and the one with the best market potential will be launched. Both scenarios can be easily accommodated by revising the formulation of the Stage 0 (launch) model. Instead of assuming all products are equivalent, we could formulate probabilistically the payoff at Stage 0 as an extreme value problem, with the payoff of a successful product following a specific probability distribution function. As a result, having more successful products is likely to generate more profit for a firm. This problem has the well-known characteristic of concavity under the most commonly used probability distribution function. Hence, Proposition 1 remains valid. The model could also accommodate the scenario in which there are two levels of payoffs for a particular NPD project. We have essentially set the low payoff to be zero in our analysis; conceptually, we could easily accommodate the situation where the low payoff is nonzero. Under this scenario, the low payoff is guaranteed as long as one development approach is funded at all stages, and the high payoff requires the development of, for example, additional product attributes whose success is stochastic at each stage. The insights under this scenario, however, remain the same.

Extension 4: Certain NPD Stages May Be Repeated

The basic model assumes that delayed time to market due to repeating an NPD stage will render the business opportunity unprofitable and thus managers will drop the project altogether if no approach survives an NPD stage. This is true for most new drug development projects mainly due to competition and, to a certain extent, patent expiration if no new approaches (patents) are available. Under certain conditions, however, it might be worthwhile to repeat one or more NPD stages. This is true especially when there are no competitors or competitors are far behind, and the business opportunity is not expected to dwindle too much due to the time delay. To make the model applicable to these situations, we have examined the scenarios in which delayed time to market will generate less profit and managers will consider repeating an NPD stage if no approach survives that stage. Instead of a linear three-stage NPD process used in our basic model, the customized process will more look like a tree structure in which the process, when stalled in the original branch (failed all alternatives), is allowed to branch out to a previous stage.

The general approach in this situation is the following: (1) optimize the latest possible NPD repetition first; (2) downstream only the NPD stage repetition that will affect current stage optimization; and (3) optimize only the stage in which repetition is allowed and needs to be modified. It will, in general, involve simultaneous optimization of the total number needed and the optimal division between the original branch and the repeat branch.

The end of planning horizon (last profitable repeat) could be identified when the expected return allowing this repeat equals the expected return disallowing

this repeat. Our analysis indicates that the optimal pipeline will become wider (larger optimal parallel approaches) prior to the branch, while the pipeline remains the same, compared with the no repetition scenario, once the development passes the branching point.

Finally, other possibilities for further research include incorporating calendar time into the model and allowing managers to "crash" a development stage by increasing the amount of resources available for each approach; endogenize the number of stages for a particular NPD project, and incorporate learning into the process, allowing for information updating.

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