Strategic Flexibility, Real Options, 

and

Product-Based Strategy

by

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ABSTRACT

This thesis proposes and undertakes to provide a theoretical foundation for the notion that there exists an optimal strategic flexibility which a value-maximizing firm will seek to acquire when competing in product markets characterized by uncertainty about technological outcomes and market preferences.

A central proposition of this thesis is that a firm's strategic flexibility can be exhaustively defined by certain basic types of choices a firm can make and that these basic choices can be characterized as generic real options which can be valued analytically. An options theoretic framework is developed for valuing some critical choices which a firm might make in setting its strategy for developing and producing new products. This exercise leads to several insights into possible optimal (i.e., value-maximizing) product development strategies based on design modularity in components, on designing new products as platforms for change, and on engineering design regimes which allow a potentially large number of new models to be leveraged from a common system design. The product design and engineering skills on which these product strategies are based are then asserted to be critical core competencies which a firm can use to generate valuable new product options and thereby to achieve significant competitive advantage in dynamic product markets.

When product markets are characterized by uncertain technological outcomes and market preferences, the strategic flexibility/real options framework developed in this thesis is suggested as a means of illuminating the economic value which can be created by a firm which possesses these core competencies in product design and engineering. This thesis concludes by relating the strategic flexibility/real options framework for firm strategy developed in this thesis to other theoretical frameworks for formulating competitive strategy currently being used in the field.

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Any researcher's efforts to add some measure of new knowledge, however modest, inevitably draws on the work of many others who have dedicated themselves to the search for greater understanding. To the doctoral student, the members of his or her thesis committee become the embodiment of the state of human understanding in a given area of inquiry. To a great extent, therefore, the eventual success or failure of the student in saying anything new and interesting depends on the skills of the thesis committee members in guiding the novice researcher to an approach to research in which his or her abilities can most productively be applied. For their wisdom and patience in guiding me to an approach in which my interests and intuition could most fruitfully mesh with the rigor of theory, I am truly grateful and indebted to my thesis committee members.

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Introduction

1. The Objectives of This Research

For both practitioners and researchers in strategic management, the salient characteristic of a growing number of important markets for products and services is a high degree of uncertainty about future technological developments and market preferences. From automobiles to computers, from financial services to telecommunications, quickening technological change and shifting market needs are making it increasingly difficult to predict with any real confidence what "bundles" of product features and performance levels customers will value most in the future. Uncertainties about appropriate technologies and market preferences in the future raise fundamental strategic questions about the core competencies which a firm must have to be competitive in the long term and about how the firm should be organized to compete in various product markets. As more markets become technologically dynamic and as market preferences become more volatile, a growing challenge to both theorists and practitioners in strategy is to develop a coherent theoretical framework for formulating competitive strategy in the face of significant technological and market uncertainty.

As technological and market uncertainty has increased, both theorists and practitioners have begun to advocate that firms try to manage uncertainty by developing strategic flexibility, a concept which usually denotes some capability of the firm to respond advantageously to uncertain future events. The discussion about strategic flexibility in the strategy literature to date, however, has remained largely contextual. In a typical case, the uncertainties in a specific situation are studied and alleged to require some specific form of flexible response to maintain the strategic position of the firm in the future. The prescriptions for strategic flexibility thus obtained are inevitably idiosyncratic or opportunistic and often do not transfer well from one context to another.

At the intuitive level, the appeal of "flexibility" as an appropriate response to future uncertainties is usually strong. Yet a rigorous and robust conceptualization of what strategic flexibility is appears to be lacking in the strategy field, and as a result efforts to operationalize strategic flexibility often
seem to lack a clear direction or the means to judge whether one possible form of flexibility is to be preferred to another.

One basic set of objectives of this research, therefore, is (1) to develop a better understanding of what strategic flexibility is in its essential features, (2) to propose a more structured conceptualization of strategic flexibility, and (3) to suggest how application of an options-based theory of strategic flexibility might improve a firm's ability to formulate product strategies in markets characterized by uncertainties about technologies and market preferences.

A second basic objective of this research is to build an argument for re-emphasizing the fundamental importance of products and therefore of product strategies in the overall competitive strategy of the firm. A perspective which has strongly influenced the framing of this thesis is the view that the ultimate source of the value of the firm is the creation and providing of products which are valued by the marketplace. Given this perspective, concerns about which strategic resources the firm should acquire and which organizational processes make for competitive advantage would logically be approached with basic regard to how given resources or processes would affect the ability of the firm to compete in specific product markets.

An important premise of this thesis is that the proper objective of the strategic managers of the firm is to maximize the value of the firm. The last part of this thesis therefore seeks to "close a conceptual loop" by linking the notions that strategic flexibility is the fundamental basis for strategy under uncertainty, that creating and selling products is the ultimate source of firm value, and that strategic managers ought to try to maximize the value of the firm. The conceptual loop is joined by proposing that the fundamental task of a firm's strategic managers is to understand and strengthen the capabilities and resources which give the firm the strategic flexibility to exploit uncertainty and change in its product markets. An important consequence of this conceptualization of firm strategy is that optimal strategies will be highly contextual and dependent on the particular possibilities for competing in specific product markets. This view of competitive strategy shares a theoretical perspective with what has come to be known as the resource-based theory of firm strategy, but adds to that theory by suggesting that the firm resources that matter fundamentally are those that give the firm the strategic
flexibility to compete in specific product markets.

2. Options Theory as the Economic Framework for This Research

The point of departure for this research is the premise that the objective of a firm's strategy is to devise a plan of action which, if carried out successfully, will maximize the value of the firm. Although the "value of the firm" is a concept which can clearly include non-monetary assets such as the firm's stock of human capital, its internal organization-specific skills, or its reputation with customers and suppliers, one would nevertheless expect any broadly applicable conceptualization in strategy to provide some framework for the economic valuation of the primary benefits to be expected from pursuing one strategic alternative in preference to another.

In the 1970s, the industrial organization framework for competitive analysis led to important insights into industry structures, basic generic kinds of competitive strategies, and the economic viability of alternative strategies for competing in an industry with given structural characteristics (Porter 1980 and Porter 1985). Underlying much of the industrial organization framework for strategy, however, is an implicit assumption that relevant technologies and market preferences are known with certainty or, at least, are fairly predictable. In the 1980s, however, the accelerating pace of technological change and the increasing transiency of market preferences weakened some of the underpinnings of the industrial organization framework, thereby diminishing much of its predictive power and undermining some of its basic prescriptions for competitive strategy. In view of the turbulence in technologies and markets expected in the 1990s and beyond, there is an evident need for an economic framework for formulating firm strategy which is viable in a context of significant technological, market, and other uncertainties.

Options theory, a revolutionary development in finance theory launched the early 1970s, provides a powerful method of analysis that differs significantly from much prior economic analysis in its ability to explicitly recognize and place a value on the flexibility to choose alternative courses of action in the future. Since strategic flexibility is essentially the ability of the firm to choose alternative actions at some time in the future, this research
undertakes to use options pricing models as the basis for the study and valuation of strategic flexibility and, by extension, for the determination of optimal (i.e., value-maximizing) strategies based on strategic flexibility.

Using options theory as the economic framework for the study of strategic flexibility leads to the following propositions made in this thesis:

- Strategic flexibility in its essential features is exhaustively defined by a limited number of basic kinds of choices a firm can have.
- These basic kinds of choices are described by eight generic real options.
- Given certain representations of uncertain future outcomes, these generic real options can be valued.
- Therefore, the search for the optimal strategy for the firm facing uncertainty becomes an effort to identify the value-maximizing set of real options the firm can acquire, and this value-maximizing set of real options constitutes the optimal strategic flexibility which the firm should strive to acquire.

These propositions are meant here to apply generally to strategy formulation in all the functional activities of the firm. Given the perspective of this thesis that a firm creates value by developing and providing products, this conceptualization of strategic flexibility is elaborated through a study of the ways in which a firm can maximize the value of its product development opportunities. Thus, the specific context for most of the analysis in this thesis is the role that various forms of strategic flexibility can play in shaping optimal product development and production strategies when a firm faces uncertainty about technological and market outcomes. Although strategic flexibility is studied here primarily in a context of product development, the general results of the options analysis are intended to extend readily to strategic issues in other functional areas of the firm, such as how the firm could maximize value in its marketing and distribution activities.

3. General Organization of This Thesis

This thesis is organized into four parts.

Part I introduces options theory and lays the groundwork for its application to product development strategy. Chapter 1 develops a definition of
strategic flexibility as consisting of three generic real options, and it defines an optimal strategy for a firm facing uncertainty as the plan of action that enables the firm to acquire the package of real options that will maximize the net present value of the firm.

Part II develops a real options analysis of product strategies. Chapter 2 develops a basic options model of product development opportunities that serves as the vehicle for analysis of product strategies throughout the thesis. Chapter 2 also shows how valuation methods that ignore flexibility systematically undervalue product development opportunities and can lead to suboptimal product development strategies. The chapter concludes with an application of the basic options model to an evaluation of the development of the Lockheed 1011 Tristar jetliner.

Part II then analyzes the generic real options that are the sources of the firm's strategic flexibility. Chapter 3 analyzes the initiative options which give the firm the strategic flexibility to produce new products in the future. The firm can extract initiative options from its set of product development opportunities by investing in development. Chapter 4 then investigates the timing options that give the firm the strategic flexibility to vary the timing of its initiative options to produce products. The chapter examines the factors which encourage "early exercise" of product initiative options and then values the options to wait to begin production, to abandon production, and to shut down production temporarily. Chapter 7 then discusses the implementation options that are the sources of the firm's strategic flexibility to choose the way in which it implements an initiative option.

Part III then explores the application of the real options analyses of Part II to product strategy formulation and implementation. Chapter 6 discusses a number of strategies for components design and shows how successful application of these strategies can contribute to the overall options value of a product development opportunity. Chapter 7 provides a real options evaluation of the strategy of designing a product as a "platform for change" from which later models can readily be derived. A product designed as a platform for change is characterized as having embedded options to create later versions of the product at reduced costs of development. Chapter 8 discusses the strategy of creating system designs from which a potentially large number of related
products can be leveraged. This approach to product design is characterized as one that proliferates low-cost options on a large number of product related models.

Part IV undertakes to link the concept of strategic flexibility introduced in Part I with the discussion of options value creation elaborated in Parts II and III. Chapter 9 develops a product-based statement of the options value of the firm and defines the task of strategic managers as managing the strategic flexibility value chain of the firm to optimize the real options value of the firm. Using the strategic flexibility value chain as a model for strategy formulation, Chapter 9 proposes that the primary tasks of a firm's strategic managers are to identify, acquire, and strengthen the strategic resources, capabilities, and core competencies which enable the firm to fully exploit new product opportunities. The firm's strategic managers must also search out and exploit synergistic linkages among the firm's existing capabilities and among its present capabilities and those it could acquire.

Chapter 10 relates the options-based, strategic flexibility framework for firm strategy developed in this thesis to three other frameworks for strategy formulation (competitive forces, strategic interaction, and resources-based/dynamic-capabilities).

A statement of conclusions then summarizes the primary findings and contributions of this thesis.
Part I

Strategic Flexibility
1. Strategic Flexibility, Generic Real Options, and Optimal Strategies

This chapter undertakes to clarify the fundamental role which real options analysis can play in discovering and evaluating alternative firm strategies in the face of significant uncertainty about technological and market outcomes. Section 1.1 defines a real option and summarizes the development of real options pricing models in the finance literature to date. Section 1.2 introduces the proposition that three basic kinds of real options -- referred to as generic real options -- constitute the basic sources of strategic flexibility available to a firm and therefore provide the means to value a firm's strategic flexibility. Section 1.3 then defines the optimal strategy of the firm as the plan of action to acquire the set of real options that maximizes the net present value of the firm. This value-maximizing set of real options is also identified as the optimal strategic flexibility for the firm to acquire. Section 1.4 provides a preliminary discussion of real options valuations and suggests how applying real options analysis to the evaluation of the firm's strategic alternatives can lead to the discovery of optimal strategies in various product markets. Section 1.5 comments generally on the use of real options analysis in strategy formulation and suggests that real options analysis can be usefully carried out for the three purposes of (a) determining the expected economic value of pursuing a given strategy, (b) investigating the dominance of one strategy over another, or (c) simply clarifying conceptually the forms that strategic flexibility might take in a variety of contexts.

1.1 Real Options

An option, in essence, is a right to choose whether or not to take some action now or at some future time. Broadly speaking, options can be classified into two types: financial options and real options. Financial options are rights to buy, sell, or exchange claims on traded financial securities like stocks or bonds. The first method for valuing a financial call option using only observable variables was developed by Black and Scholes in the early 1970s (Black and Scholes 1973). Subsequently, the methodology behind the Black-Scholes valuation formula for a European call option was formalized
by Merton (1973a) and has become the basis for an extensive literature in finance analyzing a growing variety of options and contingent claims on financial securities.

In 1977, Myers (1977a) first suggested that the market value of a firm consists of the present value of its expected cash flows (the traditional valuation basis in finance) plus the value of the firm's opportunities for growth, which Myers described as the firm's real options. Following on this insight, Baldwin, Mason, and Ruback (1983) recognized that a firm's growth opportunities may have varying degrees of flexibility associated with them; they termed as operating options the choices that determine the operational flexibility associated with each of the firm's opportunities for growth. More recently, the term real options has come generally to denote both the basic opportunities for growth as defined by Myers and the operating options noted by Baldwin, Mason, and Ruback. In this thesis, the term real options denotes both kinds of options.

Some researchers in capital budgeting theory have subsequently sought to apply options pricing models developed formally in the financial options literature to identifying and valuing some of the kinds of operating options that characterize the growth opportunities available to a firm. These options and their authors include:

- The option to abandon a project: Myers and Majd (1983).
- The option to shut down a project temporarily: McDonald and Siegal (1985); Majd and Pindyck (1987a).
- The option to wait to invest in a project: McDonald and Siegal (1986).

A number of authors have also applied options analysis to specific kinds of capital budgeting decisions. Among the areas of application and their authors are:

- Valuing flexible production systems: Kulatilaka (1986); Kulatilaka (1988b); Triantis and Hodder (1988); and He and Pindyck (1989).

Others writers have undertaken general expositions of the role of options theory as a basis for valuation in capital budgeting decisions. These writers include:
• Kester (1984); Mason and Merton (1985); Trigeorgis (1986); Kemna (1987); and Sick (1990).

In addition, the use of options analysis as a general basis for valuation of the flexibility typically available to managers in capital budgeting projects has been discussed by:
• Trigeorgis and Mason (1987) and Kulitilaka and Marcus (1988).

The primary focus of this real options literature has been on identifying various kinds of options inherent in capital budgeting scenarios and providing methodologies for valuing identified kinds of real options. Noticeably absent from the literature to date has been any effort to explicitly link options analysis to strategy formulation at a level beyond that of the individual capital budgeting project. One of the objectives of this thesis, therefore, is to articulate a clear conceptual linkage between real options valuations of strategic alternatives, on the one hand, and the formulation of optimal firm strategies in product markets, on the other.

1.2 Strategic Flexibility and Generic Real Options

As noted in the introduction to this thesis, strategic flexibility is said to exist when managers have the ability to choose among alternative actions, now or at some time in the future. A central argument developed in this thesis is that for firms facing significant uncertainty about future technologies and market preferences, the basic task of the firm's strategic managers is to lead the firm in identifying and acquiring the strategic flexibility it will need to pursue the course(s) of action that will be most appropriate under a range of uncertain future conditions.

Although much has been written about strategic flexibility in a variety of specific contexts, no attempt to define strategic flexibility theoretically or comprehensively has been offered in the literature. The effort made in this thesis to apply an options perspective to the notion of strategic flexibility, however, suggests that in its essential features strategic flexibility can be
reduced to certain fundamental kinds of choices a firm can make as to what strategic actions it will initiate, when it will undertake its strategic actions, and how it will implement its strategic actions.

From an options perspective, these three kinds of choices that make up a firm's strategic flexibility can be characterized as three basic kinds of generic real options, which are referred to hereafter as initiative options, timing options, and implementation options. In other words, from the real options perspective, strategic flexibility can be defined generally as consisting of:

(1) The strategic flexibility to choose a strategic action. When a firm can choose to initiate (or continue) a strategic action, it can be said to have an initiative option.

(2) The strategic flexibility to choose the timing of a strategic action. When a firm can choose when to begin, terminate, or shut down temporarily a strategic action, the firm can be said to have timing options associated with its initiative options.

(3) The strategic flexibility to choose how to implement any strategic action the firm may choose to initiate. When the firm can choose -- either wholly or in part -- the manner in which it implements a strategic action, the firm can be said to have implementation options associated with its initiative options.

In this thesis, which develops a product-based perspective on firm strategy, the ability of the firm to develop and produce products is characterized as being the ultimate source of the value of the firm, and the strategic flexibility of the firm is therefore viewed as being fundamentally defined by the choices the firm has with regard to products it can develop and produce. Thus, in the strategic flexibility framework developed in this thesis, the strategic actions that can give rise to initiative options are essentially the firm's efforts to develop and produce products. Timing and implementation options are then associated with specific product initiative options, and those operating options encompass all the possible forms of operating flexibility the firm has in deciding when and how to develop and produce products. The timing options associated with an initiative option define the ability of the firm to choose when to begin, terminate, or shut down development or production of a product. The implementation options associated with an initiative option define the choices the firm can make about how it develops
and produces products, including choices of technologies, capacity levels, interfirm arrangements for sourcing materials and components, product positioning, geographic markets, modes of distribution, requirements for human skills, etc.

The three kinds of generic real options that define a firm's strategic flexibility can, in principle, all be valued by options analysis. In determining the options value of a given "bundle" of initiative, timing, and implementation options that might make up any of the firm's strategic alternatives, each of the firm's generic real options can be decomposed into analytically distinct subcategories of generic real options for which options valuations methodologies have been developed. The analytically distinct subcategories which are included in each kind of generic real option and which are discussed in this thesis are as follows:

**Generic Real Options #1: Initiative Options**
(1a) Option to choose whether or not to produce a new product
(1b) Option to choose a single (most valuable) product to produce from among two or more alternative new products
(1c) Option to choose two or more (most valuable) products to produce from among multiple alternative new products

**Generic Real Options #2: Timing Options**
(2a) Option to wait to produce a product (inputs = 0 until some future time)
(2b) Option to shut down production temporarily (inputs = 0 during one or more future periods)
(2c) Option to abandon production of a product (inputs = 0 after some future time)

**Generic Real Options #3: Implementation Options**
(3a) Option to increase the demand for the output of the firm
(3b) Option to expand the supply of inputs available to the firm
(3c) Option to improve the efficiency of the processes of the firm
(3d) Option to change the output rate of the firm
(3e) Option to reduce the response time of the firm to changes in
technology or market preferences
(Other implementation options exist as well)

Some simple examples drawn in part from the discussion of product-based strategy in the following chapters of this thesis may help to illustrate how various kinds of choices that make up a firm's strategic flexibility can be described by each of these generic real options.

Generic Real Option #1a: Initiative option to choose whether or not to produce a new product. Suppose that a firm identifies an opportunity to develop a new product. Developing the new product would give the firm the flexibility to choose whether or not to produce the new product in the future. Having the initiative option to choose whether or not to produce a newly developed product would be a source of strategic flexibility for the firm in the future.

Generic Real Option #1b: Initiative option to choose a single (most valuable) product to produce from among two or more alternative new products. Suppose a firm is constrained to produce only one new product at a time and has to decide now whether it should develop more than one new product. Developing more than one new product would give the firm the flexibility to choose in the future which one (if any) among alternative new products it will produce. Having the initiative option to choose the single best of several possible new products to produce in the future would be a source of strategic flexibility.

Generic Real Option #1c: Initiative option to choose two or more (most valuable) products to produce from among multiple alternative new products. Suppose a firm is constrained to produce a limited number of products and has to decide now how many new products it should develop. Developing more products than the firm can actually produce in the future would give the firm the flexibility to choose the most desirable mix of products in the future, up to the limit of its production capacity. Having the initiative option to choose the most valuable set of new products from among many developed products in the future would be a source of strategic flexibility for the firm.
Generic Real Option #2a: Timing option to wait to produce a product.
Suppose a firm has developed a new product and has to decide whether to produce it now or to wait before bringing the product to market. If putting the product into production requires incurring non-recoverable costs (for example, for production capacity or advertising) and if demand is not adequate for the new product now but future demand is uncertain, having the option to wait would give the firm the flexibility to delay making irreversible investments while it waits to see if demand will improve. The timing option to wait to produce a new product can be a source of strategic flexibility.

Generic Real Option #2b: Timing option to shut down temporarily production of a product. Suppose a firm has developed a new product for which demand is uncertain and must decide whether to seek long-term or short-term contracts with its suppliers. Short-term subcontracting would give the firm the flexibility to shut down production at low cost if demand proves inadequate in the future and then to resume production later if demand improves. In this case, short-term contracting would bring with it a timing option to shut down temporarily at low cost which can be a source of strategic flexibility for the firm.

Generic Real Option #2c: Timing option to abandon production of a product. Suppose a firm has developed a new product and can choose between two production technologies: a dedicated production system with no other uses, or a flexible production system which could readily be switched to the production of other products. If demand for the new product falls in the future, the ability to switch the flexible production system to other uses would give the firm the strategic flexibility to abandon production of the new product if future demand proves inadequate. In this case, choosing the flexible production system would give the firm a potentially valuable timing option to abandon production which could be an important source of strategic flexibility.

Generic Real Option #3c: Implementation option to reduce the response time of the firm to changes in demand. Suppose the firm and its competitor firms have identified a change in technology or market needs which creates a new product opportunity, and each firm has decided to develop its version of
the new product. As the firms successively introduce their new products in the future, prices are expected eventually to fall to a competitive, economically profitless level. If the firm can create a faster development process or a faster way of tooling up to begin production, the firm could acquire the flexibility to respond more quickly to new product opportunities, and it may be able to capture some monopoly rents by being among the first companies to bring a new product to the marketplace. In this case, achieving faster development or tooling up capabilities would give the firm an implementation option which could be a valuable source of strategic flexibility to bring new products to market quickly.

Like the examples above, some of the choices which make up a firm's strategic flexibility in a real situation may be described well by a single generic real option and one or two associated timing or implementation options. Generally, however, the strategic flexibilities implicit in a firm's real strategic alternatives are likely to be considerably more complex than these simple examples. Yet careful analysis of complex strategic alternatives should show that their apparent complexity can be decomposed into choices among multiple initiative options, and although each of these initiative options may have several associated timing and implementation options, these too can in principle be valued. In other cases, the firm's real options may be interdependent with other generic real options; fortunately, options that are dependent on other options can also be analyzed and valued. Thus, the apparent complexity of strategic flexibility in real situations should not be a bar to fruitful options analysis, although some simplifications which reduce the complexity of real strategic decisions will no doubt be useful and appropriate in many situations.

As proposed above, the three generic real options are the sources of the strategic flexibility available to a firm in responding to the technological, market, and other uncertainties in its competitive environment, and all of these generic real options can, in principle, be valued by options analysis. If the strategic flexibility available to a firm is in fact reducible to these generic real options, and if all of these generic real options can be valued by options analysis, then real options analysis ought to provide both a framework for understanding strategic flexibility and an analytic methodology for valuation
of the various forms of strategic flexibility that may distinguish the strategic alternatives available to a firm. Given a framework for identifying the components of strategic flexibility and a method for valuing strategic flexibility, it becomes possible for the firm's strategic managers to determine what kind of and how much strategic flexibility the value-maximizing firm should seek to acquire in a given situation. The next section discusses the economic rationale for determining how much strategic flexibility the firm ought to acquire in a given situation.

1.3 Optimal Strategic Flexibility

If acquiring strategic flexibility were costless, any rational manager facing uncertainty would seek to acquire every bit of strategic flexibility the firm could possibly use in responding to uncertain future events. Just as financial options can only be obtained for a price, however, acquiring the real options that are the source of a firm's strategic flexibility almost invariably entails some real cost to the firm. A firm can only acquire the strategic flexibility to choose whether or not to produce a new product, for example, by paying the costs of developing the product and acquiring the initiative option to produce the product.

Since the real options that are the sources of strategic flexibility have both a value and a cost of acquisition, one can expect that in some cases the economic benefits of the strategic flexibility conferred by a given bundle of real options will exceed their cost of acquisition, and in other cases the acquisition costs may exceed the benefits. Acquiring strategic flexibility that confers a total economic benefit greater than its cost of acquisition will add to the net present value of the firm, while acquiring strategic flexibility whose economic benefit is less than its cost of acquisition would decrease the value of the firm.

A basic premise of this thesis is that the objective of a firm's strategy is to maximize the economic value of the firm, and therefore that the optimal strategy for a firm is the plan of action which will maximize the net present value of the firm. In terms of strategic flexibility, the optimal strategy for the firm is to acquire the set of real options that has the greatest positive excess of economic benefits over cost of acquisition -- i.e., the set of real options that
will maximize the net present value of the firm. Thus, in any given situation there will be an optimal strategic flexibility for the firm -- which is exactly the strategic flexibility conferred on the firm by its value-maximizing set of real options. It is important to note that the firm's optimal strategic flexibility is not likely to be the maximum strategic flexibility the firm could acquire, since the cost of acquiring "maximum" strategic flexibility would be unbounded. The fundamental task of the firm's strategic managers, therefore, is to correctly determine the set of real options that would maximize the value of the firm and to plan for the creation or acquisition of the firm's optimal strategic flexibility defined by the value-maximizing set of real options -- no more, no less.

In order to determine which "bundle" of real options will contribute most to the net present value of the firm, managers must have the means to value the generic real options that are the sources of the firm's strategic flexibility. The following section presents a simplified explanation of the basic methodology for valuing real options. (Valuation methods for the various subcategories of the three kinds of generic real options are presented in more detail in Part II of this thesis.) The section also raises two important implications of real options valuations for optimal firm strategies.

1.4 Real Options Valuations and Optimal Firm Strategy

That the generic real options that make up strategic flexibility have real economic value can readily be demonstrated by two simple examples.

First, consider the case of a firm evaluating two alternative approaches (Projects A and B) to producing a new product P for which demand is uncertain, as shown in Figure 1.1. In Project A, construction of the plant to produce P starts at time $t_0$ and ends at $t_1$, and the firm would implement its production of P in such a way that it must commit to producing new product P in the plant from $t_1$ to $t_2$. In Project B, construction of the plant also starts at time $t_0$ and ends at $t_1$, but the firm retains its flexibility to decide at $t_1$ whether or not to produce the new product P in the plant from $t_1$ to $t_2$. In other words, in Project A the firm takes on an obligation to produce a new product P regardless of demand for the product once the plant is built. (In
this regard, Project A mirrors a key assumption of project valuation by conventional discounted cash flow analysis.) In Project B, on the other hand, the firm retains its initiative option to produce (or not produce) \( P \) at \( t_1 \). Because demand for the new product is uncertain, the price which the firm will get for product \( P \) during the period \( t_1 \) to \( t_2 \) is uncertain, so that the price may or may not exceed the unit cost of production. Thus, under Project A the firm must run the plant whether it makes or loses money, but under Project B the firm can avoid incurring losses by simply declining to produce \( P \) at \( t_1 \) if price is less than unit cost.

Clearly, if the firm is free to choose which project to take, it will choose Project B every time, because the initiative option inherent in Project B gives the firm an important source of strategic flexibility at \( t_1 \). Since the firm will always prefer Project B over Project A, it must be the case that Project B has greater economic value than Project A. The difference in the values of the two projects to the firm, in fact, is exactly the value of the strategic flexibility inherent in Project B's option to choose whether or not to initiate production of new product \( P \) at \( t_1 \).

Now consider the case of a firm trying to decide on a strategy for new product development. Suppose the firm is trying to decide whether to "place all its bets" on developing the currently most promising single new product (Project C) or to "hedge its bets" by developing more than one new product (Project D), as shown in Figure 1.2. To make the problem more interesting, suppose that the firm is constrained by its production capacity to produce only one newly developed product from \( t_1 \) to \( t_2 \). If the future value of each new product which the firm could develop is uncertain, the value-maximizing firm would clearly prefer to be in the position of choosing which one of several new products to produce at \( t_1 \), because then it could select the single product with the greatest value to produce with its limited production capacity. Since Project D would give the firm more initiative options at \( t_1 \) than Project C, selecting Project D would give the firm greater strategic flexibility to capture the greatest possible value from its production activity in the
The foregoing examples should make clear that the real options that are the source of a firm's strategic flexibility have real economic value. The question is, how much are those real options -- and the strategic flexibility they confer -- actually worth? Because strategic flexibility can only be obtained at some cost, it is essential to be able to value the real options that make up a given strategic alternative in order to determine which alternative offers the optimal (i.e., the value-maximizing) strategic flexibility. For example, in comparing Project D to Project C, we must remember that it will no doubt cost the firm more to develop several new products than to develop just one. Whether or not Project D, which gives the firm more strategic flexibility at \( t_1 \), is in fact preferable to Project C depends on which project has the greater excess of expected economic benefit over costs at \( t_0 \) -- i.e., on which project has the greater net present value. The difference in the net present values of the two projects at \( t_0 \) is the difference between the value of Project C's initiative option to produce a single new product, less its cost of development, and Project D's initiative option to choose the single most valuable product among two or more newly developed products, less their total costs of development. Thus, the value at \( t_0 \) of the strategic flexibility which each development strategy brings to the firm is given by the options-determined net present value of each strategy at \( t_0 \), and the optimal strategy for the firm is to choose the value-maximizing strategic flexibility conferred by the development strategy with the greatest net present value.

One approach to placing an economic value on the real options that constitute strategic flexibility might be simply to ask the managers of a firm how much they would be willing to pay for some specific form of strategic flexibility -- for example, for Project B's initiative option to produce new product P (Figure 1.1). Since traditional capital budgeting techniques typically ignore real options and thus have not provided managers with the tools they need to value an option like this analytically, it is unlikely that most managers would be able to calculate an exact dollar value for this option. More than likely, the managers would try intuitively to value the
flexibility of Project B compared to Project A; they would probably make a few discounted cash flow calculations for a few "most likely" (and deterministic) scenarios, and finally arrive by consensus at some amount the firm would be willing to pay to have the greater flexibility of Project B.

Such intuitive valuations of the real options that are the sources of strategic flexibility are no doubt made thousands of times a day by managers in a great variety of contexts. These intuitive valuations of real options have one advantage and one disadvantage relative to more formal options analysis. Their advantage is that they can simultaneously consider -- or try to consider -- a large number of relevant factors that may be both individually complex and subtly interrelated. Their disadvantage is that, given any set of assumptions about relevant factors and their interrelatedness, managers' purely intuitive determinations of the economic values of reals option are likely to be imprecise at best and could well be grossly in error.

To carry out a more explicit analysis of the value of a real option, it is necessary to adopt certain representations of a real situation as inputs to an options valuation model, and we need to make some basic assumptions about financial markets. The assumptions about financial markets are discussed in Chapter 2, but two important representations of real situations incorporated into options models are discussed in general terms here. First, we have to be able to identify the set of possible future choices which a firm could make in a given situation and then to order them temporally, as shown for example in Figure 1.1. This temporal ordering of decision points (including decisions whether to exercise options or let them lapse) will be referred to hereafter as a contingency structure. Second, we have to represent the future uncertainties that the firm will face at each decision point by some form of time-dependent probability distribution. In the simplest cases, these distributions might consist of discrete probabilities; for example, the firm's managers might believe that they have a 60-40 chance of obtaining a fixed price contract for a new product in the future. More commonly, however, uncertain future outcomes are likely to be better represented by some kind of continuous probability distribution, such as the lognormal distributions of uncertain future values of the opportunity to produce a new product shown in Figure 1.3 and Figure 1.4.
Given some basic assumptions about financial markets and these representations of future contingencies and uncertainties, we can determine an "exact" value for a real option. Of course, the "exact" value calculated for a real option will probably never be the true exact value of the real option. Because the inputs to an options valuation model are inevitably approximate representations of present situations and estimates of future uncertain outcomes, the output from an options valuation model will never be more than a rigorously derived estimate of the true value of the real option. However, for any given set of representations and approximations which constitute managers' beliefs about a real situation, an options valuation model will give an analytically correct value for a real option which almost assuredly will be more accurate than a manager's purely intuitive estimate of the value of the real option. The greater reliability of explicit analytic valuations of real options over intuitive valuations is likely to become more pronounced with increasing complexity and interdependency of the firm's available real options.

The present value of a real option is based on the expectation of the future value of a real option, which is portrayed graphically in Figure 1.3 and Figure 1.4. The distribution of future values at \( t_1 \) of Project B to produce new product \( P \) (see Figure 1.1) is represented by the distribution shown in Figure 1.3. In this case, the value of the initiative option to produce new product \( P \) at \( t_1 \) is derived from the expectation of the value of the positive-value portion of the distribution (shaded area), conditional on future revenues from the project turning out to be greater than total costs of producing the product. Note that even though the future project value may lie anywhere on the distribution including the negative value outcomes, only the positive-value area (to the right of the vertical axis) is used to determine the value of the option to produce \( P \), because the firm has the option to decline to produce new product \( P \) at \( t_1 \) if the expected revenue from selling \( P \) turns out to be less than \( P \)'s costs of production. In other words, a real option like Project B's initiative option to produce \( P \) gives the firm the strategic flexibility to avoid proceeding with a money-losing project once the eventual value of producing product \( P \) is discovered in the future.
This feature of the value of a real option has an important implication for firm strategy. Since an option is a right -- but not the obligation -- to take some action in the future, the strategic flexibility the firm derives from its real options essentially allows the firm's managers to intervene in future outcomes and, in effect, to alter future distributions of uncertain outcomes in favor of the firm by truncating undesirable (i.e., negative value) outcomes. As will be shown later in this thesis, options analysis provides the methodology for valuing the asymmetric, "truncated" distributions of uncertain outcomes that result when managers have the strategic flexibility to influence future outcomes.

Another feature of options valuations that has important implications for firm strategy is illustrated by the following example. Suppose the firm is considering which of two potential products to develop. For either product, the firm will have the option at $t_1$ to choose whether or not to produce the developed product. The uncertain future values of producing the two products are represented by the two probability distributions shown in the Figure 1.4. Product A is a relatively "low-risk" product in that its uncertain future revenues are thought to be fairly tightly distributed around an expected total revenue which is greater than the future total cost of manufacture. Product B, by contrast, is a riskier product in that its future revenues are thought to be broadly distributed around an expected total revenue which, in this example, is lower than the future cost of manufacture. Traditional discounted cash flow analysis, which typically ignores the option to choose not to produce the developed product, would determine that at $t_0$ developing Product A has a greater net present value than producing Product B (all other things being equal). An options analysis might determine, however, that developing Product B could have a greater value to the firm at $t_0$ than developing Product A, because there is a greater likelihood that Product B could generate a very large revenue stream at $t_1$ compared to Product A, while the worst case scenario for both products is that the value of the opportunity to produce either product at $t_1$ would equal zero, since the firm has the option to choose not to produce either developed
product at $t_1$ if revenues would be less than costs. Thus, an options analysis, which compares the expectations of only the positive portions of the distributions of future values of each product (i.e., the area to the right of the manufacturing costs in the distributions in Figure 1.4) might show that the expectation of the future value of the option to produce Product B would be greater than that of Product A. In that case, if the costs of developing either product were equal, options analysis would determine that the optimal strategy would be to develop the riskier product.

This example leads to a second important insight which characteristically emerges from a real options analysis. Because having real options gives the firm the ability to avoid or "truncate" negative-value outcomes in the future, building strategic flexibility (in the form of real options) into the firm's plans for the future can limit the losses the firm might incur by following a seemingly "high-risk" strategy -- like developing Product B -- but leaves intact the potentially significant upside value of that strategy. Because having real options gives the firm the flexibility to capture potential future gains while avoiding potential future losses, real options have the strategically important general property that the greater the uncertainty the firm faces, the more valuable are its real options. Thus, the greater the uncertainty the firm faces in its product markets, the more essential it becomes to base the firm's strategy on the acquisition of the right (i.e., value-maximizing) real options for the future, and the more imperative it becomes for the firm's strategic managers to be able correctly to identify and to optimize the real options available to the firm.

Later chapters of this thesis will suggest that when competitive strategies in some selected dynamic product markets are examined through the strategic flexibility lens of real options analysis, significant systematic differences in the relative options values of strategic flexibilities conferred by alternative product-based strategies become apparent. These systematic differences in real options values suggest that in product markets with dynamic technologies and uncertain market preferences, some specific product-based strategies will be more likely than others to optimize a firm's strategic flexibility, to consistently create greater value for the firm, and
therefore to contribute significantly to the firm's long-term competitive success in the product markets in which it participates. Part III of this thesis applies real options analysis to selected product strategies for manufactured products in dynamic markets in an effort to identify the specific features of product-based strategies that appear capable of systematically optimizing strategic flexibility in each product market.

Part IV then suggests that the essence of the strategic manager's task in product markets with dynamic technologies and market preferences is to manage the firm's strategic flexibility value chain, illustrated in simplified form in Figure 1.5. (A more complete model of the strategic flexibility value chain is developed in Chapter 9.) The strategic flexibility value chain is the process by which the firm generates and optimizes its initiative, timing, and implementation options to develop and produce products. It therefore represents the fundamental process by which the firm creates value in the product markets in which the firm participates. To manage a firm's strategic flexibility value chain, a firm's strategic managers must be able to identify, assess, and lead the firm in acquiring the core competencies and strategic capabilities and assets (termed the strategic core of the firm in this thesis) that can generate and optimize the firm's real options in its product markets. In applying real options analysis to selected product markets, Chapter 9 also identifies some core competencies and strategic capabilities and assets which appear to constitute the strategic core of product-based strategies that are likely to optimize strategic flexibility in the selected product markets.

1.5 Uses of Real Options Analysis in Strategy Formulation

Real options analysis may be used in strategy formulation to determine exact values of specific real options, to establish the possible dominance of one set of real options over another across a range of future scenarios, or as a conceptual tool for improving a firm's understanding of its sources of strategic flexibility. As noted earlier, when the diverse strategic choices which collectively make up the strategic flexibility of the firm are explicitly valued as real options, the reliability of the valuations obtained will depend on how well the significant aspects of real situations have been captured by the
representations used as inputs to the options valuations models. Clearly, since any valuation model is inevitably an abstraction, applying any options valuation to a real strategic decision will almost always exclude some of the complexities and subtleties of a real situation. However, in complex situations discerning even relative real options values of strategic alternatives (much less their absolute values) may not be possible by intuition alone. In such cases, even the magnitudes of the real options values of alternative strategies may only be discernible by a careful, methodical application of options analysis.

In some situations, there may be significant uncertainty even about the uncertainties which the firm faces, and it might be quite unreasonable to try to represent all the uncertainty in the firm's future by a single contingency structure or probability distribution. In such cases, options analysis can be used to compare the values of alternative strategies under different contingency structures, under different probability distributions of uncertain future outcomes, or under other conditions. This type of comparison may be able to establish that one bundle of real options that define a given form of strategic flexibility stochastically dominates others -- that is, has a greater net present value than others -- either in all cases or perhaps only in specific cases. When one bundle of real options is not clearly superior to all others in all cases, stochastic dominance analysis can help to establish under what conditions one form of strategic flexibility may be preferred to others.

Even in cases where the complexity and fundamental uncertainties of real situations make it difficult to identify contingency structures or to represent future outcomes as time-dependent distributions with any real confidence, it is still useful to look for the kinds of real options that might be generated by pursuing different courses of action available to the firm. For example, in evaluating alternative strategies in basic research, the effort to identify real options -- even at the conceptual level -- that might be generated in different areas of basic research may shed much light on the relative attractiveness of the strategic flexibility that progress in each area of basic research might bring to the firm.
Firm must commit to building plant and to production

Project A

Firm must commit to building plant but has option to abandon plant at $t = t_1$

Project B

Construction Period

|$t_0$| $t_1$ | $t_2$

Production Period

Figure 1.1: Two Projects for Producing a New Product

Firm "places all its bets" on developing a single new product

Project C

Firm "hedges its bets" by developing multiple new products and has option to choose most profitable product at $t = t_1$

Project D

Development Period

|$t_0$| $t_1$ | $t_2$

Production Period

Figure 1.2: Two Strategies for Developing Products
Figure 1.3: Distribution of Uncertain Future Value of Producing Product P

Figure 1.4: Distributions of Uncertain Future Values for Two Product Opportunities
Investing Cash Flows from Producing Products

Strategic Core Competencies

Strategic Capabilities and Assets

Opportunities to Develop New Products

Real Options to Produce Products

Learning From Developing and Producing Products

Figure 1.5: The Strategic Flexibility Value Chain
Part II

Real Options
2. A Real Options Model of Product Development

To study the ways in which real options analysis can contribute to devising effective product strategies under conditions of uncertainty about technologies and markets, it will be useful to build a simple options model of the product development process which incorporates both the major decisions which firms must make in the development process and representations of the uncertainty which firms face in selecting new products to develop and produce. This section develops a basic model which will be used initially to illustrate how a product development opportunity can be viewed as a potential initiative option to produce a new product in the future. For simplicity, the basic model developed in this chapter ignores any possible constraints on firm resources and all timing and implementation options, but the basic model is extended in following chapters to include constraint conditions and important operating options. In addition, all options analysis in this thesis ignores inflation, taxes, and the possible effects of a project's financial structure on the project's value.

The basic premise of the options model developed here is that the firm creates a future production option by investing in developing a new product. The basic uncertainty which the firm faces is uncertainty about the value of the revenue stream which the new product will generate in the future if it is produced and sold by the firm. Again for simplicity, development and production costs are assumed to be known with certainty. The model also introduces the notion that there are essentially three competitive contexts to which newly developed products can be exposed. Each competitive context describes a characteristic competitive environment which affects the future value of a newly developed product.

Since the flexibility which options bring to a firm's managers have real value, any valuation method which ignores real options in a development project will lead a firm to systematically undervalue product development opportunities and thus to underinvest in product development. To demonstrate this systematic bias, a conventional "no-option" discounted cash flow valuation is compared analytically to a (theoretically correct) options valuation of a product development opportunity.

Finally, to illustrate how the basic options model of product development
opportunities can be applied to specific development decisions, Lockheed Corporation's decision in the spring of 1968 to develop the Lockheed 1011 Tristar jumbo jet is re-evaluated as a simple initiative option by applying the basic options model of this chapter. The Lockheed 1011 example in this chapter also provides the basis for later examples illustrating the value of some timing and implementation options.

The basic model of product development described in this chapter provides a framework for determining the options values of simplified characterizations of product development opportunities. The basic model thus provides a point of departure for investigating how alternative product strategies could affect the value of product development opportunities available to the firm. To investigate how options values might be determined in more varied product development situations, following chapters elaborate options analyses which can be used to value more complex initiative, timing, and implementation options. Chapter 3 investigates how initiative options can be valued and selected under different resource constraint conditions the firm is likely to face and under different approaches the firm might apply to managing the product development process. Chapter 4 then investigates the valuation of timing options to wait, shut down, or abandon, and Chapter 5 discusses the valuation of certain implementation options.

2.1 The Basic Model

At any given time, a firm will possess a finite "opportunity set" of product development possibilities which includes all the new product concepts which the firm is capable of imagining for any markets in which the firm competes now or in which it could compete in the future. The size and make-up of the firm's opportunity set will be determined by the firm's technological, manufacturing, marketing, and other capabilities and by its knowledge of market needs which could be served by products which the firm could provide. In the basic model developed here, the contingency structure faced by the firm consists of two decisions. First, the firm must choose which products, if any, in its opportunity set it will actually develop. (In this model, the terms develop and development are taken to include all the activities associated with
defining, designing, engineering, prototyping, and proving a new product.) Second, after completing development of a new product, the firm must decide whether or not to produce and sell the new product. For simplicity, in the basic model the firm must decide at \( t = 0 \) whether or not to develop a new product; if the firm does not begin development of a given new product at \( t = 0 \), it is assumed to lose the opportunity to do so. Similarly, the firm must decide on completing development at \( t = t^* \) whether to produce or abandon the new product. These decision points in the product development process are shown in Figure 2-1.

In Figure 2-1, at some point in time \( t = 0 \), a firm evaluates its opportunity set of \( N \) new product concepts and decides whether or not to invest in developing one or more new products, \( P_i \ldots P_N \). If it decides to develop a new product, the firm must invest development funds over a development period \( T_D \) (\( 0 \leq t \leq t^* \)). On completing the development of a new product \( P_i \) at \( t = t^* \), the firm must decide whether to produce and sell the newly developed product. In this basic model, if the firm decides to produce a new product \( P_i \), the firm can begin production instantaneously and will irreversibly commit to produce a total of \( Q \) units of a new product during the period of production and sales \( T_P \) (\( t^* \leq t \leq t_P \)). \( Q \) is assumed to be the firm's profit-maximizing quantity, but how the firm determines this quantity is exogenous to the present model. The rate of production is assumed to be constant at \( Q/T_P \) over the period of production \( T_P \).

The development costs which the firm will incur may include both initial start-up costs and periodic expenditures throughout the development period, but both kinds of development costs are assumed to be known with certainty and represented in this basic model by \( C_D \), the present value at time \( t = 0 \) of the total development costs for a new product. The firm is also assumed to be able to determine with certainty the cost \( c_{p,i} \) of producing one unit of the new product during the production period \( T_P \). In the model developed here, \( c_{p,i} \) is determined jointly with \( Q \) when the firm (exogenously) determines its profit.
maximizing production quantity, and is assumed to be a constant over the production period $T_p$. Since $Q$ units are produced at invariant rate $Q/T_p$ and cost $c_{p,i}$ during the production period $T_p$, the firm can also determine $C_p$, the present value at $t = t^*$ of the total (certain) production costs to be incurred once the firm begins producing a new product.

2.2 Characterization of Uncertainty

Some models of product innovation take the outcomes of investments in product development to be uncertain as to both the timing and the value of the outcome. The source of uncertainty in the product development processes studied here, however, is limited to the uncertain value of a new product when, after undergoing a significant period of time in development, the product is produced and sold during the term of production $T_p$.

There are two reasons why uncertainty about the time duration of development is not included in this model. First, unlike basic research in which the timing of discoveries is fundamentally uncertain, the development of a new product (other than a truly radical new product innovation) often has fairly well understood time requirements for any given firm. Thus, taking development times to be certain should involve no significant loss of realism for a broad spectrum of product development cases. Second, in many product markets firms are now focussing on improving the management of their development activities and are trying to use shortened development times to gain competitive advantage. Treating required development time as a control variable will allow the options analysis presented in later chapters to focus more clearly on development time as a strategic variable to be managed by the firm.

Since all costs associated with developing and producing a new product are assumed to be known with certainty in this model, the uncertainty about the value of a newly developed product derives from the uncertain revenue stream which will be generated by the sale of the new product during the term of production $T_p$. Further, since the total production quantity $Q$ and the constant rate of production $Q/T_p$ are also assumed to be known, the uncertainty about
the value of a new product in this model reduces to uncertainty about the (observable) random variable price $p_{i,t}$ which the market will pay for each unit of new product $P_i$ during the term of production and sale. In this model, price uncertainty exists from the inception of development at $t = 0$ until production and sale ceases at $t = T_f$. The random variable price $p_{i,t}$ is assumed here to follow a Markov diffusion process (random walk), with the result that the revenue stream generated by the sale of a new product also follows a Markov diffusion process, as illustrated in Figure 2-1.

As in conventional discounted cash flow valuation, real options analysis begins with certain assumptions about the time-dependent distributions of an asset's uncertain market value in the future. Under those assumptions, both expected and unanticipated changes in an asset's market value are specified. When both expected and unanticipated changes in the asset's future distributions are specified, the dynamics of moment-to-moment movements in the market value of the risky asset are also implicitly specified. In the model developed here, therefore, both the time-dependent distributions of future market values of the product and thus the dynamics of the evolution of the market value of the product development project are assumed to be specifiable.

Begin by defining some key variables relating to the *uncertain revenue stream* which will be generated by the sale of $Q$ units of product $P_i$ at a random variable price $p_{i,t}$, produced and sold at a constant rate of $Q/T_P$ units per unit time during the production and sales period $T_P$. First, let $(V_i)$ be the cumulative nominal dollar value of the uncertain revenue stream over the whole period of production $T_P$; thus, $(V_i)$ is the total cash inflow from producing and selling product $P_i$, undiscounted for time or risk. Then let $V_{i,t}$ be the random variable, risk-adjusted, market equilibrium present value at time $t$ of the random variable revenue stream $(V_i)$. Thus, $V_{i,t^*}$ is the present value at $t = t^*$ of the uncertain revenue stream which the firm will receive if it decides to produce and sell a newly developed product $P_i$. Similarly, $V_{i,0}$ is the
present value at \( t = 0 \) of the uncertain revenue stream \( V_{i,t} \) the firm will receive
if it decides at time \( t = 0 \) to develop and at \( t = t^* \) to produce new product \( P_i \).
Finally, let \( V_{i,t} \) denote the distribution of possible outcomes of \( V_{i,t} \) at any time
\( t \), and let \( V_{i,t} \) denote the realization of \( V_{i,t} \) at any time.

In keeping with the common characterization of future risky asset values
as lognormal distributions, this model assumes that \( V_{i,t} \) is a random variable
whose outcomes follow a lognormal distribution as it evolves over time. The
representation of \( V_{i,t} \) as a lognormal distribution assures that \( V_{i,t} \) will always
be non-negative -- a sensible condition in this case since a revenue stream
could have no value less than zero. (For discussion of the use of lognormal
distributions to represent future values of risky assets, see Cox and Rubinstein
1985, p204.)

The assumption that the market value of a risky asset (in this case, \( V_{i,t} \), the
equilibrium market value of the uncertain revenue stream \( (V_j) \)) follows a
lognormal distribution as it evolves over time implies that the
moment-to-moment random changes in the logarithm of the equilibrium asset
value must follow these dynamics (see Jarrow and Rudd 1983, pp 88-89):

\[
\ln(V_{i,t+\Delta t} / V_{i,t}) = \mu \Delta t + \sigma Z \sqrt{\Delta t}
\]

Equation 2-1

where

\( V_{i,t} = \text{market equilibrium present value at time} \ t \ \text{of the risky asset} \ (V_j) \)

\( V_{i,t+\Delta t} = \text{market equilibrium present value at time} \ t+\Delta t \ \text{of the risky asset} \)

\( V_{i,t+\Delta t} / V_{i,t} = \text{asset return over the interval} \ \Delta t \)

\( \mu = \text{the mean of the logarithm of the asset return per unit time} \)

\( \sigma \sqrt{\Delta t} = \text{the standard deviation of the logarithm of the asset return}
\text{per unit time} \)

\( Z = \text{the standard normal random variable with mean} \ 0 \ \text{and}
\text{variance} \ 1 \)

The dynamics of Equation 2-1 will result in the time-dependent normal
distribution of \( \ln(V_{i,t+\Delta t} / V_{i,t}) \) shown in Figure 2-2(a).

Appendix A1 shows that the dynamics of \( \ln(V_{i,t+\Delta t} / V_{i,t}) \) stated in Equation 2-1 lead to this equation for the dynamics of changes in \( V_{i,t} \):

\[
\Delta V_{i,t} / V_{i,t} = (\mu + (\sigma^2 / 2)) \Delta t + \sigma Z \sqrt{\Delta t} \quad \text{Equation 2-2}
\]

The lognormal distribution of \( \Delta V_{i,t} / V_{i,t} \) which results from the dynamics of Equation 2-2 is shown in Figure 2-2(b).

Then, using the mean \( \alpha \) and the standard deviation \( \sigma' \) of the returns per unit time to the lognormally distributed risky asset \( V_{i,t} \) (see Appendix A1), the distribution of \( V_{i,t} \) at any future time \( t + \Delta t \) can be stated as

\[
V_{i,t+\Delta t} = V_{i,t} \alpha \Delta t + V_{i,t} \sigma' \sqrt{\Delta t} \quad \text{Equation 2-3}
\]

Time-dependent distributions of \( V_{i,t} \) which would result from the dynamics of Equation 2-3 are illustrated in Figure 2-2(c) for \( t = 0, t = t^* \), and \( t = t_f \) for \( \mu = 0 \) and a constant \( \sigma > 0 \).

2.3. Real Options Valuation of a Product Development Opportunity

In the product development scenario characterized by the basic model, there is a simple but fundamentally important real option available to the managers of the firm. That option is the right to choose at time \( t = t^* \) whether or not to proceed with production of a new product once its development is completed. Managers who seek to increase the value of the firm will only proceed with production of a new product \( P_i \) if the project to produce \( P_i \) has a positive NPV at \( t = t^* \). Since managers are assumed in this model to be able to observe the realized price \( p_{i,t^*} \) of a new product at time \( t = t^* \) before they commit to producing \( P_i \), they can determine both \( V_{i,t^*} \) and \( C_P \) and will have the option to proceed with production only if \( V_{i,t^*} > C_P \).

Traditional discounted cash flow analysis often ignores this and other kinds of options which give strategic flexibility to the firm. By ignoring the flexibility that managers would have to intervene in the future to alter
uncertain outcomes in favor of the firm, a "no-option DCF" analysis implicitly assumes that risky cash flows resulting from developing new product $P_i$ are exposed to symmetric uncertainty. In the lognormal distribution of the uncertain revenue stream $V_{i,t^*}$ shown in Figure 2-3(a), for example, a no-option DCF analysis implicitly assumes that the full range of project value outcomes included in the distribution between 0 and $+\infty$ are possible or, in effect, unavoidable. Only if the firm is irreversibly committed to producing $P_i$ at $t = t^*$, however, does Figure 2-3(a) correctly describe the range of possible outcomes for the product development project.

When the firm has the option to choose not to proceed within production of $P_i$ if $V_{i,t^*} < C_P$, the distribution of possible outcomes to the development project can be truncated by managerial intervention, so that the production of $P_i$ will only proceed if $V_{i,t^*} > C_P$, as shown in Figure 2-3(b). Since all the negative net present values for the project at $t = t^*$ that lie to the left of $C_P$ are included (implicitly) in the no-option DCF valuation -- even though they would be avoided at $t = t^*$ by value-maximizing managers -- the consequence of applying a no-option DCF valuation method will be a systematic undervaluation of the product development opportunity when there is any significant probability that $V_{i,t^*} < C_P$ at $t = t^*$. Section 2.4 illustrates the systematic undervaluation of a no-option DCF vs. options valuation of a product development opportunity.

A correct valuation of the product development opportunity will therefore require a method of analysis which can determine the expected value of the distribution of $V_{i,t^*}$ to the right of $C_P$, conditional on $V_{i,t^*}$ being greater than $C_P$. Fortunately, the valuation of truncated, time-dependent lognormal distributions of future outcomes has been well developed in recent years for the purpose of valuing options to purchase or sell financial securities or, by extension, of valuing any contingent claim the exercise of which depends on uncertain future outcomes which conform to certain specified distributions. The basic kinds of options which can now be valued include both call options and put options. An American call option gives the holder of the option the right to buy a given security at a specified exercise price at any time up to the
expiration date; a European call option gives the same right except that the option may be exercised only on a specified exercise date. Similarly, an American put option gives the holder of the option the right to sell a given security at a specified sale price at any time up to the expiration date, and a European put option gives the same right except that the option to sell may be exercised only on a specified exercise date.

To value financial options, one must know the exercise price which will be paid for the security if the option is exercised, the expiration date of the option, the variance of the time-dependent distribution of future security values, the current stock price, and the riskless interest rate. In terms of the model of product development presented here, if one substitutes (a) the uncertain revenue stream \((V_i)\) for the underlying financial security, (b) the market equilibrium present value \(V_{i,0}\) for the current stock price, and (c) the costs of production \(C_P\) to be paid at \(t = t^*\) for the exercise price, the problem of valuing the opportunity to produce and sell \(P_i\) at time \(t = t^*\) and thereby to claim the uncertain revenue stream \((V_i)\) is isomorphic with the problem of valuing a European call option to purchase a security at \(t = t^*\).

Extending the analogy one step further, the opportunity to produce \(P_i\) at \(t = t^*\) and thereby claim \((V_i)\) is created at \(t = 0\) by the decision to develop \(P_i\). Thus, deciding at \(t = 0\) to develop a new product \(P_i\) is tantamount to creating an option on the revenue stream \((V_i)\) which can be exercised at \(t = t^*\) by paying the "exercise price" \(C_P\). Given this characterization of a new product development opportunity, the value of developing new product \(P_i\) is the value of a call option \(C_{i,0}\) on \((V_i)\) exercisable at \(t = t^*\) by paying \(C_P\), the present value at \(t = t^*\) of the costs of production. If \(C_{i,0}\) is greater than \(C_D\) (the present value at \(t = 0\) of the costs of developing \(P_i\)), then proceeding with development of \(P_i\) would be a positive net present value undertaking which could be used to maximize the value of the firm.

Appendix A2 shows that under certain assumptions -- especially that markets for risky assets are perfect, efficient, frictionless, and complete -- the
options value of a product development opportunity characterized by the basic model of this chapter is given by

$$C_{i,0} = V_{i,0} N(h) - e^{-rt^*} C_P N(h - \sigma\sqrt{t^*})$$  \hspace{1cm} \text{Equation 2-4}$$

where \(N(.)\) is the standard normal cumulative probability function and

$$h = \left[ \ln\left(\frac{V_{i,0}}{C_P} \right) + rt^* + (\sigma^2/2)t^* \right] / \sigma\sqrt{t^*}$$

The value of \(C_{i,0}\) given in Equation 2-4 corresponds to the Black-Scholes (1973) formula for the value of a European call option at \(t = 0\). More generally, at any time \(0 \leq t \leq t^*\), the firm's call option on the development project will have the value

$$C_{i,t} = V_{i,t} N(h) - e^{-\gamma(t^*-t)} C_P N(h - \sigma\sqrt{(t^*-t)})$$  \hspace{1cm} \text{Equation 2-5}$$

where

$$h = \ln\left(\frac{V_{i,t}}{C_P} \right) + r(t^*-t) + (\sigma^2/2)(t^*-t)) / \sigma\sqrt{(t^*-t)}$$

and \(C_D\) is interpreted as the present value of the remaining development costs.

Equations 2-4 and 2-5 can be interpreted conceptually as follows (Cox and Rubenstein 1985, p. 205): \(V_{i,t} N(h)\) is the present value of receiving the revenue stream \(V_{i,t}\) from producing and selling \(P_i\), conditional on \(V_{i,t}\) turning out to be greater than the present value of the costs of production \(C_P\) at \(t = t^*\). Similarly, \(e^{-\gamma(t^*-t)} C_P N(h - \sigma\sqrt{(t^*-t)})\) is the present value of the production costs that must be paid or committed to at \(t = t^*\), conditional on \(V_{i,t}\) turning out to be greater than the present value of the costs of production \(C_P\) at \(t = t^*\). Then \(C_{i,t}\) is the present value of the net gain the firm will acquire at \(t = t^*\), conditional on the firm exercising its option to produce \(P_i\) at \(t = t^*\) -- i.e., conditional on \(V_{i,t^*} > C_P\) at \(t = t^*\).

2.4 Impact of Real Options vs. "no-Option DCF" Valuations on Product Strategy

As proposed in Chapter 1 and elsewhere in this thesis, the fundamental objective of a firm's product strategy is to identify and carry out those product development projects that will maximize the net present value of the firm. In
order to achieve this objective, the firm must be able to correctly choose from among its opportunity set the feasible set of development projects with the greatest net present value.

An important element in the firm's product strategy, therefore, is the firm's method of evaluating product development opportunities. As this section will show, a no-option DCF analysis that ignores the strategic flexibility embedded in the option not to produce a newly developed product at \( t = t^* \) will systematically undervalue the firm's product development opportunities, leading to systematic underinvestment by the firm in product development. An options analysis of a product development opportunity, by contrast, can capture the value of flexibility and thus can avoid biasing the firm towards suboptimal levels of product development.

If development costs \( C_D \) are paid or committed to at \( t = 0 \), the difference at any time \( 0 < t \leq t^* \) between the no-option DCF and options valuations of the opportunity to produce \( P_i \) is the difference between \( V_{i,t} - C_P e^{-r(t^*-t)} \) and \( C_{i,t} \), where \( C_{i,t} \) is given by Equation 2-5. Given the options valuation of the product development project in Equations 2-4 and 2-5, the net present value at \( t = 0 \) of the opportunity to develop and produce a new product \( P_i \) can be stated as

\[
NPV_{i,0} = C_{i,0} - C_D \quad \text{Equation 2-6}
\]

When \( t = t^* \), the term \( t^*-t \) in Equation 2-5 becomes zero, \( h \) becomes infinite, and the terms \( N(h) \) and \( N(h - \sigma\sqrt{(t^*-t)}) \) both equal one. Thus at \( t = t^* \)

\[
NPV_{i,t^*} = C_{i,t^*} = \text{Max} [0, V_{i,t^*} - C_P] \quad \text{Equation 2-7}
\]

Equation 2-7 indicates that the options value of the project converges to the no-option DCF valuation of the project at \( t = t^* \) when \( V_{i,t^*} \geq C_P \). For the case of \( V_{i,t^*} < C_P \), however, \( C_{i,0} = 0 \), but the no-option net present value \( V_{i,0} - C_P < 0 \). These differences between the no-option DCF and options valuations at \( t = t^* \) imply differences in valuations at \( t = 0 \), when the firm evaluates its product development opportunity. The following comparison accordingly focuses on the two valuations at \( t = 0 \), \( V_{i,0} - C_P e^{-rt^*} \) and \( C_{i,0} \). (Since the development cost affects the two valuations equally at \( t = 0 \), \( C_D \) is omitted from the following
discussion.)

The no-option DCF analysis which ignores the option not to produce $P_i$ at $t = t^*$ will be most misleading when there is a significant probability that $V_{i,t^*}$ will be less than $C_P$ -- a condition which usually implies a relatively low ratio of $V_{i,0}$ to $C_P e^{-rt^*}$. At the same time, the options valuation depends on $V_{i,0}$ and $C_P e^{-rt^*}$ weighted respectively by the transformed probabilities $N(h)$ and $N(h - \sigma \sqrt{t})$. Since the valuations by both methods will depend significantly on the ratio of $V_{i,0}$ to $C_P e^{-rt^*}$, it will be useful to investigate how no-option DCF and options valuations at $t = 0$ of the opportunity to produce $P_i$ will differ across the range of possible ratios of $V_{i,0}$ to $C_P e^{-rt^*}$.

To make a simple comparison, assume that all variables other than $V_{i,0}$ and $C_P e^{-rt^*}$ are held constant. Begin by finding the relationships between $V_{i,0}$ and $C_P e^{-rt^*}$ that give the results $V_{i,0} - C_P e^{-rt^*} = 0$ and $C_{i,0} = 0$:

$$V_{i,0} - C_P e^{-rt^*} = 0$$

$$V_{i,0} = C_P e^{-rt^*}$$

Equation 2-8

and

$$C_{i,0} = 0$$

$$C_{i,0} = V_{i,0} N(h) - C_P e^{-rt^*} N(h - \sigma \sqrt{t^*}) = 0$$

$$V_{i,0} = C_P e^{-rt^*} [N(h - \sigma \sqrt{t^*})/N(h)]$$

Equation 2-9

The two relationships between $V_{i,0}$ and $C_P e^{-rt^*}$ resulting from Equations 2-8 and 2-9 are shown by the two "zero-value" rays for no-option DCF and options valuations in Figure 2-4. The slope for the DCF zero-value ray equals one, and the slope for the options valuation zero-value ray equals $N(h - \sigma \sqrt{t^*})/N(h)$. Since $N(h - \sigma \sqrt{t^*})/N(h) < 1$, the options zero-value ray must lie below the DCF zero-value ray.

Figure 2-4 shows that when $V_{i,0} \leq C_P e^{-rt^*}$, an options valuation will lead to a greater project value than a no-option DCF valuation which ignores the
production option. In Areas A and B of Figure 2-4, a no-option DCF analysis leads to a negative value $V_{i,0} - C_P e^{-rt^*}$ for the value of the opportunity to produce $P_i$ (again, after payment of $C_D$). In Area A, however, $C_{i,0}$ is still positive and is therefore greater than the no-option DCF valuation. In Area B, $C_{i,0} = 0$, since the option to produce $P_i$ at $t = t^*$ can at worst be worth nothing. In Area B, too, $C_{i,0} = 0$ will be greater than the no-option DCF valuation $V_{i,0} - C_P e^{-rt^*}$, which has assigned a negative value to the production opportunity.

Thus, in projects for which the ratio of $V_{i,0} / C_P e^{-rt^*}$ is low (Areas A and B occupy much of this region in Figure 2-4), the tendency of no-option DCF valuations to undervalue projects will be especially pronounced.

As the ratio $V_{i,0} / C_P e^{-rt^*}$ becomes very large, $N(h) \to 1$, and $N(h - \sigma\sqrt{t^*}) \to 1$, and the value of $C_{i,0} = V_{i,0} - C_P e^{-rt^*}N(h - \sigma\sqrt{t^*}) \to V_{i,0} - C_P e^{-rt^*}$. The largest possible ratio for $V_{i,0} / C_P e^{-rt^*}$ lies along the vertical axis, which is the ray for $C_P e^{-rt^*} = 0$. Along the vertical axis, $C_{i,0} = V_{i,0}$ because $C_P e^{-rt^*} \to 0$ implies $N(h) \to 1$ for any $V_{i,0} > 0$, while the term $C_P e^{-rt^*}N(h - \sigma\sqrt{t^*})$ vanishes.

A no-option DCF valuation increases from zero along the zero-value ray and, moving counterclockwise in Figure 2-4, will also approach $V_{i,0}$ as the ratio $V_{i,0} / C_P e^{-rt^*}$ approaches the vertical axis. Thus, between the zero-value line for the options valuation and the vertical axis, the options valuation will be greater than the no-option DCF valuation, but the two valuations will converge whenever the ratio $V_{i,0} / C_P e^{-rt^*}$ approaches the vertical axis.

Therefore, for all ratios $V_{i,0} / C_P e^{-rt^*}$ (i.e., Areas A, B, and C), an options valuation will give a larger valuation than the no-option DCF analysis -- which is to be expected, since only the options valuation includes the value of the flexibility embedded in the option not to produce $P_i$ at $t = t^*$. This finding will apply to all ratios of $V_{i,0} / C_P e^{-rt^*}$, except for those cases where $V_{i,0} / C_P e^{-rt^*}$ is extremely large (i.e., directly along the vertical axis), in which case the two valuations will converge.
(The convergence of the two valuations along the vertical axis of Figure 2-4 can also be explained by the effect of the condition $C_p e^{-rt^*} = 0$ on the two distributions of outcomes on which the two valuations are based. $C_p e^{-rt^*} = 0$ implies $C_p = 0$ for any finite $r$ and $t^*$. If $C_p = 0$, then there will be no need for truncation by management intervention of the distribution of $V_{i,t^*}$ at $t = t^*$, since $V_{i,t^*} \geq 0$ and no outcome of $V_{i,t^*}$ will result in a realized negative present value for the production opportunity. If the distribution of outcomes would never be truncated at $t = t^*$, since the option not to produce would never be exercised (which would always be the case if $C_p = 0$), then both the options and no-option valuations will be based on identical distributions of outcomes at $t = t^*$ and will give identical valuations at $t = t^*$. By the no arbitrage argument, if the two valuations give identical values at $t = t^*$, they must have identical values at $t = 0$, so that $C_{i,0}$ will be equal to the no-option DCF value $V_{i,0}$ - $C_p e^{-rt^*} \rightarrow V_{i,0}$ along the vertical axis of Figure 2-4.)

2.5 Product Options Values in Three Competitive Contexts

When introduced to a market, a newly developed product may face different kinds of competitive pressures from competing products. These different kinds of competitive pressures are incorporated in this model by characterizing three competitive contexts into which the firm may introduce its new products: competitive immunity, value erosion by imitation, and value erosion by diffusion. Each of these competitive contexts represents a competitive environment which results in a specific pattern of anticipated price behavior for a newly introduced product during the period of production $T_p$. Thus, each competitive context implies a different distribution of possible present values of $V_{i,t}$ for a newly developed product.

A context of competitive immunity characterizes markets in which a firm's new product will not be exposed to significant direct competitive pressure from close substitute products. Such markets may exist when a firm has a patent, proprietary technologies, superior market knowledge, exclusive distribution channels, or other competitive advantages which make it impossible or
uneconomic for competitors to offer close substitutes for the firm's new product. In a context of competitive immunity, the price which a firm will obtain for its new product is unaffected by direct product competition and thus does not experience downward "price pressure" over time. However, the exact price which the firm will obtain at any future time remains uncertain. This mode of price behavior in a context of competitive immunity is characterized here as a pure demand-driven Markov diffusion process (random walk), as illustrated in Figure 2-5(a).

A context of value erosion by imitation exists when competitor firms are able to copy or closely replicate an originator firm's successful new product and to sell their clones in the markets served by the originator firm. In this model, imitator firms are assumed to require some predictable amount of time to replicate a new product. Imitator firms have access to a new product when it is introduced to the market by the originator firm at time $t = t^*$ and are able to introduce their clones of a successful new product at (a predictable) time $t = t'$.

The firm which originally developed a successful new product enjoys competitive immunity during the period $t^*$ to $t'$, but prices for the originator firm's product will experience downward pressure after imitators bring their clones to market at time $t = t'$.

Downward pressure on prices in a context of value erosion by imitation could take any number of functional forms. For simplicity, in this model the downward tendency in prices for $P_i$ resulting from competitive pressure during the period $t'$ to $t_f$ is assumed to result in an instantaneous fall in $p_{i,t}$ to the level of variable production costs. In other words, prices are assumed to fall to an economically profitless level under perfect competition at $t = t'$, as shown in Figure 2-5(b). Thus, in a context of value erosion by imitation, if the revenue stream is assumed only to cover costs in the period after $t = t'$, an approximate product option value can be calculated based solely on revenues received during the initial pre-imitation period of competitive immunity, $t^* \leq t \leq t'$. In this simplified form, the product option value will be given by Equation 2-3 when $V_{i,t^*}$ and $C_P$ are calculated over the period $t^* \leq t \leq t'$.

The context of value erosion by diffusion is intended to describe situations in
which two or more firms of relatively equal capability are competing in the same product market. All competing firms develop at least one new product and are able to introduce their products to the market at varying times \(0 \leq t \leq t_f\). Some of the new products that could be brought to market will be discovered to be unprofitable and will therefore not be produced, but some products will be well received by the market and will be produced. As competitors learn which products are succeeding in the market, they may be able to modify some of their less successful product designs to change them into products that are more acceptable to the market. Thus, as knowledge about which product configurations are succeeding in the market diffuses throughout the industry, the market gradually becomes filled with roughly comparable competing products. As Figure 2-5(c) shows, this form of value erosion due to diffused capabilities can be characterized by prices subjected to steady downward pressure from time \(t = 0\). For simplicity, the downward tendency in prices for \(P_i\) resulting from competitive pressure during the period \(0 \leq t \leq t_f\) is represented by \(\delta\), a constant proportional rate of value depreciation from \(t = 0\), as shown in Figure 2-5(c).

The options value at \(t = 0\) of a product development opportunity subject to this kind of value erosion can be found by applying Merton's (1973a) formula for the value of a European call option on a dividend-paying stock (from the perspective of the option holder, a dividend-paying stock loses value at the dividend rate because the dividend accrues to the owner of the stock, not the option holder):

\[
C_{i,t} = V_{i,t} e^{-\delta(t^*-t)}N(h) - CP e^{-r(t^*-t)}N(h - \sigma\sqrt{(t^*-t)})
\]

Equation 2-10

This formula can be used to value a product option when value erosion either continues after exercise of the option or stops on exercise, the difference in use being limited to whether \(V_{i,t^*}\) is evaluated as eroding in value after \(t = t^*\) or not.

(A more general interpretation of the applicability of Equation 2-10 to valuing options on risky assets is that Equation 2-10 will apply whenever (1) cash flows are forfeited if an option is not exercised or (2) the underlying risky asset will not earn a market rate of return during the option holding period. In
the first case, any risky asset whose net cash flows are transitory will be subject to value erosion over time. A new product opportunity subject to value erosion by diffusion faces falling net cash flows during the option holding period, and thus belongs to the transitory class of depreciating assets. In the second case, an asset like a natural resource may not have an expected rate of increase in value ("capital gain") as great as the market-required rate of return for holding the asset. In such cases, holding the option on the asset -- i.e., electing not to extract and sell the natural resource -- leads to erosion in the value of the underlying asset value over time.)

A fourth competitive context -- that of dynamic competitive pre-emption -- may exist when one firm can take actions which effectively preclude other firms from selling new products in its market. When a firm is able to take such actions, it can in effect create a context of competitive immunity for itself. In this case, the firm's competitors have no prospect of earning an economic profit from producing any new products; therefore they do not produce any new products and, if they can correctly foresee this outcome at time t = 0, they will not initiate development of new products for that market. This special competitive context is discussed in Chapter 9.

2.6 Example of a Product Development Option Valuation:

The Lockheed 1011 Tristar

In the spring of 1968, Lockheed Corporation decided to proceed with a 42-month program to develop the Lockheed 1011 Tristar, a 260-400 passenger jumbo jet intended to compete against the McDonnell-Douglas DC-10 and the Aerospatiale Industries A-300 Airbus, both of which were also under development at that time. In mid-1971, after more than 36 months of 1011 Tristar development, Lockheed was forced to ask the U.S. Government to guarantee a bank loan of $250 million to complete development of the 1011 Tristar, because cost overruns on its military aircraft contracts had severely depleted Lockheed's financial resources. During Congressional hearings on Lockheed's request, much information on Lockheed's 1011 Tristar development costs and projected production costs and revenues was made public. Lockheed's cost and revenue data were reported and analyzed (using a conventional no-option DCF analysis) by Reinhardt (1973) to suggest that

55
development of the 1011 Tristar should never have been undertaken, because a DCF analysis of Lockheed's own data showed the 1011 Tristar to be a negative net present value development project under any reasonable future scenarios.

This section reconstructs the Lockheed 1011 Tristar development decision using data in the Reinhardt article and applies the basic options model of product development to re-evaluate the 1011 Tristar development decision from the real options perspective. In so doing, it has been necessary to make certain assumptions about patterns of cash flows and an estimate of the average unit price of a 1011 Tristar in 1971, but neither the assumptions or the estimate seem likely to have materially affected the options valuations obtained here.

In the following analysis, the point of view taken is that of Lockheed Corporation in April 1968. The data used in the example are therefore those available to Lockheed in April 1968, not ex post historical data.

Options analysis of this and subsequent 1011 Tristar examples was carried out on a Macintosh IIcx using Theorist, Version 1.0, a symbolic mathematics program from Prescience Corporation. The formulas and variables used in the analysis are shown in Appendix A3. The formula for approximating the standard normal cumulative probability functions N1 and N2 is from Figlewski (1990, p. 133) and is generally accurate to at least four significant figures.

**Contingency Structure.** In April 1968, Lockheed foresaw a 42-month development period for the 1011 Tristar. At the end of that period, production could begin at a rate of three or more jets per month for an indefinite period of time. No information is available on how long Lockheed expected to continue production of the 1011 Tristar, but a typical production run for a major airframe model would be at least 10 years (Boeing's 737 has been in production for over 20 years). If the production period is conservatively taken to be 10 years, the contingency structure for the 1011 Tristar becomes that shown in **Figure 2-6.** In terms of the basic model developed in this chapter, Lockheed must decide in April 1968 whether to commit to pay development costs with present value \( C_{D,Tristar} \) to obtain the option to claim the revenue stream \( V_{Tristar,42} \) in October 1971 by committing to production costs with present value \( C_{P,Tristar} \).
Representation of Uncertain Revenue Stream. The revenue stream which Lockheed hoped to derive from the 1011 Tristar was uncertain. Lockheed estimated the total market for jumbo jets like the 1011 Tristar to be approximately 775 units in 1971, with annual growth in demand expected at 5% to 10% per year thereafter of the base 775 units. Lockheed further expected to capture 35% to 40% of the total market. Assuming that Lockheed would produce at a constant monthly rate of 3, 4, or 5 jets for a fifteen-year period would yield total output quantities of 360, 480, or 600 Tristars over a ten-year production period, which would roughly correspond to pessimistic, expected, and optimistic production levels for Lockheed in this jumbo jet market.

The selling price of a 1011 Tristar in 1971 was estimated by Lockheed at one time to be $14.7 million, but advance orders were taken at the outset of development at $15.5 million per plane. A simplifying assumption made in this example is that the average price Lockheed expected in 1968 to receive in 1971 was $15.0 million. In addition, during the development period Lockheed received a total of $260 million in downpayments from airlines on 103 aircraft and payments for options to purchase 75 additional aircraft. No data are available on the dates of these payments or the percentage of downpayments vs. options payments. However, since these payments represent funds which Lockheed would have to repay either in the form of reduced revenues received on delivery or in the form of refunds if the 1011 Tristar was not produced, these advanced payments are treated by Reinhardt as simple loans to Lockheed. That treatment is followed here, and thus advance payments are not considered in the evaluation of the option value of the development project.

No data are available to definitively characterize the uncertainty about price or output quantities which Lockheed faced in 1968. Therefore, to study the value of the 1011 Tristar development opportunity under a range of scenarios, $V_{Tristar,0}$ is evaluated for pessimistic, expected, and optimistic output levels (3, 4, and 5 units per month) and across a spectrum of uncertainty corresponding to annual variance in $V_{Tristar,0}$ of $\sigma_Y = 0.10, 0.20, 0.30, 0.40$, and $0.50$.

Costs. Lockheed had prepared detailed estimates of both its development and production costs. Since Lockheed apparently had considerable confidence in its cost estimates -- especially its estimates of production costs -- Lockheed's
costs are assumed here to be known with certainty in April 1968. (Historical data largely confirmed the accuracy of Lockheed's cost estimates.)

Exact development costs were estimated by Lockheed were not made public, but other data suggest that development costs were thought *ex ante* to be between $800 and $1000. Taking a mid-range figure of $900 million in development costs, and assuming a payment pattern equivalent to $150 million in month 12 of development, $300 million each in months 24 and 36, and $150 million, the present value of development costs, $C_{D, Tristar}$, would have been $861 million in April 1968, using a risk-free interest rate of 3% per year.

Production cost estimates prepared by Lockheed apparently relied heavily on progressive unit cost reductions from learning. Reinhardt deduces that Lockheed anticipated reductions in the cumulative average unit production cost (in nominal dollar terms) given by

$$Y_Q = Y_1 Q^{-b}$$  \hspace{1cm} \text{Equation 2-11}

where

- $Y_Q$ = the cumulative average unit production cost at the $Q$th unit
- $Y_1$ = the cost of producing the first unit
- $b = 0.369$, corresponding to a $\gamma = 77.4\%$ reduction in cumulative average unit production cost with every doubling of cumulative output ($Y_{2Q} = \gamma Y_Q$ and $\gamma = 2^b$)

This learning curve effect is shown in *Figure 2-7*, which plots the anticipated cumulative average unit production cost (in nominal dollars) against cumulative output levels for the 1011 Tristar.

Reinhardt also derives an equation for the present value of production costs for various levels of production per month. In terms of the variables used in the program in Appendix A3, this expression for present value of production costs is

$$K = \sum Y_1 [(n(t - A)1^{-b} - (n(t - A - 1)1^{-b}) / (1 + k')^{t-A}$$  \hspace{1cm} \text{Equation 2-12}

where

- $Y_1$ = the cost of producing the first Tristar (thought to be $100$ million)
- $n$ = number of Tristars produced per month
\[ t = \text{the month production costs are incurred} \]
\[ A = \text{the month development ends and production begins} \]
\[ k' = \text{the monthly discount rate for Lockheed's cost flows} \]

(Equation 2-12 is evaluated over the production interval, \( A \leq t \leq T \), in the program in Appendix A3.)

**Option Value of the 1011 Tristar Under Competitive Immunity.** In markets which are expanding rapidly, firms may not feel a need to compete on price, and price levels may primarily be determined by fluctuations in demand. If future demand for jumbo jets were to grow at a 10% annual rate from 1968, all three producers (Lockheed, McDonnell-Douglas, and Airbus) might be likely to have sufficient demand to avoid having to resort to price competition to assure adequate production levels. Thus, one setting in which the 1011 Tristar development opportunity could usefully be evaluated is that of competitive immunity from price competition.

**Figure 2-8** shows how the option value of the 1011 Tristar in April 1968 varied across a range of uncertainties for three output levels under an assumption of immunity from price pressure. The figure shows that under low levels of uncertainty about the future value of the revenue stream to be earned from selling the 1011 Tristar, development of a single-model 1011 Tristar would not have been a positive net present value undertaking at any of the three likely production levels. However, if future revenues from the 1011 Tristar were in fact subject to greater uncertainty, so that either the total number of units sold or the price at which each unit would be sold had significant upside potential, the option to produce the 1011 Tristar in October 1971 could have had a greater present value than its costs of development at higher levels of production (\( n = 4 \) or \( n = 5 \)).

**Option Value of the 1011 Tristar Under Value Erosion by Diffusion.** If price competition were to become a factor in the jumbo jet market after April 1968, prices at which Lockheed would be able to contract for future deliveries of 1011 Tristars could be depressed from the original expectation of $15.0 million per plane. If McDonnell-Douglas and Airbus were to bid down prices for their products in an effort to build market share, downward price pressure on sales of the 1011 Tristar would cause an erosion of the value of the 1011 Tristar.
project. This value erosion can be represented by the constant proportional rate of value depreciation $\delta$ given in Equation 2-10. Figure 2-9 shows how a 3% per year rate of value erosion during the development period would affect the value in April 1968 of the option to produce the 1011 Tristar beginning in October 1971, again across a range of uncertainties. As the figure shows, anticipated price pressure by Lockheed's competitors could make development of a single-model 1011 Tristar unattractive across the full range of uncertainties considered and at all but the highest level of output.

(Examples in later chapters will investigate the possible impacts on the options value of the 1011 Tristar development opportunity of developing related versions of the 1011 Tristar type -- for example, an extended range version and a short-hop version -- and of shortening the product development period.)
Firm creates initiative option by developing new product

Present Value of Development Costs \( C_D \)

Present Value of Production Costs \( C_P \)

Uncertain Revenue Stream from Sales of New Product \( P_i \)

\( V_{i,t} \)

Development Period = \( T_D \)

Production Period = \( T_P \)

\( p_{i,0} \)

\( t = 0 \) to \( t = t^* \)

\( t = t_f \)

Firm evaluates its opportunity set of product development opportunities and decides whether to invest in developing new product \( P_i \)

Firm observes the realized price \( p_{i,t^*} \) and decides whether to produce new product \( P_i \)

Firm can exercise option to claim \( V_{i,t} \) by paying production costs \( C_P \)

Production ceases

Figure 2-1: Basic Model of Initiative Option Created by Product Development
Figure 2-2(a): Normal Distribution of $\ln(V_{i,t+\Delta t}/V_{i,t})$

$$\text{Mean} = \mu \Delta t = E[\ln(V_{i,t+\Delta t}/V_{i,t})]$$

Figure 2-2(b): Lognormal Distribution of $(\Delta V_{i,t}/V_{i,t})$

$$\text{Mean} = \alpha \Delta t = (\mu + \sigma^2/2)\Delta t$$

Figure 2-2(c): Time-Dependent Distributions of $V_{i,t}$
Distribution of $V_{i,t^*}$, Present Value at $t = t^*$ of Uncertain Revenue Stream Generated by Producing and Selling New Product $P_i$

$V_{i,0} = \text{Present Value at } t = 0 \text{ of } \{V_i\}$

Figure 2-3(a): Symmetric Distribution of Outcomes Implicit in "No-Option" DCF Analysis

Management Can Truncate Distribution When Firm Has Flexibility Not to Produce Product $P_i$

Distribution of $V_{i,t^*}$, Present Value at $t = t^*$ of Uncertain Revenue Stream Generated by Producing and Selling New Product $P_i$

$V_{i,0} = \text{Present Value at } t = 0 \text{ of } \{V_i\}$

Figure 2-3(b): Truncated Distribution of Outcomes Resulting from Managerial Intervention
Figure 2-4: Relation Between No-Option DCF Valuation and Options Valuation
Figure 2-5(a): Price Behavior Under Competitive Immunity

Figure 2-5(b): Price Behavior Under Competitive Erosion by Imitation

Figure 2-5(c): Price Behavior Under Competitive Erosion by Diffusion
Lockheed can create production option at t = 42 by developing 1011 Tristar

Lockheed can exercise its production option by producing the 1011 Tristar from t = 42

Production Period = 120 Months

Present Value of Development Costs
$C_D = $861 million

Present Value of Production Costs

$150 million
$300 million
$300 million

$150 million

Development Period = 42 Months

t = 0

Unit Costs Decline as Cumulative Output Increases

t = 42
Production begins in month 42

K

t = 162
Production ceases in month 162

V_A
Uncertain Revenue Stream from Sales of 1011 Tristar

Figure 2-6: Contingency Structure for Opportunity to Develop Lockheed 1011 Tristar
Figure 2-7: Anticipated Effect of Learning on Cumulative Average Unit Cost of Production (Nominal Dollars) of Lockheed 1011 Tristar Jumbo Jet
Options Value of 1011 Tristar
Development Opportunity
($ millions, April 1968)

Lockheed 1011 Tristar
Development Has:

Cost of Development = $861 Million
Positive Net Present Value
Negative Net Present Value

1346.2
1105.4
1001.0
856.3
800.8
679.2
592.6
522.6
52.6
362.1
379.3
343.6
165.0
54.6

Figure 2-8: Options Value of Developing Lockheed 1011 Tristar In Context of Competitive Immunity

Variable Values: Risk-free interest rate = r = 0.03/year. Lockheed's monthly discount rate = k' = 0.0094888.
Initial unit production cost = Y = $100 million. Expected sales price per plane = $15 million.
Development period = A = 42 months. Production period = T = 120 months.
Figure 2-9: Options Value of Developing Lockheed 1011 Tristar In Context of Value Erosion By Diffusion ($ \delta = 0.03$)

Variable Values: Risk-free interest rate $r = 0.03$/year. Lockheed's monthly discount rate $k' = 0.0094888$. Initial unit production cost $Y = 100$ million. Expected sales price per plane $S = 15$ million. Development period $A = 42$ months. Production period $T = 120$ months.
3. Initiative Options

Any firm interested in serving a specific market for products must at some point decide which products in its opportunity set it will develop for that market. In general, when future market preferences are uncertain, the greater the number of promising new products the firm can start to develop now, so that more products will be available to the firm to produce at some point in the future, the greater will be the firm’s strategic flexibility to respond to advantageously to uncertain conditions in the future by choosing the most appropriate (i.e., the value-maximizing) products to produce and offer to its product markets. Thus, the fundamental source of a firm's strategic flexibility is its options to produce new products in the future which the firm creates through its product development activities. The economic value of the strategic flexibility the firm can create by developing new products can be determined by valuing the firm's real options to produce new products in the future.

Of course, the benefit of increased strategic flexibility which developing a new product brings to the firm, as measured by the real option value of that product, must be weighed against the cost of developing the product. Obtaining additional strategic flexibility by developing another new product is desirable only when developing that new product will add to the net present value of the firm -- i.e., when the real option value of the new product exceeds its cost of development. To show how a firm can use options analysis to value its product development opportunities and create the value-maximizing amount of strategic flexibility, this chapter applies financial options pricing models to the valuation of initiative options which the firm can create from its product development opportunities.

The analysis of this chapter focusses on the valuation and selection of initiative products to produce new products when the firm faces various levels of constraints on its production resources. Section 3.1 values product initiative options for the unconstrained firm (corresponding to generic real option #1a) and leads to a simple value-maximizing decision rule for accepting or rejecting development of a new product opportunity. Section 3.2 analyzes initiative options when the firm is constrained to produce only one
product (generic real option #1b). Section 3.3 evaluates a firm's product
development opportunities when the firm is constrained to produce a limited
number of products (generic real option #1c).

Since development of new product is often phased -- *i.e.*, periodically
re-evaluated during the development period -- this chapter also investigates
the impact of a phased approach to product development on a firm's initiative
options. Section 3.4 shows that a product initiative option should be valued as
a compound option when a decision to develop a new product can be
re-considered and, if desired, reversed during the development period.

Before proceeding with the analysis of this chapter, two final comments
about the options valuations developed in this chapter may be helpful. First,
the product development opportunities valued as real options in this chapter
have intentionally been stripped of operating options to vary the timing or
implementation of development or production, since these aspects of strategic
flexibility will be investigated in Chapters 4 and 5, respectively. Second, it is
also assumed in the following analysis that the firm will engage in "early
exercise" of its product options, and that it will be optimal for the firm to do
so. For financial options, early exercise is often suboptimal. As Chapter 4
will argue, however, the possible depreciation of real options values caused
by competitive value erosion, the potentially significant costs involved in
"holding" real options, and the need to maintain organizational momentum
in product development may be sufficient in many product markets to make
it optimal to "early exercise" a firm's product initiative options. Thus, the
analysis in this chapter typically assumes that a firm will exercise its
product options as soon as they are available, but the arguments in support of
this assumption are deferred to Chapter.

3.1 Initiative Options for the Unconstrained Firm

When a firm is unconstrained in its capacity for development and
production -- *i.e.*, when the firm can develop and produce as many of the
products in its product development opportunity set as it chooses -- each
product development opportunity in its opportunity set can be evaluated
simply as an independent or "free-standing" real option. In this case, each
product development opportunity which the firm pursues creates a simple
product initiative option (generic real option #1a) to choose whether or not to produce a new product on completing development.

The contingency structure for product development opportunities held by an unconstrained firm is shown in Figure 3-1. To evaluate each product development opportunity, the unconstrained firm can simply apply Equations 2-10 and 2-6 developed in Chapter 2:

\[ C_{i,0} = V_{i,0} e^{-\delta t^*} N(h) - e^{-r t^*} C_P N(h - \sigma \sqrt{t^*}) \quad \text{[Equation 2-10]} \]

\[ NPV_{i,0} = C_{i,0} - C_D \quad \text{[Equation 2-6]} \]

where \( C_{i,0} \) is the value at \( t = 0 \) of the option to produce product \( P_i \) at \( t = t^* \) and \( C_D \) is the present value at \( t = 0 \) of the development costs for \( P_i \). The unconstrained firm will maximize its net present value by simply developing all product opportunities in its opportunity set with a positive net present value. In other words, the firm should develop all products for which the present value of the real option (the value at \( t = 0 \) of the option to produce a new product at \( t = t^* \)) exceeds the present value of the cost of creating the option (the present value at \( t = 0 \) of the cost of development).

3.2 Initiative Options When the Firm Is Constrained to Produce a Single Product

The strategic flexibility of a firm which may have many development opportunities, but is constrained to produce only one product at a time, is described by generic real option #1b, the option to choose a single most valuable course of action from among two or more alternatives.

The contingency structure for product development opportunities held by the single-product firm is shown in Figure 3-2. In this case, for the firm constrained to produce only one product, developing additional products may increase the value of the firm’s option to choose which of two or more newly developed products to produce at \( t = t^* \). Intuitively, one can readily imagine that even if the firm is constrained to produce only one new product, there may be some value in having the ability at time \( t = t^* \) to choose among two or
more fully developed products whose uncertain values $V_{i,t^*}$ will only be realized at $t = t^*$.

Developing each additional product bestows a marginal benefit on the firm in the form of an increase in the value of the firm's generic real option to choose among two or more alternatives. When the firm is constrained to produce a single product, the firm will maximize its net present value by developing one or more products until the marginal benefit (in the form of increases in the value of generic real option #1b) of developing one more product becomes less than the marginal cost of developing that product. This approach to determining the optimal number of products to develop is illustrated in Figure 3-3 for a firm facing constant unit costs of development. As suggested by the figure, options analysis may show that the optimal number of products to develop for the firm constrained to produce only one product might be more than one.

The strategic flexibility to choose which of two or more newly developed products to produce can be analyzed formally as the option to choose the maximum of two or more risky assets at some future time. If we can value of this kind of option, and if we can determine the marginal costs of developing each additional new product, we will be able to determine which combination of product development opportunities available to the firm will, if developed, contribute the greatest net present value to the firm.

The option to exchange one risky asset for another has been analyzed by Margrabe (1978), whose analysis was extended by Stulz (1982) to value the specific option to choose the maximum or minimum of two risky assets, and by Johnson (1987) to value the option to choose the maximum of several risky assets. Their analyses can be applied to the basic model of product development to obtain a pricing model that gives the value now of the option to choose a single new product to produce from among two or more developed products at some future date.

The following discussion first applies Stulz's (1982) analysis to develop an options equation for the value of the real option to choose the single most valuable product among two alternatives. The options analysis is then extended by applying Johnson's (1987) analysis to obtain the options pricing
equation for the value of a real option to choose the single most valuable product among *three or more* alternatives. After developing these valuation equations, the decision rule that leads to the value-maximizing product strategy for the single-product firm is stated. This section concludes with some comments on the sensitivity of these options valuation models to their underlying variables.

**Choosing Between Two Product Initiative Options.** To value the real option to choose between two developed products, begin by letting $\text{MAX}_{1,2;t}$ denote the value at time $t$ of the option to choose at $t = t^*$ the *maximum* of two risky assets, $V_{1,t^*}$ and $V_{2,t^*}$ (which are the present values at $t = t^*$ of $V_{1,t}$ and $V_{2,t}$, the uncertain revenue streams obtained by producing and selling new products $P_1$ and $P_2$, respectively), for an exercise price $C_P$ (the present value at $t = t^*$ of all production costs). Also, let the value of the option to choose the *minimum* of the two risky assets be denoted by $\text{MIN}_{1,2;t}$. The real options value of an independent product development opportunity is given by $C_{i,t}$.

Then

$$\text{MAX}_{1,2;t} + \text{MIN}_{1,2;t} = C_{1,t} + C_{2,t}$$

and therefore

$$\text{MAX}_{1,2;t} = C_{1,t} + C_{2,t} - \text{MIN}_{1,2;t} \quad \text{Equation 3-1}$$

Stulz showed that the value of $\text{MIN}_{1,2;t}$ at time $t$ is given by

$$\text{MIN}_{1,2;t} = V_{1,t} N_2(\alpha_2, \beta_2, \theta_2) + V_{2,t} N_2(\alpha_1, \beta_1, \theta_1)$$

$$- e^{-\alpha(t^*-t)} C_P N_2(\alpha_1, \alpha_2, \rho_{12}) \quad \text{Equation 3-2}$$

where

$$N_2(\alpha, \beta, \theta) = \text{the bivariate standard normal distribution with upper limits of integration } \alpha \text{ and } \beta \text{ and coefficient of correlation } \theta$$

$$\alpha_1 = \gamma_1 + \sigma_2 \sqrt{(t^*-t)}$$

$$\alpha_2 = \gamma_2 + \sigma_1 \sqrt{(t^*-t)}$$
\begin{align*}
\beta_1 &= \left[ \ln \left( \frac{V_{1,t}}{V_{2,t}} \right) - \sigma^2(t^{*}-t)/2 \right] / \sigma \sqrt{t^{*}-t} \\
\beta_2 &= \left[ \ln \left( \frac{V_{2,t}}{V_{1,t}} \right) - \sigma^2(t^{*}-t)/2 \right] / \sigma \sqrt{t^{*}-t} \\
\theta_1 &= (\rho_{12} \sigma_1 - \sigma_2) / \sigma \\
\theta_2 &= (\rho_{12} \sigma_2 - \sigma_1) / \sigma \\
\gamma_1 &= \left[ \ln \left( \frac{V_{2,t}}{V_{1,t}} \right) + (r - (\sigma_2)^2/2)(t^{*}-t) \right] / \sigma_2 \sqrt{t^{*}-t} \\
\gamma_2 &= \left[ \ln \left( \frac{V_{1,t}}{V_{2,t}} \right) + (r - (\sigma_1)^2/2)(t^{*}-t) \right] / \sigma_1 \sqrt{t^{*}-t} \\
\sigma &= (\sigma_1)^2 + (\sigma_2)^2 - \rho_{12} \sigma_1 \sigma_2
\end{align*}

In Equation 3-2, \(\rho_{12}\) is the coefficient of correlation between \(V_{1,t}\) and \(V_{2,t}\), which is assumed to be constant, and \(\sigma_1\) and \(\sigma_2\) are the standard deviations for \(\Delta V_{i,t} / V_{i,t}\) (see Appendix A1) which are also assumed constant. Also note that Equation 3-2 presumes that both products have the same exercise price (cost of production \(C_P\)).

The net present value at time \(0 \leq t \leq t^*\) of the real option created by developing two products \(P_1\) and \(P_2\) when only one can be produced at \(t = t^*\) can be stated as

\[
\text{NPV}_{1,2;t} = \text{MAX}_{1,2;t} - \Sigma (C_D)_i \quad \text{for } i = 1, 2 \quad \text{Equation 3-3}
\]

Choosing Among Several Product Initiative Options. When a firm has more than two product development possibilities in its opportunity set, the options value of developing more than two products can be found by applying Johnson's (1987) analysis of the value of the option to choose the maximum of several risky assets. Let \(\text{MAX}_{1,2,...,n;t}\) denote the value at time \(t\) of the option to choose at \(t = t^*\) the maximum (i.e., most valuable) product among \(n\) developed products (\(n \geq 2\)). Applying Johnson's option pricing model to the basic model of product development gives the following expression for \(\text{MAX}_{1,2,...,n;t}\):

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\[
\text{MAX}_{1,2...n; t} = \\
V_{1,0} N_n [d_1(V_{1,t}, C_P, (\sigma_1)^2), \\
d_1(V_{1,t}, V_{2,t}, (\sigma_{12})^2)...d_1(V_{1,t}, V_{n,t}, (\sigma_{1n})^2), \\
(\rho_{112}, \rho_{113}...\rho_{11n}) + \\
V_{2,t} N_n [d_1(V_{2,t}, C_P, (\sigma_2)^2), \\
d_1(V_{2,t}, V_{1,t}, (\sigma_{12})^2)... \ d_1(V_{2,t}, V_{n,t}, (\sigma_{2n})^2), \\
(\rho_{212}, \rho_{223}...\rho_{22n})] \\
... + V_{n,t} N_n [d_1(V_{n,t}, C_P, (\sigma_n)^2), \ d_1(V_{n,t}, V_{1,t}, (\sigma_{1n})^2)... \\
d_1(V_{n,t}, V_{n-1,t}, (\sigma_{(n-1)n})^2), \rho_{n1n}, \rho_{n2n}...\rho_{n(n-1)n}] \\
- e^{-r(t^*-t)} C_P \left(1 - N_n [-d_2(V_{1,t}, C_P, (\sigma_1)^2), -d_2(V_{2,t}, C_P, (\sigma_2)^2), \\
...-d_2(V_{n,t}, C_P, (\sigma_n)^2), \rho_{12}, \rho_{13}...\rho_{1n}] \right)
\]

Equation 3-4

where

\[N_n[... ] = \text{the n-variate standard normal cumulative probability}\]

\[d_1(V_{i,t}, V_{j,t}, (\sigma_{ij})^2) = \left[\ln(V_{i,t}/V_{j,t}) + (1/2)(\sigma_{ij})^2(t^*-t)\right]/\sigma_{ij}\sqrt{(t^*-t)}\]

\[\rho_{ijk} = \left( (\sigma_i)^2 - \rho_{ij}\sigma_i\sigma_j - \rho_{ik}\sigma_i\sigma_k + \rho_{jk}\sigma_j\sigma_k \right)/\sigma_{ij}\sigma_{ik}\]

This complex equation expresses the value of the option to choose the single most valuable of \(n\) newly developed products at \(t = t^*\) as the sum of the value of the expected revenue stream from each product development opportunity, conditional on that revenue stream being positive and having the greatest value among the \(n\) possible revenue streams, minus the expected value of the cost of producing one new product (assumed to be the same for all \(n\) products), conditional on at least one product having a revenue stream whose present value at \(t = t^*\) \((V_{i,t^*})\) exceeds \(C_P\), the present value at \(t = t^*\) of
the cost of production (Johnson 1987).

Value-Maximizing Strategy for the Single Product Firm. When a firm has the opportunity to develop two or more products, but is constrained to produce only one product at $t = t^*$, the net present value at time $t$ of the real option created by developing $n$ ordinary products ($P_1, P_2, \ldots P_n$), when $n \geq 3$ and when only one product can be produced at $t = t^*$, can be stated as

$$\text{NPV}_{1,2,\ldots,n; t} = \text{MAX}_{1,2,\ldots,n; t} - \sum (C_D)_i \quad \text{for } i = 1, 2, \ldots n \quad \text{Equation 3-5}$$

Note that $\text{NPV}_{1,2,\ldots,n; t}$ as given in Equation 3-4 reduces to $\text{NPV}_{1,2; t}$ as given by Equation 3-2 for $n = 2$ (Johnson 1987, p. 281) and reduces to $C_{i,t}$ as given by Equation 2-10 for $n = 1$ (and $\delta = 0$). In this regard, for the firm constrained to produce only one ordinary product in the basic model of product development, Equation 3-5 can be considered the general equation for the value of an option to choose a single developed product at time $t$ for any number of products $i = 1, 2, \ldots n$.

The decision rule that gives the value-maximizing strategy for the single-product firm with multiple product development opportunities is as follows: When the firm is constrained to produce only one product but has $n \geq 1$ ordinary product development opportunities, the firm should develop the number ($1 \leq i \leq n$) and combination of products that gives the maximum positive $\text{NPV}_{1,2,\ldots,n; 0}$, as given by Equation 3-5. If no combination of product development opportunities gives a positive $\text{NPV}_{1,2,\ldots,n; 0}$, the firm should not develop any new products in its current opportunity set.

Sensitivity of $\text{MAX}_{1,2; t}$ and $\text{MAX}_{1,2,\ldots,n; t}$ to Underlying Variables. Stulz (1982) analyzed the comparative statics of the option to choose the minimum of two risky assets, $\text{MIN}_{1,2; t}$. Since $\text{MAX}_{1,2; t} = C_{1,t} + C_{2,t} - \text{MIN}_{1,2; t}$, the sensitivity of $\text{MAX}_{1,2; t}$ can be found by combining the sensitivities of $C_{1,t}$, $C_{2,t}$, and $\text{MIN}_{1,2; t}$, as shown in the table in Figure 3-4.

Not surprisingly, this table shows that increases in the value of $V_{1,t}$ or $V_{2,t}$
(the revenue streams associated with products \( P_1 \) and \( P_2 \)) or decreases in \( C_P \) (the cost of production) will result in increases in \( \text{MAX}_{1,2,t} \). The effects of changes in \( \sigma_1 \) or \( \sigma_2 \), however, depend on the relative values of \( V_{1,t} \), \( V_{2,t} \), and \( C_P \). However, for the not uncommon case where \( V_{1,t} \) and \( V_{2,t} \) have approximately comparable values and are greater than \( e^{-rt^*} C_P \), \( \text{MAX}_{1,2,t} \) increases with increases in either \( \sigma_1 \) or \( \sigma_2 \).

An important mode of behavior for \( \text{MAX}_{1,2,t} \) is that it strictly decreases with increases in \( \rho_{12} \), the coefficient of correlation between \( V_{1,t} \) and \( V_{2,t} \). Since \( V_{1,t} \) and \( V_{2,t} \) vary directly with the prices the firm can get for products \( P_1 \) and \( P_2 \), and since prices will vary directly with demand for the two products, \( \text{MAX}_{1,2,t} \) will decrease with increasing correlation of the demand for the products \( P_1 \) and \( P_2 \). In the extreme case, the single-product firm might be able to maximize \( \text{MAX}_{1,2,t} \) by developing two products for which demand is perfectly negatively correlated, ceteris paribus. Similarly, the firm would gain nothing over the option value of the most valuable single product by developing a second product whose value is perfectly correlated with the first product.

The sensitivity of \( \text{MAX}_{1,2,t} \) shown in Figure 3-4 is that it increases with increasing time to completion of development, \( t = t^* \). This sensitivity could be reversed, however, for options on products whose value depreciates over time (\( \delta > 0 \) in Equation 2-10) or for options which are costly to hold (discussed in Chapter 4).

The sensitivity of \( \text{MAX}_{1,2,...,n,t} \) cannot be stated in general terms for most of the underlying variables. For those variables, the sensitivity will depend on the specific values of the variables associated with each new product. However, Johnson (1987) does derive two general properties of \( \text{MAX}_{1,2,...,n,0} \).

First, \( \text{MAX}_{1,2,...,n,t} \) increases as \( n \) increases (so long as demand for the \( n \)th product is not perfectly correlated with demand for any of the other \((n - 1)\)
products. Second, $\text{MAX}_{1,\ldots,n;\tau}$ can have "very large" values for large $n$ or large $t^*$. (As noted above, however, this sensitivity to $t^*$ can be reversed for $\delta > 0$, a result which differs from Johnson's result for financial options.)

3.3 Initiative Options When the Firm Is Constrained To Produce a Maximum of $m$ Products

When a firm is unconstrained in development resources, is constrained to produce no more than $m$ multiple products at $t = t^*$, and has more than $m$ product development possibilities in its opportunity set, the real options value of developing more than $m$ new products is analogous to the value of the option to choose up to $m$ maxima of $M$ risky assets, where $M > m$. The contingency structure for a firm's product development opportunities in this case is shown in Figure 3-5.

No options pricing model for this type of option has been formally developed in the options literature, although a general valuation equation for such an option could be of great use in product development decisions since firms often have to make this kind of valuation. In lieu of a formal pricing model for this type of option, an option to choose the $m$ most valuable of $M$ risky assets (like new products) may be valued by constructing a duplicating portfolio consisting of combinations of options on the $M$ risky assets. For example, the value of $\text{MAX}_{2,3;\tau}$, the option to choose the most valuable two of three new products ($A$, $B$, and $C$) at $t = t^*$ can be duplicated by the portfolio

$$\text{MAX}_{2,3;\tau} (A,B,C) = \text{MAX}_{1,2;\tau} (A,B) + \text{MAX}_{1,2;\tau} (B,C) + \text{MAX}_{1,2;\tau} (A,C)$$

$$- \text{MAX}_{1,3;\tau} (A,B,C) \quad \text{Equation 3-6}$$

In his equation, the minus sign for $\text{MAX}_{1,3;\tau} (A,B,C)$ indicates that a call is being written on the maximum of $A,B$, or $C$. Writing such a call decreases the value of the duplicating portfolio, but corrects for the presence of three options on maxima when only two are included in $\text{MAX}_{2,3;\tau} (A,B,C)$. Since both $\text{MAX}_{1,2;\tau}$ and $\text{MAX}_{1,3;\tau}$ have analytic solution (Equations 3-2 and 3-4, respectively), the value of $\text{MAX}_{2,3;\tau} (A,B,C)$ can be found by solving the
right-hand side of Equation 3-6. Appendix A4 explains the principle behind this valuation methodology and gives solutions for valuing options on m of M new products up to m = M = 7.

Let the option to choose the m most valuable of M new products be denoted by MAX_{m,M; t}. Increasing M by the addition of a new product option will always increase the value of the option to choose the m best product options at t = t*, provided the new product option is not perfectly correlated with one of the existing M product options. In general, MAX_{m,M; t} will also increase in value with increasing V_{i,t} and with decreasing costs, but it is usually not possible to predict whether higher or lower variabilities \( \sigma_v \) in V_{i,t} or in correlations between various V_{i,t} will increase MAX_{m,M; t} without reference to specific values for V_{i,t} and costs.

When a firm has the opportunity to develop M products but is constrained to produce a maximum of m products at t = t*, the net present value at time t of the real option created by developing M products (P_1, P_2, ..., P_M) when only m products can be produced at t = t* can be stated as

\[
NPV_{m,M; t} = MAX_{m,M; t} - \sum (C_D)_i \quad \text{for } i = 1, 2, ..., M
\]

Equation 3-7

where MAX_{m,M; 0} can be found by applying the methodology of Appendix A4.

Equation 3-7 leads to the decision rule that gives the value-maximizing strategy for the firm constrained to produce m new products but having M product development opportunities: The firm should develop the number and combination of products that gives the maximum positive NPV_{m,M; t}, as given by Equation 3-7; if no combination of product development opportunities gives a positive NPV_{m,M; t}, the firm should not develop any new products in its current opportunity set.

3.4 Compound Initiative Options

The valuations of product development opportunities as simple options in the preceding sections will give correct options values when the firm
commits irreversibly to developing its selected products. Although product
development does occur under such conditions (e.g., in military hardware
development and supply contracts), it is not unusual for a firm to have the
flexibility at one or more points in the development process to choose whether
or not to continue developing a given product. This flexible development
approach, which will be referred to here as phased development gives the
firm a new option to decide at some intermediate point whether or not to
continue on to the next phase of design. In such cases, a product initiative
option becomes an option that depends not just on the firm's initial decision
at $t = 0$ to begin development, but also on an affirmative decision at some
intermediate point $t = t^*$ to continue development. Options like this belong to a
special class of options called compound options.

As an illustration of how the product development process can be phased
and thereby structured as a series of compound options, Section 3.7
summarizes the phased development of the Canon Personal Copier. This
section, however, first discusses the general impact on a product initiative
option's value of adopting a phased development strategy.

When the firm structures its development process to have one or more
intermediate decision points, the firm is in effect converting a simple product
initiative option to a compound initiative option. A later section (3.5) will
show that the net present value -- and thus the strategic flexibility -- of a
product development opportunity will be greater when the development
process is decomposed into compound options through phased development
than will be the case when the decision to develop at $t = 0$ is irreversible and
creates a simple option. First, however, this section applies Geske's (1977 and
1979) compound options pricing models to develop valuation equations for
compound product initiative options held by an unconstrained firm.

Suppose that a firm that is unconstrained in development and production
can use a phased development plan that gives it the ability to review each
product under development at some intermediate time $t = t^*$ in the
development process and to decide at that point whether to continue
developing the product. Figure 3-6 shows the contingency structure for the
firm's product development process in this case. At $t = 0$, the firm evaluates
its opportunity set of product development opportunities and selects all
positive net present value product opportunities for initial development. The firm then pays \( C'_D \), the present value of development costs for each product up to the intermediate decision point \( t = t^* \), and begins development. At \( t = t^* \), the firm again evaluates each product under development and selects those product development opportunities that have an options value at \( t = t^* \) that exceeds \( C''_D \), the present value at \( t = t^* \) of the cost of completing development.

For each positive net present value product at \( t = t^* \), the firm then pays \( C''_D \), and completes development. On completing development at \( t = t^* \), the firm evaluates its new product production options and determines which new products will generate a revenue stream whose present value \( V_{i,t^*} \) at \( t = t^* \) exceeds \( C_P \), the present value at \( t = t^* \) of the cost of producing a new product. The firm then pays \( C_P \) to exercise each new product production option with a positive net present value, and begins production of the selected products.

Given this contingency structure, each new product idea in the firm's opportunity set at \( t = 0 \) can be viewed as an opportunity to create an option to choose at \( t = t^* \) whether to complete development, which if exercised will create an option to choose at \( t = t^* \) whether to produce a new product.

Applying Geske's (1977 and 1979) option pricing model for a compound European call option to the basic model of product development gives the following equation for \( CC_{i,t} \), the real options value at \( 0 \leq t \leq t^* \) of a compound product initiative option:

\[
CC_{i,t} = V_{i,t} N_2 \left( h + \sigma \sqrt{(t^* - t)} \right) + \sigma \sqrt{(t^* - t)} \sqrt{((t^* - t) / (t^* - t))}) \\
- e^{-r(t^* - t)} C_P N_2 \left( h, k; \sqrt{((t^* - t) / (t^* - t))}) - e^{-r(t^* - t)} C''_D N (h) \right)
\]

Equation 3-8

where

\[
h = \left[ \ln \left( \frac{V_{i,t}}{V_{i,t^*}} \right) + (r - \sigma^2/2) (t^* - t) \right] / \sigma \sqrt{(t^* - t)}
\]

\[
k = \left[ \ln \left( \frac{V_{i,t}}{C_P} \right) + (r - \sigma^2/2) (t^* - t) \right] / \sigma \sqrt{(t^* - t)}
\]

and \( V_{i,t} \) is the value of \( V_{i,t} \) at time \( t \) that solves the equation

\[
C_i(t^* - t') - C''_D = V_{i,(t^* - t')} N \left( k + \sigma \sqrt{(t^* - t')} \right) - e^{-r(t^* - t')} C_P N (k) - C''_D \)

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\( V_{i,t} \) is the minimum value that \( V_{i,t} \) must have in order for \( C_{i,t} \) to equal or exceed \( C''_D \) at \( t = t^* \). Thus, \( V_{i,t} \) defines the upper limit of the standardized normal probability distribution for the "h" term above; the cumulative probability of that distribution (up to \( V_{i,t} \)) gives the probability that the option \( C_{i,t} \) will pass the "hurdle" of at least equalling \( C''_D \) at \( t = t^* \) and that development will continue past \( t = t^* \).

Under a phased development process, the net present value at \( t = 0 \) of each product development opportunity in the unconstrained firm's opportunity set is the difference between the value of each compound product initiative option and the cost of initial product development:

\[
\text{NPV}_{i,0} = CC_{i,0} - C'_D
\]

This equation for net present value differs from the equation for the net present value of a simple product initiative option \( C_{i,0} \) (see Equation 2-6) in two ways. First, the value of the initiative option has been reduced in Equation 3-9 by the greater stringency of having to clear two hurdles -- being greater than \( C''_D \) at \( t = t^* \) and being greater than \( C_P \) at \( t = t^* \). Second, the cost \( C''_D \) of completing development of a leveraged product is now a contingent cost that becomes part of (and detracts from) the initiative option value.

When an unconstrained firm intends to convert its product development opportunities into compound initiative options by following a phased development process, the value-maximizing strategy for the unconstrained firm at \( t = 0 \) can be stated as follows: Develop all product development opportunities for which \( \text{NPV}_{i,0} = CC_{i,0} - C'_D > 0 \).

The sensitivity of compound options to their underlying variables is investigated by Geske (1979) using comparative statics analysis. Geske's analysis shows that compound options values increase with increases in \( V_{i,t} \), \( t^* \), \( r \), and \( \sigma^2 \), and decrease with increases in \( C''_D \) and \( C_P \). However, as noted previously for simple real options, the positive sensitivity of a financial compound option to increasing \( t^* \) may be reversed for a product initiative option exposed to competitive value erosion or high costs of holding the
option. For any given $t^*$, however, compound product initiative options will increase in value with increasing $t^*$, \textit{ceteris paribus.}

3.5 Simple vs. Compound Product Initiative Options

This section will show that a compound initiative option is less valuable than a simple option, \textit{ceteris paribus}, but that structuring a product initiative option as a compound option will \textit{increase} the net present value -- and thus the strategic flexibility -- of the underlying product development opportunity. The latter result is interesting because it suggests (1) that continuous evaluation of development projects could assure that the firm would invest in developing no more than the value-maximizing set of product initiative options throughout the development process, and therefore (2) that continuous review of a development project (equivalent to infinite compounding of the initiative option) could help to assure that each new product's options value helps to optimize the strategic flexibility of the firm.

A simple, intuitive explanation why compound options are worth less than simple options, all other things being equal, can be given as follows. A simple option is "transformed" into a compound option by introducing the contingency that the option will become worthless if some specified condition is not met at some time prior to the time at which the option can be exercised. In Geske's (1977 and 1979) evaluation of common stock as a compound option on a levered firm's assets, the stock becomes worthless if the value of the firm's assets is less than the face value of the firm's debt on the due date of the debt. because the firm will have to liquidate and use all its assets to pay off whatever it can of its outstanding debt.

Similarly, in a product development project, the project is dropped if the option value of the project at $t = t^*$ is less than the present value of the remaining development costs. If the project is dropped, the firm loses an option to claim the revenue stream from a new product at $t = t^*$ (or equivalently, the product initiative option becomes worthless to the firm. Thus, in the case of a compound-option stock or development project, imposing the condition that the stock or project will become worthless if it does not have at least some minimum value at some time ($t = t^*$) prior to the exercise date ($t = t^*$) increases the probability that the stock or project will
become worthless, thereby reducing the value the stock or option would have if it were a simple option free of any intermediate contingency.

Since imposing criteria which must be met at some intermediate point in order to continue a project -- i.e., phasing development -- increases the probability that one or more projects will be dropped prior to completion, phasing development may reduce the probability that a given product will be fully developed and therefore may reduce the number of products the firm has to choose from when it is ready to begin production at $t = t^*$. A decrease in the number of newly developed products available to the firm at $t = t^*$ in effect reduces the product initiative options and thus the strategic flexibility the firm would have at $t = t^*$.

Why then would a firm ever organize its development process as a phased development with intermediate decision points? The answer is that although organizing development as a compound option reduces the options value of the firm's product development opportunities, it increases the net present value of the firm's development opportunities. The increase in net present value results because the potential decline in the options value of the firm's development opportunities when they become compound options is more than offset by the potential savings to be realized from not incurring further development costs for new products that at some intermediate point in the development process become unlikely ever to be produced. This net increase in the present value of the firm's product development opportunities under phased development can be demonstrated as follows.

Geske (1979, pp. 72-73) has pointed out that a common stock valued as a compound option will have a value identical to a simple option value if the face value of the levered firm's debt is zero. In phased product development, the analogue of zero-face-value debt would be for $C''_D$ to equal zero; that is, the firm would have to pay zero additional development costs at $t = t^*$ to complete development. In this case, the simple option $C_{1,t}$ and the compound option $CC_{1,t}$ would have identical values. Since the total cost of development will be the same in each case, $C_D = C'_D + C''_D = C'_D + 0 = C'_D$. Since the option values are identical and the costs of development are identical, the net
present values $NPV_{i,t}$ of the product development opportunity valued as a compound option or as a simple option would also be identical. Thus,

$$NPV_{i,t}^{\text{simple option}} = NPV_{i,t}^{\text{compound option}}$$

for $C''_D = 0$

or equivalently

$$C_{i,t} - C_D = CC_{i,t} - C'_D$$

Equation 3-10

The product development opportunity can be converted into a "true" compound option by letting $C''_D$ become some positive amount $K$. The change in the option value of the product development opportunity will then be given by

$$dCC_{i,t} = (\partial CC_{i,t} / \partial C''_D) dC''_D = (\partial CC_{i,t} / \partial C''_D) K$$

Equation 3-11

From Equation 3-8, $\partial CC_{i,t} / \partial C''_D = -e^{-r(t'-t)} N(h) < 0$. Therefore,

$$dCC_{i,t} = -e^{-r(t'-t)} N(h) K$$

Equation 3-12

The term $-e^{-r(t'-t)} N(h)$ is bounded by $-1 \leq -e^{-r(t'-t)} N(h) \leq 0$. Thus, converting a simple option to a compound option by increasing $K$ from zero to some positive amount causes a negative change in initiative option value.

The positive increase in $C''_D$ from zero to $K$ correspondingly reduces $C'_D$ by the amount $Ke^{-r(t'-t)}$. The net change in the net present value of the product development opportunity induced by making payment of $K$, the remaining development costs at $t = t'$, contingent on the option value of the development project exceeding $K$ at $t = t'$ is then given by:

$$dNPV_{i,t}^{\text{compound option}} = dCC_{i,t} - dC'_D$$

$$= -e^{-r(t'-t)} N(h) K - (-Ke^{-r(t'-t)})$$

$$= Ke^{-r(t'-t)} [1 - N(h)]$$

Equation 3-13

Since $0 \leq N(h) \leq 1$ and $0 \leq e^{-r(t'-t)} \leq 1$, the expression $Ke^{-r(t'-t)} [1 - N(h)]$ is positive, but less than $K$. The expression $Ke^{-r(t'-t)} [1 - N(h)]$ gives the positive marginal benefit to the firm of shifting $K$ dollars of development costs from $t = 0$ to $t = t'$. Thus, phasing development so that commitments to development costs become contingent on meeting criteria at an intermediate decision point increases the net present value of a given product development opportunity. For any fixed $t = t^*$, the firm would extract the maximum possible net present
value from its product development opportunity if it could shift all development costs to \( t = t^* \). The ability of the firm to shift development costs to a later time will of course be limited by practical and technical considerations in each development project, but in general the value-maximizing firm may benefit if it can defer and make contingent as much of its development costs as it can.

Since phasing development can increase the net present value of a given product development opportunity, applying this approach to product development may convert some opportunities which would have a negative net present value if valued as simple options at \( t = 0 \) into positive net present value projects. This would result in the firm initiating more development projects, which would tend to increase the number of products the firm develops, thereby potentially increasing the number of developed products the firm will have available at \( t = t^* \) and potentially offsetting the reduction in the number of product initiative options and thus strategic flexibility the firm would experience by dropping development of some products at intermediate stages of development. Thus, the overall net effect of phased development will be to maximize the net present value of the firm's product development opportunities while providing the firm with the "right" (i.e., value-maximizing) amount of strategic flexibility at \( t = t^* \). In the extreme case, continuous review of product development projects -- that is, the conversion of development opportunities into infinitely compounded options -- would enable the firm to extract the maximum possible net present value from its product development opportunities and to invest in creating only the "correct," value-maximizing amount of strategic flexibility.

3.6 Some Preliminary Conclusions About Product-Based Strategic Flexibility

The preceding options valuations of product development opportunities as simple real options lead to some useful insights into what might constitute the optimal strategic flexibility that a firm could hope to achieve through product development under certain conditions. This section suggests two such insights. First, this section comments on the number and kinds of
product initiative options that may make up the value-maximizing bundle of initiative options that will optimize the strategic flexibility of the firm. This section also discusses the potential of phased development to contribute to the strategic flexibility of the firm.

The Number of Products the Firm Should Develop. Chapter 2 showed that a discounted cash flow analysis that ignores the value of the firm's option to choose whether or not to produce a new product will systematically undervalue product development opportunities. As this chapter has shown, the firm will maximize its value only if it develops new products until the marginal benefit (in the form of real options value) of developing an additional product falls below the cost of developing that product. Because the firm that does not recognize the full options value of its product development opportunities will systematically undervalue the marginal benefit of developing an additional product, that firm is likely to develop fewer than the value-maximizing number of products in its opportunity set. As a result, the firm is likely to achieve a sub-optimal level of strategic flexibility through product development.

Even if the production-constrained firm values its individual product development opportunities as initiative options, developing only a number of product initiative options equal to the number of products the firm can produce in the future could lead to a sub-optimal level of product development. As this chapter has shown, it is possible to value options to choose among two or more developed products (generic real options #1b and #1c). Any of these valuations can be used to show that the option to choose maxima among M developed products, where M > m, has a greater value than simply holding options on any m products in the opportunity set. (For example, in Equation 3-1, it must be the case that $\text{MIN}_{1,2,t} \leq C_{1,t}$ and $\text{MIN}_{1,2,t} \leq C_{2,t}$, therefore implying that $\text{MAX}_{1,2,t} \geq C_{1,t}$ and $\text{MAX}_{1,2,t} \geq C_{2,t}$.) Thus, even when individual product development opportunities are valued as initiative options, ignoring the value of the option to choose among multiple new products will likely lead to systematic undervaluation of product development opportunities and development of fewer than the value-maximizing number of products. Consequently, sustaining a level of
product development which will generate more products than the firm can actually produce may be a value-maximizing product development strategy for the production-constrained firm.

Similarly, phased development increases the net present value of any given product development opportunity, tends to increase the number of positive net present value development projects in the firm's opportunity set, and thus to increase the number of products the firm will put into development. Phased development can therefore add to the firm's strategic flexibility by increasing the number of positive NPV product opportunities the firm can put into development. Equally important, however, is phased development's ability to provide an ongoing check that the firm is selecting the value-maximizing number and mix of product development projects and therefore is investing in creating the optimal amount of strategic flexibility.

The Kinds of Products the Firm Should Develop. The sensitivity analyses of product initiative options in this chapter also lead to some insights into the kinds of products that are likely to maximize the net present value of the firm. The insights into value-maximizing kinds of products are much clearer for the case of unconstrained firms, but a few general properties can be observed for constrained firms as well.

For firms unconstrained in development and production, the value of a simple-option product development opportunity will increase with increases in \( r, V_{i,t} \), and \( \sigma \), and with decreases in \( C_D \) and \( C_P \).

Increases in the riskless interest rate \( r \) are unrelated to the characteristics of any product, but extraneous increases in \( r \) make all product development opportunities more valuable. Increases in options value with rising \( V_{i,t} \) or falling \( C_D \) or \( C_P \) are no surprise; any economic valuation method would give the same result. However, the increase in product initiative option value with increasing \( \sigma \), the variance of the value of the developed product, does run counter to the results of traditional valuation methods based on discounting cash flows by a price for risk-bearing (e.g., the risk-return relationship of the Capital Asset Pricing Model). From the
options perspective, if two products would generate revenue streams with the same expected value at $t = t^*$ ($V_{1,t^*} = V_{2,t^*}$) but with different variabilities (say, $\sigma_1 \neq \sigma_2$), the product with the greater variance of value ($\sigma_1 > \sigma_2$) would give a greater option value, *ceteris paribus*. In other words, options analysis suggests that if two products have equal expected values but one is considerably riskier than the other, the firm would be better off with an option on the product that has the potential to be a big winner than with an option on the "safer," more predictable product.

Analysis of financial options shows that they will increase in value with increasing exercise date $t = t^*$. This chapter has echoed the idea introduced in Chapter 2 that real options value may decrease with increasing exercise date $t = t^*$. When real options values decrease with increasing time to exercise $t = t^* -- a typical feature of technologically dynamic and volatile product markets -- the firm will be better off choosing products that can be developed quickly, all other things being equal. A corollary result is that the firm may increase the options value of a given product development opportunity if it can find ways to develop that product more rapidly. These results are also discussed further in Chapter 4.

When the unconstrained firm can create compound options through phased product development, the intermediate decision point $t = t^*$ is a variable which also affects the value of the product development opportunity. Equation 3-8 shows that for any given $t^*$, compound option values increase with increasing $t^*$. This result holds for any given $t^*$, independent of whether real options values increase or decrease with $t^*$. The net present value of a compound option development opportunity also increases with increases in deferred development costs $C''D$ and corresponding decreases in initial development costs $C'D$, increasing by an amount $[1 - e^{-r(t^*-t)} N(h)]$ for every dollar of development cost that can be deferred to $t = t^*$ (Equation 3-13). Thus, *ceteris paribus*, the value-maximizing firm will prefer products whose development can be phased so that commitments to incur the greatest fraction of total development costs are deferred for the longest possible time.

The underlying variables with perhaps the most significance for product
development strategy for the production-constrained firm are the coefficients of correlation $\rho$ among the revenue streams associated with the firm's developable products. In general, increasing the correlation between two products will always reduce the value of the option to choose the maximum of two developed products. Thus, if a firm must choose only one of two developed products to produce at $t = t^*$, it might maximize its net present value by choosing to develop two perfectly negatively correlated products, ceteris paribus. If the firm must choose $m$ maxima among $M$ products, the effect of an increase in correlation is ambiguous and will depend on exact values of other variables. Thus, finding the optimal combination of products in a constrained firm's set of product development opportunities will usually require iterative evaluations of all possible combinations of product initiative options.

**Phasing Development.** This chapter has suggested that phased product development is likely to be the value-maximizing strategy for a firm and can guide the firm in extracting the optimal amount of strategic flexibility from its set of product development opportunities. This suggestion will hold as long as any extra costs involved in phasing development do not exceed the increases in net present value which can result from phasing development. As a practical matter, phasing a project requires the firm to identify technically the milestones at which a project might most sensibly be reviewed, to plan and carry out careful project reviews, to specify the next installment of development commitments the firm would like to make at any point in time, and to negotiate those commitments with suppliers of inputs to the development process. The importance of these costs could vary widely relative to the increase in the net present value of the project which results from phasing development.

Since phasing development may add to the net present value of a development project by curtailing investments in developing products that become negative net present value projects during the development process, incurring extra costs to phase development is most likely to be value-maximizing when the uncertainty surrounding the value of a developed
product is greatest. When uncertainty about outcomes is high, there is a greater chance that a given product may turn into a negative net present value project during the development process, and phasing development will therefore give the firm an important chance to stop investing in that project at some intermediate point in development. If the technological and market outcomes of a development project have little or no uncertainty associated with them, however, technological or market conditions are not likely to change during the development process. In this case, planning and committing to the entire project at \( t = 0 \) may be optimal, because the extra costs of phasing development may exceed the increase in net present value from phasing, which is likely to be small when uncertainty is low.

3.7 Phased Development and Compound Initiative Options:

The Canon Personal Copier Development Project

The development of the Canon PC-10 and PC-20 personal copiers from 1979 to 1982 created a completely new market segment for copiers that are sufficiently lightweight, low-cost, and easily maintained to make home use practical and attractive. The developers of the PC copiers faced significant technological uncertainty about their ability to make unprecedented reductions in the size and weight of the paper handling mechanisms and the photoreceptor drum, the two most critical functional elements of any copier. Because the price the firm could expect to obtain in the market for this new kind of copier would depend on the degree to which its development staff was successful in achieving previously unimagined portability and ease of maintenance, Canon faced significant uncertainty about the ultimate value of the developed product once development was completed.

To guide the development of the PC copiers in this highly uncertain environment, Canon adopted a plan for phasing development of the personal copier. (The following discussion is based on Yamanouchi's (1989) study of the development of the Canon Personal Copier series.) At the outset of development in 1979, the development program was organized into the six phases shown in Figure 3-7. Each phase represented a commitment by the firm to invest more money and to move further in the direction of specific
technical developments. Progression from one phase to the next was made contingent on satisfactory review of the developing product at the completion of each stage.

The contingency structure implicit in Canon's phased development program is shown in Figure 3-8, which indicates how a number of multiply compounded product initiative options available to Canon in 1979 was progressively narrowed down to a single initiative option as development was completed in 1981.

In the Canon PC series development, the emphasis in each of the first four steps was on clarifying the available technical solutions and their corresponding costs. On completing the fourth stage of phased development (stage DD in Figures 3-7 and 3-8), the firm had to choose which one of a number of feasible designs ("feasibility models" in Figure 3-7) would be selected for prototype development. Interestingly, Yamanouchi refers to this step as a process of "narrowing the options" available to the firm (Yamanouchi 1979, p. 18). At the fifth stage (DE) of development, the firm had to decide whether the prototype model designed to prove the functionality of the product should be advanced to the engineering model stage, during which refinements to the design will be made to improve its manufacturability. The last stage in the phased development process for the PC series was "trial mass production" to prove and improve the manufacturability of the product design. Only after a product model successfully progressed through all six stages did Canon finally a simple initiative option to produce a new product.

Development of each of what eventually became the PC-10 copier (and a later version, the PC-20 copier) had to clear three key decision points: whether to advance each product to prototype model (phase ED), to engineering model (phase DE), and to trial mass production (phase MT). At each of these latter decision points, the technological feasibility of each product became progressively more certain, and the firm's criteria for deciding whether to continue development could become more explicitly economic. Yamanouchi does not discuss Canon's economic criteria for deciding whether to advance development of either product to a latter stage of development. In the last three stages of development, however, it is
conceivable that Canon might have had information on prices and remaining development costs sufficient to support an explicit valuation of each product development project as a compound product initiative option, using the valuation methods presented in this chapter.

Canon's phased development of the PC series copiers helped guide the firm to introduce two very profitable products. From the real options perspective, one could describe phasing development as guiding Canon to extract what is probably a large part of the maximum possible net present value obtainable from the product development opportunities included within the general new product concept of a "personal copier." In the early stages of development, phasing enabled the firm to eliminate from further development any technical approaches in its original opportunity set that were discovered to have negative net present value because full development would be too costly or would produce a product of inferior value. Eliminating product configurations that were discovered at various early stages to have negative net present value reduced Canon's potential total costs of development. In the later stages of development, Canon may have been in a position to evaluate if developing particular improvements to a product configuration would add to the options value of the product by an amount in excess of their costs of development. Thus, phasing development could have given Canon the flexibility to progressively discover the product configurations that promised to add the most to the options value of the product opportunity at the least costs of development, thereby potentially guiding Canon towards a product configuration that would maximize the net present value of the firm's new product development opportunity. (Note: there is no information in Yamanouchi's study to indicate that Canon might have attempted to apply explicit options valuations methods to this project.)
Figure 3-1: Product Initiative Options for the Unconstrained Firm (Generic Real Option #1a)

Figure 3-2: Product Initiative Options for the Firm Constrained to Produce a Single Product (Generic Real Option #1b)
Marginal Cost
or
Marginal Benefit
of Developing One More
New Product
($PV$)

Value-maximizing firm will develop products
until marginal benefit falls below marginal cost

Marginal Benefit
(Incremental Options Value)

Constant
Marginal Cost

0 1 2 3 4
Number of New Products Developed

Figure 3-3: Determining the Optimal Number of Products to Develop
When a Firm Faces Constant Marginal Costs of Development
Figure 3.4: Sensitivity of \( \text{MAX}_{1,2} \) to Underlying Variables

(Source: Stulz 1982)

<table>
<thead>
<tr>
<th>Underlying Variable</th>
<th>( V )</th>
<th>( A )</th>
<th>( C )</th>
<th>( t^* )</th>
<th>( \rho )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V )</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( A )</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C )</td>
<td></td>
<td></td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( t^* )</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>( \rho )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
</tr>
</tbody>
</table>

Note (1): Sign will be negative for sufficiently large rate of value erosion \( (k^* > 0) \) and/or sufficiently large \( t^* \).
Figure 3-5: Product Initiative Options for a Firm Constrained to Produce No More Than $m$ Products (Generic Real Option #1c)

Figure 3-6: Compound Product Initiative Options
<table>
<thead>
<tr>
<th>Classification of stage</th>
<th>Development stage</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>DA</td>
<td>Product concept stage</td>
<td>The distinctive features of the product with respect to market and technological factors are determined and the originality of the new product is investigated.</td>
</tr>
<tr>
<td>DB</td>
<td>Elemental key device stage</td>
<td>Factors (key devices, components, processes and materials) which influence product functions, are investigated.</td>
</tr>
<tr>
<td>DC</td>
<td>Feasibility model stage</td>
<td>From the results of stage DB, the feasibility of the product is investigated through studying the machine-unit function.</td>
</tr>
<tr>
<td>DD</td>
<td>Prototype model stage</td>
<td>The first trial model of the product is designed and made in the trial production plant. The functioning, cost, industrial design and serviceability of the model is investigated.</td>
</tr>
<tr>
<td>DE</td>
<td>Engineering model stage</td>
<td>A second trial model is designed, made and evaluated in the trial production plant with mass production in mind.</td>
</tr>
<tr>
<td>MT</td>
<td>Trial mass production stage</td>
<td>A few hundred units are made using mass production facilities and the problems of mass production are solved.</td>
</tr>
</tbody>
</table>

**Figure 3-7: Stages in the Phased Development of the Canon Personal Copier**
(Source: Yamanouchi 1989, page 15)
Phases in Development Process Established by Canon for Personal Copier

Product Concept Phase DA  Functional Device Evaluation Phase DB  Feasibility Model Phase DC  Prototype Model Phase DD  Engineering Model Phase DE  Trial Mass Production Phase MT

Concept #1  Concept #2  Concept #3  Concept #4  ...  Nth Concept

Early Product Concepts Are Multiple-Compound Product Initiative Options

Development Process Viewed As a "Narrowing Down" of Product Options

Compound Initiative Option

Simple Product Initiative Option

Figure 3-8: Compound Product Initiative Options in the Phased Development of the Canon Personal Copier
4. Timing Options

The preceding chapter elaborated a framework for valuing the strategic flexibility a firm gains from creating product initiative options. This chapter investigates operating options to vary the timing of a firm's exercise of its initiative options. As discussed in the strategic flexibility framework presented in Chapter 1, three kinds of timing options define the scope of the strategic flexibility a firm may have to vary the timing of its actions:

- Generic real option #2a: the option to wait;
- Generic real option #2b: the option to shut down temporarily;
- Generic real option #2c: the option to abandon.

Each of these timing options can exist only by being associated with a product initiative option (generic real options #1a, #1b, or #1c).

Methods for valuing these timing options in some typical capital budgeting settings have been developed in the options literature and are applied here to the basic model of product development introduced in Chapter 2. Section 4.1 investigates two kinds of conditions which may make it optimal to exercise a new product option as soon as development is completed at \( t = t^* \) rather than deferring exercise to some later time. The section first considers the optimal exercise time for an initiative option on a product whose value is depreciating in the marketplace. The Lockheed 1011 Tristar development project evaluated in Chapter 2 is used to illustrate how a high rate of value depreciation can make it optimal to immediately exercise a product option. A second condition which tends to favor immediate exercise exists when deferring a new product option entails significant organizational costs, the cumulative effects of which may be to reduce the value of a new product option that will be held in reserve or to impair the ability of the firm to develop future new product options. Each of these two conditions may impose significant costs on holding a new product option, and such holding costs must be weighed against the expected benefits of deferring a product option in deciding the optimal exercise time.

Section 4.2 investigates the option to wait to invest in producing a new
product, and Section 4.3 considers the option to abandon production of a product once begun. Each of these sections provides illustrative examples from the options literature to suggest representative values of these two timing options relative to the value of the underlying production project. Section 4.4 examines the timing option to shut down temporarily the production of a new product. After examining these three generic timing options, this chapter concludes by investigating the interdependent behavior of multiple timing options attached to a single initiative option.

4.1 Deferring Product Initiative Options

This section considers whether it will in general be value-maximizing for a firm to exercise a new product option immediately on completing development of a new product or to hold the product initiative option until some later exercise date. Two conditions -- depreciation of the value of the product opportunity and organizational costs of deferral -- are suggested as potentially favoring immediate exercise of a product initiative option. A value-maximizing decision rule for timing optimal exercise of an (European) initiative option is stated.

4.1.1 Real Options on Depreciating Assets

Suppose that a firm has an option on an asset (like a new product) whose value is expected to depreciate over time, and that the firm can exercise the option now or at some later time \( t = T \). Depending on the rate of expected value depreciation and on the level of uncertainty surrounding the value of the asset in the future, a European call option on the depreciating asset exercisable now may be worth more or less than the same option exercisable at \( t = T \). Whether the earlier or later option will be worth more will depend on whether the expected loss of value through asset depreciation between now and \( t = T \) is less or more than the expected value of the potential (but uncertain) increases in asset value the firm might capture during the period \( 0 \leq t \leq T \).

In general, asset value depreciation during an option holding period may result from two causes. One cause of asset value depreciation is
something of a special case, but one which has received attention in the options literature because of its importance in the valuation of natural resources (see, for example, Siegal, Smith, and Paddock 1987). When a firm holds a claim on an unextracted natural resource like crude oil or iron ore (both of which are literally underlying assets), the firm's claim is essentially an option to extract the resource by paying the cost of drilling and lifting the crude oil or mining the iron ore. Suppose a firm could extract some oil today or in one year. If the firm elects to extract the oil today, the value of the claim is the value of the lifted oil today less the costs of lifting. If the firm were to lift the oil one year from today, however, the value of the claim on the oil to be lifted one year from now will be less than the value of the claim on the oil if it were lifted today, because the expected increase in the value of the oil during the option-holding period is typically less than the market required rate of return for bearing the systematic risk of holding oil as an asset. In this case, the shortfall of the expected increase in asset value below the market-required rate of return on the asset represents an effective rate of asset value depreciation during the option holding period.

In the more general case -- which applies directly to initiative options on products in technologically dynamic and volatile product markets -- asset value depreciation during an option-holding period results whenever a portion of the cash flows on which the asset's value is based will be forfeited if exercise of the option is deferred. In contexts of competitive value erosion by imitation or diffusion (see Section 2.5), expected increases in competition leading to expected declines in prices for competing products would cause the value of a new product to depreciate while an initiative option is held by reducing the revenue stream which the firm could obtain from the sale of a product as the date for introducing the product into the marketplace moves further into the future. Similarly, the value of a new product could depreciate from expected increases in input costs or from expected declines in total unit sales.

In terms of the basic model of a product initiative option, suppose that a firm has just completed development of a new product $P_i$ at $t = t^*$. Suppose also that the firm will now choose whether to exercise its new product option
by putting the new product into production immediately, or to defer deciding whether to produce the new product until some later time $t = T$, at which time the firm may put the product into production if it so chooses. If the firm chooses not to produce now but instead to defer deciding about production until $t = T$, it is in effect trading $C_{i,t^*} = \text{Max}[0, (V_{i,t^*} - C_p)]$, the net present value of starting production at $t = t^*$, for a deferred (European call) option to claim $V_{i,T}$, the present value of the revenue stream from product $P_i$, upon payment at $t = T$ of the present value of constant production costs, $C_p$. Let the value of the deferred option be denoted by $C_{i,t^* \rightarrow T}$. If the rate of asset value depreciation is represented by a constant proportional rate of depreciation $\delta$, then the value at $t = t^*$ of the deferred option to produce new product $P_i$ at $t = T$ is

$$C_{i,t^* \rightarrow T} = V_{i,t^*} e^{-\delta(T-t^*)} N(h') - C_p e^{-r(T-t^*)} N(h' - \sigma \sqrt{(T-t^*)})$$

Equation 4-1

where

$$h' = [\ln(V_{i,t^*} / C_p) + (r - \delta + \sigma^2/2)(T-t^*)] / \sigma \sqrt{(T-t^*)}$$

(When $\delta > 0$, Equation 4-1 is equivalent to Merton's (1973a) equation for the value of an option on a stock paying a constant proportional rate dividend $\delta$.)

When $C_{i,t^* \rightarrow T} > C_{i,t^*}$, the difference $C_{i,t^* \rightarrow T} - C_{i,t^*}$ represents an expected gain in excess of the value lost through asset depreciation by deferring possible exercise of its new product option until $t = T$. The potential gains to the firm from deferring the product option can come from two sources. First, the firm may realize an unexpected increase in the value of $V_{i,t}$ over the period $t^* \leq t \leq T$, which could occur whenever there is a positive variance $\sigma_v^'$ in the value of $V_{i,t}$. Second, the firm may benefit by not having to pay $C_p$ until $t = T$ -- and then only if it exercises its option. By delaying the date on which the constant exercise price would have to be paid, the firm might realize a savings in the present value of the exercise price equal (at $t = t^*$) to $C_p (1 - e^{-r(T-t^*)})$. 

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For any opportunity to defer a product initiative option, an *optimal exercise boundary* can be determined which defines the values of $\delta$ and $\sigma_v$ at which the expected losses from asset value depreciation exactly equal the value of the potential gains from uncertainty and reduced exercise price. **Figure 4-1** shows the optimal exercise boundary for the chance to defer introduction of the Lockheed 1011 Tristar from 42 months to 48 months after beginning development based on the Lockheed 1011 Tristar example in Section 2.6. As the uncertainty $\sigma_v$ about the value of the 1011 Tristar increases, the potential gains from deferring exercise of the product option increase (assuming a fixed production "window" of 120 months) increase, so that the level of competitive value erosion $\delta$ at which immediate exercise becomes optimal also increases.

The optimal; exercise timing relationship between $\delta$ and $\sigma_v$ has an important implication for timing the exercise of a product initiative option in a product strategy. In highly competitive product markets subject to product value erosion, immediate exercise of a product initiative option is likely to be optimal unless uncertainty about the future value of the product is very great. If uncertainty is high and the rate of competitive value erosion lies below the optimal exercise boundary, deferral to a later exercise date will be optimal. However, it does not follow that if deferral is optimal now, it will always be optimal to defer exercise of the option, because the optimal exercise relationship of $\delta$ and $\sigma_v$ also depends directly on the ratio of $V_{i,t}$ to $C_p$, which changes over time. Thus, it may be the case that deferral may be optimal for a realization $V_{i,t}$ but will be suboptimal for a later realization $V_{i,t+\Delta t}$. Thus, optimal exercise of initiative options will require continuous monitoring of changes in $V_{i,t}$, as well as ongoing evaluations of $\delta$ and $\sigma_v$.

### 4.1.2 Organizational Costs of Deferring a Product Initiative Option

When a firm has a new product option and exercises it immediately, the firm incurs a cost $C_p$, the present value of production costs, to exercise the
product option. The firm that defers production of a new product, however, may also incur some significant organizational costs associated with deferring a new product option. Before the firm can determine whether it is preferable to exercise or defer a new product option, these organizational costs must be identified, valued, and weighed against the expected net gains (if any) from deferring the new product option.

Some potentially significant costs of deferring a new product option result from the fact that organizations have imperfect memories and are subject to changes in motivational levels. Deferring production of a new product may require significant costs to mothball a new product design for later production. Deferral of a major new product initiative option may also adversely affect the attitudes and motivation of product development workers and impair their ability of the organization to develop other new products. Both of these impacts could represent significant opportunity costs of deferring a new product option to some future date. Although some of the hard costs of mothballing a product design may be calculable, determining an accurate cost figure for the adverse impact of deferral on future development capability would no doubt be difficult and perhaps impossible. Nevertheless, ignoring a significant opportunity cost on the grounds that it would be difficult to quantify precisely would be an unacceptable practice and could lead to strategically disastrous results. Therefore, to assess the overall impact of product initiative option deferral, the best obtainable estimates of these organizational costs, denoted here as $C_{org}$, must be sought out and weighed against any expected benefit of deferring a new product option.

**Costs of Mothballing a New Product Design.** Developing a new product involves not just the creation of a new product design, but also the development or adaptation of manufacturing equipment, maintenance and service procedures, marketing programs, distribution systems, and other organizational capabilities. As a normal part of the development process, some part of the organization's knowledge about the new product, its production, and intended post-production activities is recorded in engineering drawings or written in various written documents. Inevitably,
however, a good deal of detailed knowledge about the new product will not be written down during the normal course of a development project. In particular, a multitude of details related to producing a new product will be worked out but not recorded in full.

In product markets marked by competition based on rapid product development, development teams composed of designers, production engineers, marketing staff, and service personnel are increasingly being given continuous responsibility for both developing a new product and engineering and starting up the manufacturing line (Takeuchi and Nonaka 1986). When such a team approach to new product development is used, there is likely to be a high level of reliance on verbal communication and the shared "memory" of the team. In such cases, the tendency not to document in great detail may be especially pervasive.

If a firm wants to defer production of a new product option, it will usually have to take positive steps to guarantee the continued capability of the organization to put the new product into production at some future time. The organization may try to accomplish this by investing in creating as complete a set of documentation on the new product as possible or by trying to keep the development team intact for later re-deployment when the firm decides to exercise the product option. Whether it tries to capture a new product in complete documentation or elects to maintain the human assets who have knowledge of the new product, the firm that is considering deferring development or production of a new product must try to place a reasonable value on these costs of mothballing a new product design and must weigh these costs against the expected benefit of holding over a product option.

Opportunity Cost of Impaired Development Capability. It has often been remarked that new products are the lifeblood of a business. New products offer the chance to expand markets, increase revenues, and add new skills -- all of which can increase the value of the firm. The product development capability of the firm is therefore the wellspring of potential net additions to the present value of the firm, and preserving and improving its product development capability ought to be of paramount importance to the firm.

Product development is an intensely human activity, and the potency of
a firm's development capability will depend on human factors that stubbornly resist quantification. One such fundamental determinant of a firm's development capability is the confidence and organizational momentum brought by past successes with new products. As two leading researchers of product development have noted:

Perhaps the most exciting benefit [of new products]...is the most intangible: corporate renewal and redirection. The excitement, imagination, and growth associated with the introduction of a new product invigorate the company's best people and enhance the company's ability to recruit new forces. New products build confidence and momentum. [Emphasis added.]

(Wheelwright and Sasser 1989, page 112)

The emphasis on product introductions above is intended to highlight the importance of introducing newly developed products while the development organization is still primed to bring the product to market. Introducing a new product within a reasonable period after completing development can contribute to the confidence and momentum of the team that developed the product if the product proves successful. Conversely, not introducing a newly developed product can entail an opportunity cost in the form of reduced effectiveness in product development resulting from lost confidence and momentum. (A similar effect may result when development is deferred or interrupted.) When key development people lose their enthusiasm for development or exit the firm, the firm may suffer a serious strategic loss in the form of impaired ability to develop future products.

Although it is probably impossible ever to determine precisely the value of missed or diminished opportunities to develop future products which may result from exits by discouraged employees, these eventualities may have such far-reaching consequences for a firm that the potential opportunity costs implied by a dispirited development organization may be huge, even though they cannot be specified with accuracy. The firm that is considering holding a new product option must do its best to estimate how much it will
4.1.3 Decision Rule for Optimal Exercise of Deferrable Initiative Options

When a firm has developed a new product and can either decide to produce the new product now or defer the production decision to some later date, the firm has a choice between an option to produce now or a deferred option to produce at some future date. These are mutually exclusive alternatives, each of which has its own net present value. The optimal strategy for the firm in this case is simply to choose the alternative with the greater net present value.

The net present value at \( t = t^* \) of choosing the new product option exercisable at \( t = t^* \) is simply \( \text{NPV}_{i,t^*} = C_{i,t^*} = \max [0, V_{i,t^*} - C_P] \). The net present value at \( t = t^* \) of choosing a deferred option \( C_{i,t^* \rightarrow T} \) to produce a newly developed product at a later time \( t = T \) can be stated as

\[
\text{NPV}_{i,t^* \rightarrow T} = C_{i,t^* \rightarrow T} - C_{pe} - C_{org}
\]

Equation 4-2

where as previously noted in Equation 4-1

\[
C_{i,t^* \rightarrow T} = V_{i,t^*} e^{-\delta (T-t^*)} N(d') - C_P e^{-r (T-t^*)} N(d' - \frac{\sigma_v \sqrt{(T-t^*)}}{2})
\]

\[
d' = \frac{\ln(V_{i,t^*/C_P} + (r - \delta + \sigma_v^2/2)(T - t^*))}{\sigma_v \sqrt{(T - t^*)}}
\]

\[
\delta = \text{rate of competitive value erosion}
\]

\[
C_{org} = \text{present value of organization costs of deferring a product option}
\]

The value-maximizing decision rule that gives the optimal strategy for the firm considering deferring a new product option is then as follows: If \( \text{NPV}_{i,t^*} \geq \text{NPV}_{i,t^* \rightarrow T} \), exercise the product option if \( \max [0, V_{i,t^*} - C_P] > 0 \), or let the product option expire if \( \max [0, V_{i,t^*} - C_P] = 0 \). If \( \text{NPV}_{i,t^*} < \text{NPV}_{i,t^* \rightarrow T} \), defer the product option until \( t = T \).

4.2 The Timing Option to Wait to Produce a New Product

The preceding section discussed the value of the option to defer exercise
of a product initiative option to some specified future date. More typically, however, the firm may have the ability to postpone exercise to any future time it chooses. This broader ability to postpone exercise is referred to as the option to wait.

The option to wait to invest in a project has been analyzed by McDonald and Siegel (1986) for the general case in which both the present value of expected cash flows from a project and the present value of irreversible project costs are stochastic, and for the special case where project costs are constant. For simplicity and continuity with the basic options model of product development, only constant project costs are considered here. This section applies the McDonald and Siegel analysis to the model of product development to value the option to wait to invest in producing a new product.

Section 4.2.1 determines the value of the option to wait to produce a new product when the decision to begin production requires an irreversible commitment to a fixed period of production. Intrinsic to the valuation solution is the determination of the expected optimal time to begin production. Section 4.2.2 discusses the sensitivity of the option to wait to underlying variables, and Section 4.2.3 concludes the discussion of the option to wait with examples that give representative values of the option to wait relative to an underlying product option.

4.2.1 The Value of the Option to Wait and the Optimal Time to Invest

To value an option to wait to begin production of a new product, it is first necessary to determine the expected optimal time to begin production. Determining the expected optimal time to begin production requires finding the expected time of "first passage," defined as the time when the expected gain from investing in a project first equals or exceeds the expected gain from holding the option to invest in a project. This section applies McDonald and Siegel's method for finding the time of first passage and the value of the option to wait to begin production.

Begin by defining \( W_{i,t} \) as the value at any time \( t^* \leq t \leq T \) of the timing option to wait to produce newly developed product \( P_i \) at any time \( t^* \leq t \leq T \). Note that \( W_{i,t} \) can only be acquired by a firm that already possesses \( C_{i,t^*} \), the
option to produce newly developed product \( P_i \). Thus, \( W_{i,t} \) is an operating option which supplements the value of an existing product initiative option. The approach to valuing \( W_{i,t} \) followed by McDonald and Siegal (1986) is to first find \((C_{i,t^*})^W\), the value of the opportunity to produce newly developed product \( P_i \) at any time \( t^* \leq t \leq T \), and then to subtract from \((C_{i,t^*})^W\) the value of \( C_{i,t^*} \), the option to produce \( P_i \) without the option to wait. The difference \((C_{i,t^*})^W - C_{i,t^*}\) gives the value of the timing option \( W_{i,t} \).

Like other options, \( W_{i,t} \) can have no value less than zero and almost always will have some positive value. When an irreversible investment is made by paying constant production costs \( C_P \) to begin production, \( W_{i,t} \) is forfeited and some positive value will therefore be lost. Thus, in order for proceeding with production to be optimal, \( V_{i,t} \), the present value of revenues expected from beginning production at some time \( t^* \leq t \leq T \), must be greater than \( C_P \) by at least the value of \( W_{i,t} \).

Let \( R^W(t) \) be defined as the ratio of \( V_{i,t}/C_P \) at any time \( t^* \leq t \leq T \) such that \( V_{i,t} - C_P \geq W_{i,t} \). Then \( R^W(t) \) denotes the ratio of \( V_{i,t}/C_P \) at or above which it will be optimal to begin production rather than to wait. Now denote by \( t = t^- \) the time at which \( V_{i,t}/C_P \) is first expected to equal or exceed \( R^W(t) \). This time \( t = t^- \) is the time of first passage of \( V_{i,t}/C_P \) through the optimal exercise boundary established by \( R^W(t) \). Figure 4-2 illustrates the optimal exercise boundary and a first passage of \( V_{i,t}/C_P \) through \( R^W(t) \) at \( t = t^- \). As the figure also indicates, \( R^W(T) = 1 \) because it will be optimal to begin production at \( t = T \) if \( V_{i,t}/C_P \geq 1 \) (i.e., if \( V_{i,T} \geq C_P \)). Since \( W_{i,t} \) will have some positive value prior to \( t = T \), \( R^W(t) > 1 \) for \( t^* \leq t < T \).

The optimal exercise boundary \( R^W(t) \) can be found numerically, starting at \( t = T \) and working backwards through to \( t = t^* \) (see Meehan 1989 or Benninga 1989 for details on appropriate methods). The boundary \( R^W(t) \) will be the ratio of \( V_{i,t}/C_P \) that maximizes the expected present value at \( t = 0 \) of the payoff \( V_{i,t} - C_P \) at each time \( t^* \leq t \leq T \). Once \( R^W(t) \) is established, the time of
first passage $t = t^\ast$ can be determined by finding the first intersection of the expected path of $V_{i,t^\ast}/C_P$ with $R^W(t)$.

Since the option to produce $P_i$ is expected to be exercised at $t = t^\ast$, at which time exercising the product option will produce an expected benefit $V_{i,t^\ast}/C_P$, the value at $t = t^\ast$ of $(C_{i,t^\ast})^W$, the opportunity to produce $P_i$ at any time $t^\ast \leq t \leq T$, will be the expectation of the value of $V_{i,t^\ast}/C_P$ discounted back to $t = t^\ast$ at an "appropriate" discount rate "$a$" (discussed below):

\[
(C_{i,t^\ast})^W = \mathbb{E}_{t=t^\ast} [e^{-a(t^\ast - t^\ast)}(V_{i,t^\ast} - C_P)]
\]

Equation 4-3

McDonald and Siegel show that the solution to this equation is

\[
(C_{i,t^\ast})^W = C_P \left(R^W(t^\ast) - 1 \right) \left[ (V_{i,t^\ast}/C_P) / R^W(t^\ast) \right]^\varepsilon
\]

Equation 4-4

The exponent $\varepsilon$ is also discussed below. For any specified $V_{i,t^\ast}$, Equation 4-4 is solved by finding the $R^W(t^\ast)$ that maximizes the right hand side of the equation.

Once $(C_{i,t^\ast})^W$ is known, the expected value of the timing option $W_{i,t^\ast}$ will be the difference between the expected value of holding the product option until $t = t^\ast$ and the value of the option to exercise the product option only at $t = t^\ast$:

\[
W_{i,t^\ast} = (C_{i,t^\ast})^W - C_{i,t^\ast} = (C_{i,t^\ast})^W - \text{Max} \left[ 0, (V_{i,t^\ast} - C_P) \right]
\]

Equation 4-5

Suppose now that there is no fixed expiration date to the option to wait to begin production. When $T \to \infty$, $R^W(t)$ will not be sensitive to time, but rather will have a constant value greater than 1, which will be denoted here by $R^W$. The value of the option to wait without limit, denoted by $W_{i,t,\infty}$, is illustrated in Figure 4-3 for the case of first passage through a constant $R^W$. When an option to wait is infinitely lived, which is often the case, the constant value of $R^W$ allows a more direct solution to Equation 4-4. Since $V_{i,t^\ast}/C_P = R^W$, the expression $V_{i,t^\ast}/C_P$ in Equation 4-3 becomes $C_P (R^W - 1)$ and reduces to the following equation for the value of the opportunity to produce product $P_i$ at any time in the future:

\[
(C_{i,t^\ast})^{W,\infty} = \text{Maximize} \left[ C_P (R^W - 1) \mathbb{E}_{t=t^\ast} [e^{-a(t^\ast - t^\ast)}] \right]
\]

Equation 4-6

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This equation is solved by varying \( RW \) to find the value of \( RW \) and attendant optimal exercise time \( t = t^- \) that gives the greatest value for the right hand side of the equation. Once \((C_{i,t^*})W_{i,t^*}\infty \) is found, the value of an infinitely lived option to wait \( W_{i,t^*,\infty} \) is obtained by

\[
W_{i,t^*,\infty} = (C_{i,t^*})W_{i,t^*} - C_{i,t^*} = (C_{i,t^*})W_{i,t^*} - \text{Max}[0, (V_{i,t^*} - C_P)]
\]

Equation 4-7

McDonald and Siegal (1986, page 715) reason that the appropriate rate of return on an investment opportunity which includes the option to wait will be a weighted average of the required rates of return on assets with the same variances and market correlations as the revenue streams and cost streams of the optioned project. Using the risk-return relationships of the Capital Asset Pricing Model, let \( \alpha_{eq} \) denote the required rate of return on the revenue stream \( V_{i,t} \). The required rate of return on constant production costs \( C_P \) or constant development costs \( C_D \) will be \( r \), the risk-free rate. The weighted average required rate of return on the investment opportunity is then given by

\[
a = \varepsilon \alpha_{eq} + (1 - \varepsilon) r
\]

Equation 4-8

The weighting coefficient \( \varepsilon \) is a function of the differences between the required rates of return for revenues and costs and the expected rates of change in the present values of revenues and costs. Let \( \delta_v \) be the constant proportional rate of asset value erosion. For constant costs of production \( C_P \) or constant costs of development \( C_D \), let \( \delta_c = r - \alpha_c = r \). Also let \( \sigma_v \) be the variance of \( V_{i,t} \), \( \sigma_c = 0 \) be the variance of costs, and \( \rho_{vc} = 0 \) be the coefficient of correlation between \( V_{i,t} \) and costs. Applying McDonald and Siegal's (1986) Equation 12 to this case, the weighting coefficient is given by

\[
\varepsilon = 1/2 - (\delta_c - \delta_v)/(\sigma_v)^2 + \sqrt{[(\delta_c - \delta_v)/(\sigma_v)^2 - 1/2]^2 + 2\delta_c/(\sigma_v)^2}
\]
\[ = 1/2 - (r - \delta_v)/(\sigma_w)^2 + \sqrt{[(r - \delta_v)/(\sigma_w)^2 - 1/2]^2 + 2r/(\sigma_w)^2} \]

Equation 4-9

where \((\sigma_w)^2 = (\sigma_v)^2 + (\sigma_c)^2 - 2 \rho_{vc} \sigma_v \sigma_c = (\sigma_v)^2\) for constant costs.

Equation 4-8 requires that, if a production option can be and is expected to be held beyond \(t = t^*\) and if \(\delta_v > \delta_c > 0\), the expectation \(E_{t=t^*}[V_{i,t} - C_P]\) from the production opportunity must be discounted at a higher discount rate than the required rate of return from a project to produce \(P_i\) which begins production at \(t = t^*\). The higher discount rate reflects the increasing divergence in the relative values of \(V_{i,t}\) and \(C_P\) as the optimal exercise date \(t = T\) moves further into the future.

4.2.2 Sensitivity of the Option to Wait and the Optimal Exercise Time to Underlying Variables

The values of both the option to wait for a limited time \((C_{i,t^*})^W\) and of the option to wait for an unlimited time \((C_{i,t^*})^{W,\infty}\) are increasing functions of \(\sigma_v\), the variance of \(V_{i,t}\). Intuitively, as the range of possible outcomes of \(V_{i,t}\) increases, the possible gains from holding a deferrable option on \(V_{i,t}\) increase, while the worst case outcome of holding the deferrable option remains a zero gain if the underlying option is simply allowed to expire. It is also the case that \(W_{i,t^*}\) and \(W_{i,t^*,\infty}\) are increasing functions of \(\sigma_v\). From Equation 4-5,

\[ W_{i,t^*} = (C_{i,t^*})^W - C_{i,t^*} \]

\[ \partial(W_{i,t^*})/\partial \sigma_v = \partial(C_{i,t^*})^W/\partial \sigma_v - \partial C_{i,t^*}/\partial \sigma_v \]

Equation 4-10

Although \(\partial C_{i,t^*}/\partial \sigma_v > 0\), it must be the case that \(\partial(C_{i,t^*})^W/\partial \sigma_v \geq \partial C_{i,t^*}/\partial \sigma_v\), because \((C_{i,t^*})^W\) has an extended exercise date and thus could capture more unexpected increases in \(V_{i,t}\) after \(t = t^*\) which result from a larger \(\sigma_v\).

Therefore \(\partial(W_{i,t^*})/\partial \sigma_v > 0\), and the option to wait will become more valuable.
with increasing uncertainty.

When production costs $C_P$ are constant, both $W_{i,t^*}$ and $W_{i,t^*,\infty}$ are decreasing functions of the weighted average discount rate $\alpha$. From Equations 4-8 and 4-9, the two options to wait must decrease with increasing $\alpha_{eq}$, the required rate of return from $V_{i,t}$, implying that $W_{i,t^*}$ and $W_{i,t^*,\infty}$ decrease with increases in the risk-free interest rate $r$. Both options to wait are also decreasing functions of $\delta_v$, within the result that options to wait decrease in value when $V_{i,t}$ is exposed to competitive value erosion.

Increases in the value of $V_{i,t^*}$ relative to $C_P$ will tend to induce earlier exercise of the underlying option (the option to produce $P_i$) and thus decrease the relative importance of $W_{i,t^*}$ and $W_{i,t^*,\infty}$ to the total value of the product initiative option. The intuition here is that increases in the value of $V_{i,t^*}$ relative to $C_P$ directly increase the value of the production opportunity and the ratio $V_{i,t^*}/C_P$, thereby shortening the expected time when $V_{i,t}/C_P$ will first equal or exceed $R^W(t)$ or $R^W$, ceteris paribus. Reducing the expected time of first passage reduces the time to the expected exercise date of the option, thereby lowering the expected value of the option to wait relative to the underlying option to produce $P$.

Decreases in $\sigma_v$ or $\alpha_v$ or increases in $r$ or $\delta_v$ will tend to reduce the time $t = t^*$ at which exercising a production option will be optimal. However, in cases where immediate exercise of $(C_{i,t^*})^W$ at $t = t^*$ will be optimal (e.g., for large values of $\delta_v$), incremental changes in these underlying variables may have no effect on the optimal exercise time.

4.2.3 Typical Values of the Option to Wait Relative to the Underlying Option to Produce

McDonald and Siegal (1986) provide a numerical example which shows that the option to wait can be a very valuable option for a broad range of $\sigma$ and
δ. For an infinitely lived option to wait to begin a low uncertainty project
(variance \( \sigma_v = \sigma_c = 0.02 \) annually) with modest \( \delta_v = \delta_c = 0.10 \) for both prices
and costs and with \( V_{i,t^*} = C_P \), McDonald and Siegal's results show that the
option to wait \( W_{i,t^*, \infty} \) would have a value equal to 16% of \( V_{i,t^*} \), the present
value of the expected cash flows from the project without the option to wait.

For the same stated \( \sigma_v, \sigma_c, \delta_v, \) and \( \delta_c \) parameters, but allowing \( V_{i,t^*} \neq C_P \), exercise of the option to produce new product \( P_i \) would be suboptimal at \( t = t^* \) if undertaken for any ratio of \( V_{i,t^*}/C_P \) less than 1.56.

If the uncertainties about the revenue stream and production costs are
characterized by more typical uncertainty levels (variances \( \sigma_v = \sigma_c = 0.20 \)
annually), the optimal exercise ratio of \( V_{i,t^*}/C_P \) would jump to 3.73, because
the firm could gain from unexpected increases in \( V_{i,t^*} \), but would be shielded
from bearing unexpected increases in \( C_P \). If production costs are constant,
as in the basic model of product development of this thesis, the optimal
exercise ratio \( V_{i,t^*}/C_P \) would fall, but would still be significantly above one at
approximately 2.62.

4.3 The Timing Option to Abandon Production of a New Product Option

The option to abandon a project allows a firm the strategic flexibility to
terminate a project whenever quitting a project will contribute more to the
net present value of the firm than continuing the project. Quitting a project
will be value-maximizing when the salvage value of a project is greater than
the value of the project if continued. In conventional capital budgeting
analysis, the benefit of continuing a project is simply taken to be the net
present value of future cash flows (revenues and costs), including the salvage
value of project assets at the end of the project. As Myers and Majd (1983) and
other options analysts have made clear, however, the value of continuing a
project ought also to include the value of the option to abandon the project prior to the expected termination date of the project, if such an option is in fact available to the firm.

As Myers and Majd also point out, conventional capital budgeting analysis also typically interprets the salvage value of project assets too narrowly by simply assuming a terminal salvage value. As options analysis shows, proper evaluation of salvage value not only must consider the salvage value of a project's assets throughout the project life, but must also recognize that salvage value consists of the value of the nested options to abandon productive assets to their next-best use, their second next-best use, their third next-best use, and so on through all possible subsequent re-uses until the end of the physical lives of the assets (Myers and Majd 1983, page 9). In practice, trying to calculate the value of such complex nested options may be impractical. The approach taken in this section is to assume that a project's assets can be correctly valued by markets for second-hand assets at any point in the project life, and thus that the observable market value of a project's used assets will include these multiple nested options to abandon. In this analysis, therefore, the salvage value of a project's assets is taken to be a stochastic market value of the used assets.

Section 4.3.1 examines the value of the option to abandon production and the optimal time to abandon production. Section 4.3.2 examines the sensitivity of the option to abandon to underlying variables, and Section 4.3.3 considers typical values of the option to abandon.

4.3.1 The Value of the Option to Abandon Production

The value of the option to abandon a project has been studied by Myers and Majd (1983) and by McDonald and Siegal (1986). Myers and Majd characterize the option to abandon as an American put option to sell the value of the project's forefeited cash flows and the forefeited option to abandon for an uncertain exercise price equal to a project's assets (of uncertain salvage value). In this characterization, abandonment will occur if and when \( (V_{i,t})^A \), the present value of continuing production of product \( P_i \), falls below \( SV_{i,t} \), the current salvage value of the assets used in the project. Myers
and Majd emphasize that \((V_{i,t})^A\) includes not just the value of the project's remaining cash flows, \(V_{i,t}\), but also \(A_{i,t}\), the value of the operating option to abandon the project at any future time up to and including the end of the project. (This embedded timing option to abandon production is denoted here by adding the superscript \(^A\) to \(V_{i,t}\).) Thus, abandonment will be optimal only if \(V_{i,t}\) falls below \(SV_{i,t}\) by some positive amount equal to the value of the option to abandon, \(A_{i,t}\). This is shown diagrammatically in Figure 4-4, which indicates the optimal exercise boundary for the option to abandon (located below \(SV_{i,t}\)) to which \(V_{i,t}\) must fall before abandonment is optimal.

McDonald and Siegal (1986) provide an interpretation of their valuation model for the option to wait (Section 4.2) which also allows valuation of the option to abandon. In this interpretation, the firm with an option to abandon a project is construed as having an option to wait to invest an ongoing project’s present value at any point in time to acquire a second "abandon project" whose payoff is the salvage value of the ongoing project's assets. Thus, \(V_{i,t}\) in the McDonald and Siegal option to wait to begin production is replaced in an option to abandon by a stochastic salvage value of production assets, \(SVP_{i,t}\), with dynamics

\[
dSVP_{i,t} / SVP_{i,t} = \alpha_{svp} \, dt + \sigma_{svp} \, dz \tag{4-11}
\]

Equation 4-11

Note that by setting \(\sigma_{svp} = 0\), the salvage value \(SVP_{i,t}\) can be made certain, declining at a constant rate set by a negative-valued \(\alpha_{sv}\).

Production costs \(C_P\) from from the option to wait to begin production are replaced in the option to abandon by the present value of continuing production. If \(C_P\), the present value of all production costs, is paid at \(t = t^*\) as assumed in the basic model, then \((V_{i,t})^A = V_{i,t} + A_{i,t}\) and \(SVP_{i,t}\) will include the salvage value of all production assets acquired at \(t = t^*\). By the argument introduced by Myers and Majd and extended by McDonald and Siegal, abandonment of production will be optimal when the ratio \(V_{i,t}/SVP_{i,t}\) makes
its first passage through an optimal abandonment boundary $R^A(t)$. Optimal exercise of the option to abandon production will occur when $V_{i,t}$ first falls below $SVP_{i,t}$ by some positive amount equal to the forfeited option to abandon $A_{i,t}$. Thus, for a finite lived option to abandon, the optimal abandonment boundary $R^A(t) < 1$ for $t^* \leq t < T$.

Assuming a finite-lived option to abandon and applying McDonald and Siegal's approach, the expected present value at $t = t^*$ of the "project" to abandon production of product $P_i$ at the optimal time $t = t^-$ ($t^* \leq t^- \leq T$) in exchange for the salvage value $SVP_{i,t^-}$ is given by:

$$A_{i,t^*} = V_{i,t^*} \left[ R^W(t^-) - 1 \right] \left[ \left( \frac{SVP_{i,t^*}}{V_{i,t^*}} \right) / R^W(t^-) \right]^\varepsilon$$  \hspace{1cm} \text{Equation 4-12}$$

This equation is simply a restatement of Equation 4-4 for an option to wait to invest in acquiring $SVP_{i,t}$ for a cost of $V_{i,t}$. McDonald and Siegal show that this equation can be reduced to

$$A_{i,t^*} = V_{i,t^*} \left( 1 - R^A(t^-) \right) \left[ \left( \frac{SVP_{i,t^*}}{V_{i,t^*}} \right) / R^A(t^-) \right]^{1-\varepsilon}$$  \hspace{1cm} \text{Equation 4-13}$$

where

$$R^A(t^-) = (\varepsilon - 1) / \varepsilon$$  \hspace{1cm} \text{Equation 4-14}$$

$$\varepsilon = 1/2 - (\delta_v - \delta_{svp})/(\sigma_a)^2 + \sqrt{[(\delta_v - \delta_{svp})/(\sigma_a)^2 - 1/2]^2 + 2\delta_v/(\sigma_a)^2}$$  \hspace{1cm} \text{Equation 4-15}$$

In Equation 4-15, $(\sigma_v)^2 = \text{variance of the present value of remaining project cash flows} V_{i,t}$, $(\sigma_{svp})^2 = \text{variance of the salvage value} SVP_{i,t}$, $(\sigma_a)^2 = (\sigma_v)^2 + (\sigma_{svp})^2 - 2\rho_{vs} \sigma_v \sigma_{svp}$, and $\rho_{vs} = \text{the coefficient of correlation between} V_{i,t} \text{and} SVP_{i,t}$. With the option to abandon valued by Equation 4-13, we can now find the net present value of the option to produce new product $P_i$ when production may be abandoned at any time. At $t = t^*$, the time at which the decision to produce or not to produce must be made in the basic model, the net present value of the production option with the abandonment option is
\[(\text{NPV}_{i,t^*})^A = \text{Max}[0, (V_{i,t^*})^A - \text{CP}] = \text{Max}[0, (V_{i,t^*} + A_{i,t^*} - \text{CP})]\]

Equation 4-16

Although a "terminal salvage value" typically appears in conventional capital budgeting equations for net present value, it is interesting to note that the salvage value \(\text{SVP}_{i,t}\) does not explicitly appear in Equation 4-16. As Figure 4-4 shows, \(V_{i,t^*}\) is exchanged for \(\text{SVP}_{i,t^*}\) when \(\text{SVP}_{i,t}\) exceeds \(V_{i,t}\) by the value of \(A_{i,t}\). By exchanging \(V_{i,t^*}\) for \(\text{SVP}_{i,t^*}\) at \(t = t^*\), the firm realizes a net gain of 
\(A_{i,t^*}\) over \(V_{i,t^*}\). Thus, the exchange for \(\text{SVP}_{i,t^*}\) may be thought of as the 
equivalent of "restoring" \(V_{i,t^*}\) to the firm plus giving it a cash flow equal to 
\(A_{i,t^*} = \text{SVP}_{i,t^*} - V_{i,t^*}\). Therefore, the exchange at \(t = t^*\) does not change the 
value of \(V_{i,t^*}\), and the salvage value \(\text{SVP}_{i,t^*}\) is included implicitly in \(V_{i,t^*} + A_{i,t^*}\).

If the present value of all production costs is prepaid or irreversibly 
committed to at \(t = t^*\), as assumed in the basic model, and if production is 
begun at \(t = t^*\), then afterwards, at \(t^* < t \leq t_f\), the net present value of the 
project will be given by
\[(\text{NPV}_{i,t^* < t \leq t_f})^A = (V_{i,t})^A = V_{i,t} + A_{i,t}\]

Equation 4-17

In this case, prepaid production costs are *sunk costs* and are no longer 
relevant to the abandonment decision.

If production is begun at \(t = t^*\), but production costs \(\text{CP}\) are not paid in 
full or irreversibly committed to at \(t = t^*\) as assumed in the basic model, then 
the present value of remaining production costs at \(t^* \leq t \leq t_f\) can be denoted by 
\(\text{CP}(t)\) and the net present value of the production project with option to 
abandon at any time \(t^* \leq t \leq t_f\) becomes:
\[(\text{NPV}_{i,t^* \leq t \leq t_f})^A = (V_{i,t})^A - \text{CP}(t) = V_{i,t} + A_{i,t} - \text{CP}(t)\]

Equation 4-18

If production costs are incurred on a pay-as-you-produce basis, \(\text{CP}(t > t^*) \geq 0\).

Subtracting \(\text{CP}(t)\) from \((V_{i,t})^A\) is comparable to committing \(\text{CP}(t)\) for the 
purchase of the remaining inputs needed to complete the project, say by
depositing \( C_p(t) \) into an escrow account. In this case, \( SV^p_{i,t} \) will include both the salvage value of production assets and the "salvage value" of inputs which are yet to be acquired but are included in \( C_p(t) \). The abandonment decision of the firm during \( t^* \leq t \leq t_f \) then remains whether to exchange \( V_{i,t} \) for \( SV^p_{i,t} \), and both \( R^A(t) \) and the expected optimal time to abandon will be the same at \( t = t^* \) as when the present value of all costs is assumed to be prepaid at \( t = t^* \). Of course, \( R^A(t) \) and the expected optimal time to abandon can be expected to change after \( t = t^* \) according to the realizations of \( V_{i,t} \) and \( SV^p_{i,t} \), causing project net present values as given by Equations 4-17 and 4-18 to change stochastically.

### 4.3.2 Sensitivity of the Option to Abandon and the Optimal Time to Abandon to Underlying Variables

The value of \( (NPV^A_{i,t^*}) \) from Equation 4-17 or 4-18 is an increasing function of both \( \sigma_{svp} \), the variance of the salvage value \( SV^p_{i,t} \) during production, and \( \sigma_v \), the variance of the underlying production project, \( V_{i,t} \). The intuitions behind these sensitivities are as follows.

During the production period, as the range of possible outcomes of \( SV^p_{i,t} \) increases with \( \sigma_{svd} \), the possible gains from abandoning production increase, but the consequences of serious decreases in \( SV^p_{i,t} \) are avoided because abandoning is always optional. Moreover, increasing the range of possible outcomes of \( V_{i,t} \) increases possible gains from \( V_{i,t} \) which could accrue to the option holder over the holding period, while the increased possibility of serious declines in the value of \( V_{i,t} \) relative to \( SD^D_{i,t} \) makes the ability to trade \( V_{i,t} \) for \( SV^D_{i,t} \) even more valuable.

Because abandonment consists of exchanging one uncertain asset for another, the value of the option to abandon will increase with decreasing correlation between the exchangeable assets. Thus, \( (NPV^A_{i,t^*}) \) will increase
with decreasing $\rho_{vs}$.

A production project with an option to abandon will increase in value as the salvage value $SV^P_{i,t}$ of its assets increases, as the expected value of the revenue stream $V_{i,t}$ increases, and as the physical lives of project assets increase (thereby lengthening the duration of the option to abandon to re-uses).

Increases in the value of $SV^P_{i,t}$ relative to $V_{i,t}$ will invite earlier exercise of the abandonment option and increase the relative importance of $A_{i,t*}$ to the total value of the production project. Increases in $\sigma_V$, $\sigma_{svp}$, $\sigma_C$, $\sigma_{svd}$ or $\rho_{im}$ also increase the importance of the option to abandon relative to overall project value, and thereby also decrease the time $t = t^*$ at which abandonment will be optimal.

### 4.3.3 Representative Values of the Option to Abandon Relative to the Underlying Option to Produce a New Product

Myers and Majd (1983) give a numerical example of a long-term project for which the option to abandon could represent up to 15% of the value of the underlying project value.

Taking a project present value of 100 without the option to abandon and with zero salvage value at the end of 70 years of asset physical life (which corresponds to the expected project life without the option to abandon), Myers and Majd assume a standard deviation of 20% per year in forecast project value and a real risk-free interest rate of 2%. Project cash flows and present values are assumed to decline 8% per year, and project assets are assumed to depreciate exponentially at a rate of 5% annually. With these assumptions, Myers and Majd demonstrate that increasing the initial salvage value of project assets increases the present value of the project with the abandonment option, correspondingly increases the value of the option to abandon itself, and reduces the forecast project life (the time at which the exercise of the option to abandon is expected to be optimal).

Myers and Majd's (1983, Table II) results are summarized below:
<table>
<thead>
<tr>
<th>Initial Salvage Value</th>
<th>Project Present Value with Option to Abandon</th>
<th>Value of Option to Abandon</th>
<th>Forecast Project Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>101</td>
<td>1</td>
<td>54 years</td>
</tr>
<tr>
<td>50</td>
<td>106</td>
<td>6</td>
<td>23</td>
</tr>
<tr>
<td>65</td>
<td>109</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>70</td>
<td>111</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>80</td>
<td>115</td>
<td>15</td>
<td>7</td>
</tr>
</tbody>
</table>

Myers and Majd's finding that the value of the option to abandon rises as initial salvage value increases has important strategic implications for a firm's choices of production technologies and for the level of the firm's investment in producing new products. First, when a production technology utilizes dedicated production equipment and/or production workers' skills that are highly specialized and not readily transferable to other uses, investing in that production technology acquires assets with low salvage values, and the option to abandon will add little value to the production project. On the other hand, when a production technology uses readily transferable equipment and skills, as in flexible manufacturing systems, the option to abandon can become very valuable. When the asset costs of flexible production systems are high relative to those of a dedicated production systems, recognizing and calculating the value of the option to abandon may lead to the discovery that installing the more expensive flexible production system has a higher net present value than installing the dedicated equipment. Thus, recognizing the value of the option to abandon may induce a systematic change in a firm's decisions about whether to install flexible or dedicated production equipment and about whether to cultivate narrow or broad-ranging skills in its production workers.

Second, when the cost of production equipment is comparable to the present value of expected cash flows from a production project, failure to recognize the value of the option to abandon will lead to systematic under-investment in producing new products. Explicitly recognizing the value of the option to abandon may reveal that projects previously thought to have zero or negative net present value (without recognizing the option to abandon) may actually have positive net present values. Recognizing the value of the option to abandon can therefore correct one bias to under-investment characteristic of conventional "no-option" capital budgeting analysis.
4.4 The Timing Option to Shut Down Temporarily Production of a New Product

In the basic model of a product initiative option, the firm was assumed to be able to choose whether or not to produce new product $P_i$ only at $t = t^*$, and if the firm did choose to begin production at $t = t^*$, the firm was assumed to continue producing until the end of the production period at $t = t_f$. This simplified characterization of a product initiative option clearly limits the strategic flexibility of a firm, which could be enhanced considerably if the firm could continue production of a new product when it is profitable to do so and refrain from producing when it is not profitable to do so. This section investigates this important dimension of strategic flexibility by introducing the timing option to shut down temporarily production of a new product. With this timing option attached to a product initiative option, the firm may stop and resume production of a new product at will.

Section 4.4.1 applies the McDonald and Siegal analysis of the option to shut down to the basic model of product development to value the option to shut down production of a new product. Section 4.4.2 summarizes the sensitivity of the option to shut down to its underlying variables, and Section 4.4.3 comments on the possible values of the option to shut down relative to the underlying product initiative option.

4.4.1 The Option to Shut Down Production

This section analyzes the value of the option to shut down production of a new product by applying the analysis of McDonald and Siegal (1985). First, the value of a project to produce a new product is determined when production may be costlessly shut down or restarted according to the instantaneous profitability of production at any time $t^* \leq t \leq t_f$. The value of the timing option to shut down is then found by taking the difference between the value of the production project with the shut-down option and the value of the production project without the shut-down option.

When production of a new product may be costlessly shut down and restarted at will, the value-maximizing firm will produce and sell a unit of
product whenever the uncertain price the firm can get for the product exceeds the instantaneous variable costs of production. In this case, the expected value at \( t = t^* \) of the project to produce new product \( P_i \) with the shut down option can be found by taking the expectation of the revenues from each unit that could be produced, less total fixed costs and the variable costs for each unit produced, conditional on the firm producing each individual unit that could be produced in the production period. The present value of the project with the shut down option can then be obtained by discounting the expectation of revenues and costs back to \( t = t^* \) at appropriate discount rates.

To obtain the present value of the project to produce \( P_i \) with the shut down option, begin by recalling that in the basic model of a product initiative option, the dynamics of the uncertain price which the firm can get for new product \( P_i \) are a Weiner process, given here by

\[
dp_{i,t}/p_{i,t} = \alpha_p dt + \sigma_p dz_p \\
\text{Equation 4-19}
\]

Now define \( \pi_j \) as the profit the firm will receive if it uses the \( j \)th slot of \( Q \) available production slots to produce and instantaneously sell a unit of \( P_i \):

\[
\pi_j = p_{i,t} - vc_{p,i}
\]

where \( p_{i,t} \) is the stochastic price which the firm can get for a unit of \( P_i \) at the time \( t^* \leq t \leq t^*_f \) that the \( j \)th production slot becomes available, and \( vc_{p,i} \) is the variable cost of producing the \( j \)th unit (assumed to be constant in the basic model).

Note that if the present value of all production costs, \( C_P \), is paid at \( t = t^* \) to begin production, as assumed in the basic model, then \( vc_{p,i} = 0 \), and the option to shut down would become worthless since \( p_{i,t} \geq vc_{p,i} \) at all times. Thus, the assumption of the basic model must be relaxed here to allow variable costs to be paid as production occurs, and so now define \( C_P \) to represent the present value at \( t = t^* \) of any fixed production costs which must be prepaid or irreversibly committed to at \( t = t^* \).

With the option to shut down production when prices fall below variable
costs, $\pi_j$ becomes

$$\pi_j = \text{Max} \left[ 0, \left( p_{i,t} - v_{c_{p,j}} \right) \right]$$  \hspace{1cm} \text{Equation 4-21}

This equation shows that the payoff from having an option to produce $P_i$ with an option to shut down production of the $j$th unit is identical to the payoff the firm would have if it held an individual (European call) option on the $j$th unit of $P_i$. The option on the $j$th unit would have an exercise price equal to the variable cost $v_{c_{p,j}}$, and since in the basic model the firm can produce a maximum of $Q$ units of $P_i$, the option would be exercisable at a time $t_j = (t_f - t^*)(Q/j)$ removed from $t = t^*$. With this characterization, the value at $t = t^*$ of the option to produce the $j$th unit of $P_i$ is given by

$$\Pi_{j,t^*} = p_{i,t^*} e^{\delta t_j} N(d_j) - v_{c_{p,j}} e^{-r t_j} N(d_j - \sigma \sqrt{t_j})$$  \hspace{1cm} \text{Equation 4-22}

where

$$d_j = \left[ \ln(p_{i,t^*}/v_{c_{p,j}}) + (\delta' + \sigma_{p}^2/2)(t_j) \right] / \sigma \sqrt{t_j}$$

$$\delta' = \delta + \alpha_p$$

$\delta'$ = constant proportional rate of competitive price erosion

$\alpha_p$ = instantaneous expected change in $p_{i,t}$ due to expected change in stochastic demand for $P_i$

$\sigma_p$ = instantaneous standard deviation of percentage change in $p_{i,t}$

In this equation, the use of the exponential discount factor $\delta'$ corresponds to the rate of value erosion of the unit price the firm will obtain for producing the $j$th unit of product.

The net present value at $t = t^*$ of the project to produce $P_i$ with the option to shut down temporarily can now be stated as

$$(\text{NPV}_{i,t^*})_{SD} = \sum \Pi_{j,t^*} - C'p$$  \hspace{1cm} \text{for } j = 1, 2, ... Q$$  \hspace{1cm} \text{Equation 4-23}

where $C'p$ is the present value at $t = t^*$ of any production costs which must be prepaid or irreversibly committed to at $t = t^*$.  

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If $Q$ is a large number, it may be possible to closely approximate the value of $(V_{i,t^*})^{SD}$ with an integral function. For large $Q$ with resultant small intervals of time $dt = (t_f - t^*)/Q$ corresponding to the production duration for one unit of $P_i$, define $\Pi_{t^*}(t_j)$ as the present value at $t = t^*$ of the conditional expected instantaneous rate of profit flow during the $j$th interval $dt$. Thus,

$$\Pi_{t^*}(t_j) \, dt = \Pi_{j,t^*}$$  \hspace{1cm} \text{Equation 4-24}

$\Sigma \Pi_{j,t^*}$ can then be approximated by the integral $\int \Pi_{t^*}(t_j) \, dt$ taken over the interval $0 \leq t_j \leq (t_f - t)$. In this case, the net present value of the project to produce new product $P_i$ with the option to shut down can be approximated as

$$(NPV_{i,t^*})^{SD} = \int \Pi_{t^*}(t_j) \, dt - C'P \quad 0 \leq t_j \leq (t_f - t)$$  \hspace{1cm} \text{Equation 4-25}

The value of the option to shut down temporarily production of new product $P_i$ during the production period $t^* \leq t \leq t_f$ can now be stated as the difference between the present values of the production project with and without the option to shut down:

$$SD_{i,t^*} = (NPV_{i,t^*})^{SD} - NPV_{i,t^*} = (NPV_{i,t^*})^{SD} - \text{Max} \, [0, (V_{i,t^*} - C_P)]$$  \hspace{1cm} \text{Equation 4-26}

### 4.4.2 Sensitivity of the Option to Shut Down to Underlying Variables

To develop an intuition for how the option to shut down can vary with underlying variables, it is important to understand that the present value of a contingent claim on a stochastic asset -- for example, $\Pi_{j,t^*}$ -- depends on both the present value of the contingent payoff and the probability that the claim will be exercised. Underlying variables usually will not affect the present value of the contingent payoff or the likelihood of exercise equally, and changes in some variables may even have opposite effects on the present value of the contingent payoff and the likelihood of exercise. Since $SD_{i,t^*}$ depends directly on the values of $\Pi_{j,t^*}$, values of the option to shut down therefore may not vary monotonically with a given variable, and the direction of change in $SD_{i,t^*}$ with one variable
may depend on the relative values of other variables. Thus, in addition to discussing the monotonic sensitivities of $SD_{i,t^*}$, this section will also identify the most important instances of non-monotonic sensitivity of $SD_{i,t^*}$.

**Sensitivity to the Time of Production.** As the time $t = t^* + t_j$ at which production can take place moves further into the future, the value of the contingent claim $\Pi_{j,t^*}$ on $r_j = \text{Max} \ [0, (p_{i,t} - v_{C_{p,i}})]$ tends to increase because the range of possible positive outcomes of $p_{i,t}$ increases the option value of the claim, but the present value of the positive outcomes decreases because the discount multiplier $e^{-\delta t_j}$ decreases the present value of the possible payoffs. Depending on the variance of $p_{i,t}$ and the value of $\delta'$, $\Pi_{j,t^*}$ may increase or decrease with time to production $t = t_j$.

**Figure 4-5** adapts the results of a simulation by McDonald and Siegal (1985, Figure 2) to suggest how the value of future production slots $\Pi_{j,t^*}$ can vary with the time to production $t = t_j$ in an environment of falling unit prices ($\delta' = 0.09$) and low, moderate, and high price variances ($\sigma_p = 0.1, 0.4, \text{ and } 1.0$). In the figure, a large price variance $\sigma_p$ initially allows the production option value to dominate the effect of price erosion on $\Pi_{j,t^*}$. However, as McDonald and Siegal show, eventually price erosion must dominate the option component of present value, because the limit of $\Pi_{j,t^*} \to 0$ as $t_j \to \infty$. The result is that an option on a cash flow from a very risky production slot (like $\Pi_{j,t^*}$ for $\sigma_p = 0.4$ or 1.0) may have greater value if the cash flow is in the intermediate future than if the cash flow occurs in the near term or in the distant future. However, the figure also shows that for a low uncertainty price environment ($\sigma_p = 0.1$), price erosion dominates and the value of a production slot begins to decline immediately.

**Sensitivity to Price Variance.** If $\delta' = 0$, then increases in price variance $\sigma_p$
increase the value of options \( \Pi_{j,t^*} \) and hence \( SD_{i,t^*} \).

**Sensitivity to Production Costs.** Since variable production costs are the exercise price which must be paid to claim the stochastic price \( p_{i,t} \), increasing variable production costs decreases the option value \( \Pi_{j,t^*} \) at the variable rate 

\[
e^{-r t_j} N(d_j - \sigma \sqrt{t_j})
\]

(see Equation 4-22). When variable production costs increase relative to fixed costs, but total production costs are held constant (assuming all units were produced), an increase in variable costs \( v_{c_{p,i}} \) brings a corresponding but unequal decrease in fixed costs \( C'_p \) (prepaid at \( t = t^* \)). The rate of decrease in the present value of fixed costs \( C'_p \) is \( e^{-r t_j} \), which is greater than \( e^{-r t_j} N(d_j - \sigma \sqrt{t_j}) \), the rate of decrease in the option value \( \Pi_{j,t^*} \). Thus, when variable costs increase because constant total production costs are being redistributed from fixed costs to variable costs, \( (NPV_{i,t^*})^{SD} \) and thus \( SD_{i,t^*} \) will increase in value. Intuitively, as a greater fraction of total costs can be avoided by shutting down, the value of the option to shut down increases accordingly.

### 4.4.3 Relative Importance of the Option to Shut Down

When the price to cost ratio \( p_{i,t^*}/v_{c_{p,i}} \) is large and price variance is low, the value of the option to shut down relative to the value of the underlying project is likely to be small. For very large price/variable cost ratios and minimal price variance, the value of the shut down option may be negligible (though always some positive amount as long as \( \sigma_p \neq 0 \)).

More commonly, however, the option to shut down may add substantial value to a project. Consider, for example, a production project for which \( p_{i,t^*} = v_{c_{p,i}}, \delta = r, C'_p = 0 \) (no fixed costs), and \( \sigma_p = \sigma_c = 0 \). Without the option to shut down, such a project will have a zero net present value. With uncertainty \( \sigma_p \neq 0 \) and/or \( \sigma_c \neq 0 \), however, production could occur whenever the stochastic price exceeds variable costs and could stop when the price is less than variable costs.
With significant variability of prices, the project operated in this manner could become quite valuable. The following Section 4.5 on interdependent timing options gives a numerical illustration of this case.

4.5 Interdependency of Multiple Timing Options

A product initiative option frequently may have more than one timing option attached to it. Indeed, it is probably the rare case when a firm has no freedom to decide whether to wait to begin production of a new product and when to shut down temporarily or abandon the project, although some costs may be incurred in exercising these timing options. When more than one timing option is attached to a product initiative option, the multiple timing options are inevitably interrelated and interdependent. This interdependency of multiple timing options means that each option cannot be valued as if it were an independent option in the manner of the preceding sections. In general, the coexistence of one timing option with another will reduce the value that either option would have if it were the only timing option, and thus the values of timing options computed independently cannot simply be added together to find the value of multiple timing options. However, adding another timing option to a project will almost always add value to the project (and can never detract from the project value).

The valuation of multiple, interdependent operating option values has been studied in a series of papers by Kulatilaka (1986), Kulatilaka (1988), and Kulatilaka and Marcus (1988). Kulatilaka observes that operating options allow the actions of a firm to influence the value of a project, with the result that project value over time becomes endogenous to the valuation problem and can no longer be represented strictly as a function of an exogenous stochastic project value. Thus, Kulatilaka has argued that options valuations of projects premised on exogenous stochastic price behavior are inappropriate when significant operating options exist.

Kulatilaka (1988) provides a dynamic programming approach to the valuation of projects with multiple, interdependent timing options. This section adapts Kulatilaka's results to the basic model of product development. Section 4.5.1 demonstrates the interdependency of multiple timing option values, and
Section 4.5.2 gives a numerical example of the impact of multiple timing options on the present value of a production project. Section 4.5.3 continues Kulatilaka’s numerical example to show the impact of multiple timing options on the optimal exercise time for an option to produce a new product.

4.5.1 Illustrations of Interdependency of Multiple Timing Options

The interdependency of multiple timing options can be illustrated by some simple intuitive examples.

Suppose that a firm has a product initiative option with an attached option to wait to begin production. Now add the option to abandon production for some positive salvage value. Adding a positive-value option to abandon will increase the value of the project, shorten the optimal time to begin production, and decrease the value of the option to wait. Figure 4-6 shows that adding a positive value option to abandon \( A_{i,t} \) to project value \( V_{i,t} \) creates a project of value \( (V_{i,t})^A \) which will cross the optimal exercise boundary of the option to wait (at \( t = t_a^- \)) earlier than \( V_{i,t} \) will cross (at \( t = t^- \)). Reducing the expected exercise date of the abandonment option from \( t^- \) to \( t_a^- \) lowers the expected value of the option to wait, but raises the expectation of project value from \( E_{t=t^-}[V_{i,t^-}] \) to \( E_{t=t^-}[(V_{i,t_a^-})^A] \).

Similarly, adding the option to shut down temporarily to the option to wait reduces the expected exercise date of the option to wait and thus reduces the expected value of the option to wait, but increases total project value.

Adding the option to wait to an option to abandon will usually extend into the future both the time at which it is optimal to begin production and, thus, the time at which abandonment will be optimal. Moving the proceeds of optimal abandonment further into the future reduces the expected present value now of the option to abandon.

Adding the option to wait to the option to shut down lets the firm wait to begin production until production promises to yield the greatest present value profits, thereby diminishing the expected benefits of being able to shut down production to avoid producing at a loss.

Adding the option to abandon to the option to shut down induces the firm to quit producing earlier, thereby eliminating any part of the value of the option to
shut down which may have derived from avoiding losses during the period after the expected date of abandonnment.

Adding the option to shut down to the option to abandon increases the value of the project if continued, delays the date at which abandonment will be optimal, and thereby reduces the value of the option to abandon.

4.5.2 Example of Impact of Multiple Timing Options on Project Value

The impact of adding timing options to a production project has been modeled by Kulatilaka (1986). The simple production project modeled by Kulatil\text{\textasciitilde}ka has the following specifications:

Stochastic price for the output of the project has zero drift ($\alpha_p = 0$) and $16\%$ variance per time period and thus $\sigma_p = \sqrt{(0.16)} = 0.4$. Initial observed price per unit $p_{i,t^*} = 0.5$. Total (fixed and variable) costs are constant at $v_{c_{p,i}} = 0.5$ when production occurs. Thus, the expected operating profit for all production slots is zero. There are 10 production periods or slots. The firm may costlessly shut down and restart production, but there are fixed costs of $0.05$ per production slot when the firm does not produce. There no costs of initial investment, so salvage value is zero. Thus, the only benefit of abandonment is avoidance of possible future fixed costs of $0.05$ per production slot when production capability is maintained but not used. A real discount rate of $5\%$ per production period is applied to both revenues and costs.

Figure 4-7 shows how the ten-period production project value $V_{i,t^*}$ will vary with changes in the observed price $p_{i,t^*}$ when the project has no timing options. The figure also shows the value of individual timing options to wait ($W_{i,t^*}$), to shut down ($SD_{i,t^*}$), and to abandon ($A_{i,t^*}$). If the project has no operating options, a conventional no-option discounted cash flow analysis would be appropriate and would show that the no-option project value, indicated by $V_{i,t^*}$, has a zero net present value if the initial value of $p_{i,t^*}$ is $0.5$.

If the project has only a timing option to wait, however, the value of the option to wait $W_{i,t^*}$ will have some positive value until $p_{i,t^*}$ reaches $0.84$. At
initial unit prices of 0.84 or more, the project value is maximized by beginning production immediately, and the option to wait will therefore have a value of zero, as shown in the figure.

If the project has only the option to abandon, \(A_{i,t^*}\), the project will be "abandoned" before it is even begun if prices \(p_{i,t^*}\) are 0.16 or less. If prices are greater than 0.16, the project will be begun and the expected value of potential losses (fixed costs) which can be avoided by abandonment will steadily decline with increasing \(p_{i,t^*}\). Thus the option to abandon will have its greatest value when \(p_{i,t^*} \leq 0.16\), as shown in the figure.

If the project has only the option to shut down temporarily, \(SD_{i,t^*}\), the value of the option to shut down will decline with increasing values of \(p_{i,t^*}\). When \(p_{i,t^*} > 0.45\), it is certain that production will take place for at least one period, so \(p_{i,t^*} = 0.45\) marks a point of inflection where \(SD_{i,t^*}\) decreases less rapidly than for \(p_{i,t^*} < 0.45\). Further increases in \(p_{i,t^*}\) beyond 0.45 lead to even further declines in the value of \(SD_{i,t^*}\).

**Figure 4-8** shows total project values with each individual timing option attached. Also shown are the project value with the timing options to wait and to abandon, \((V_{i,t^*})^{WA}\), and the project value with all three timing options, \((V_{i,t^*})^{WASD}\). Adding only the option to wait increases project value to \((V_{i,t^*})^W\) and gives the project a positive net present value at any value of \(p_{i,t^*}\). Similarly, adding only the option to shut down gives the project \((V_{i,t^*})^{SD}\) a positive net present value at any initial price \(p_{i,t^*}\), and adding only the option to abandon gives the project \((V_{i,t^*})^A\) a positive net present value at any initial price \(p_{i,t^*}\). Adding the two timing options to wait and to abandon gives a total project value \((V_{i,t^*})^{WA}\) greater than either \((V_{i,t^*})^W\) or \((V_{i,t^*})^A\). However, reference to **Figure 4-7** will show that \((V_{i,t^*})^{WA}\) is less than \(V_{i,t^*} + W_{i,t^*} + A_{i,t^*}\) because of the effect of interdependency between the options to wait and to abandon. Adding all three timing options gives a total project value \((V_{i,t^*})^{WASD}\), which is greater than
(V_{i,t^*})^{WA} but less than the sum of the values of the project and the three individual timing options, V_{i,t^*} + W_{i,t^*} + A_{i,t^*} + SD_{i,t^*}.

Also, note that (V_{i,t^*})^{WA,SD} and (V_{i,t^*})^{WA} in Figure 4-8 have points of inflection that differ from those shown in Figure 4-7 for the individual option values. These shifts in project value inflection points when a project has more than one timing option also indicates the interdependency of the timing options and confirms their lack of simple additivity.

4.5.3 Impact of Multiple Timing Options on the Optimal Exercise of a Product Initiative Option

The presence of a positive-value option to wait attached to a product initiative option will in general delay the time at which exercise of the production option is expected to be optimal relative to a production project with no timing options. Conversely, positive-value options to shut down or to abandon will lead to earlier exercise of product initiative options. In addition, with any kind of timing options, the expected present value now of a product initiative option with positive-value timing options will always be greater than the option’s value without the timing options.

Kulatilaka’s (1988) numerical example from the preceding section can be continued to indicate the impact of timing options on the optimal exercise time for a production option. The table below summarizes Kulatilaka’s findings (1988, Table 1) as to the lowest initial price p_{i,t^*} at which beginning production in the first period will be optimal:

<table>
<thead>
<tr>
<th>Project Description</th>
<th>Minimum p_{i,t^*}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project with no timing options</td>
<td>0.50</td>
</tr>
<tr>
<td>Project with option to wait</td>
<td>0.84</td>
</tr>
<tr>
<td>Project with options to wait and to abandon</td>
<td>0.70</td>
</tr>
<tr>
<td>Project with options to wait and to shut down</td>
<td>0.58</td>
</tr>
<tr>
<td>Project with options to wait, shut down, and abandon</td>
<td>0.58</td>
</tr>
</tbody>
</table>
Adding the option to wait requires a higher project value (and thus a higher initial price) to make immediate production a positive net present value undertaking, since beginning production forfeits the value of the option to wait. Adding the option to abandon reduces the value of the option to wait and thus lowers the initial value and project value which the project must have in order to make beginning production immediately a positive net present value undertaking. Adding the option to shut down instead of the option to abandon reduces the value of the option to wait even further and makes it optimal to produce immediately at an even lower price. In Kulatilaka's example, adding the option to abandon to the options to wait and to shut down does not perceptibly change the price at which beginning production immediately is optimal, because the salvage value received on abandonment in Kulatilaka's example is merely the avoidance of fixed costs, which are low at 0.05 per period. In an example with a more significant salvage value, the minimum price at which immediate production would be optimal would fall even further, to something less than 0.58.
Figure 4-1: Optimal Exercise Boundary for Lockheed 1011 Tristar Product Initiative Option (Exercise at 42 vs. 48 months)
Figure 4-2: Optimal Exercise Boundary With a Finite-Lived Option to Wait

Figure 4-3: Optimal Exercise With an Infinite-Lived Option to Wait
Figure 4-4: Optimal Exercise of the Option to Abandon Production

Present Value at $t = t^*$ of the Option to Produce the $j$th Unit of New Product, for $\delta = 0.09$

Figure 4-5: Sensitivity of Value of Option to Produce to Time and Variance
(Source: McDonald and Siegal 1985, Figure 2)
Adding the Option to Abandon to the Option to Wait Reduces Expected the Exercise Date and Increases Expected Project Value at $t = t^*$

Figure 4-6: Adding the Option to Abandon to the Option to Wait
Figure 4-7: Numerical Example of Individual Timing Options
(Based on Kulatilaka 1988, Figures 1 and 2)
Figure 4-8: Numerical Example of Multiple Timing Options
(Based on Kulatilaka 1988, Figures 1 and 2)
5. Implementation Options

Chapter 3 investigated the value of the strategic flexibility which a firm can obtain from initiative options to produce new products. Chapter 4 studied the strategic flexibility which comes from timing options to wait, shut down, or abandon development or production of a new product. This chapter completes the analysis of the three kinds of generic real options which are sources of a firm's strategic flexibility by examining implementation options which a firm may have to vary the way in which it implements its initiative options. As this chapter will show, how a firm decides to implement its initiative options can greatly affect the value of a new product opportunity.

Although it is easy to recognize intuitively that alternative approaches to producing a new product can affect the value of a product option, the determination of the value of an implementation option is likely to be more involved than the valuation procedures for initiative or timing options. In fact, as this chapter will show, for non-trivial implementation options, valuations of the underlying initiative option and associated timing options are necessary inputs into the procedure for valuing an implementation option.

Section 5.1 defines an implementation option. Section 5.2 discusses some common sources of implementation options and explains the basic approach to valuing implementation options used in this chapter. Section 5.3 provides an example of a valuation of a production capacity implementation option by applying Pindyck's (1988) analysis of capacity choice to the basic model of a new product initiative option. The potential magnitude of this implementation option and its components of value are illustrated with a numerical example adapted from the Pindyck analysis. Section 5.4 concludes the chapter by illustrating the value of an implementation option to vary the speed of product development by re-evaluating the Lockheed 1011 Tristar development project under variable development times.
5.1 Defining and Valuing Implementation Options

Sections 5.3 and 5.4 will evaluate two different implementation options under some fairly realistic conditions of capital irreversibility and required times to develop a new product. Before beginning analysis of such implementation options, it will be useful first to examine implementation options in some simpler contexts of the basic model of product development. This section will explore ways in which some typical decisions a firm must make about how to implement a new product option can affect the flexibility of the firm in producing the new product and thus affect value of the firm's initiative option.

The objectives of this section are twofold. First, this section will show that any options the firm may have to vary the production levels of a new product will come from any increased flexibility the firm acquires when it can expand its control over variables that affect the frequency with which the firm can produce profitably during the production period and/or the optimal output and capacity levels for production. Second, this section will define the value of an implementation option as the value of an option to relocate from one opportunity vector to another, where an opportunity vector is defined as one available approach to producing a new product.

Section 5.1.1 defines an implementation option. Section 5.1.2 identifies three typical sources of implementation options: changes in input and output price functions, relaxing constraints on output, and changes in production technologies. Section 5.1.3 defines opportunity vectors and their relation to implementation options. Section 5.1.4 shows how implementation options can result from changes in the supply or demand functions which the firm faces. Section 5.1.5 explains how changes in constraints on inputs, utilization rates, or output can create implementation options. Section 5.1.6 shows how several kinds of changes in production technologies can create implementation options.

5.1.1 Definition of an Implementation Option

In the basic model of product development introduced in Chapter 2, the firm has no options to choose the ways in which it can implement its
production initiative option. The rate of production is assumed to be constant and total output is fixed. To study the option to vary implementation of production, it is necessary to relax at least some of the restrictions on the firm's decisions in the basic model. For production implementation options to exist, the firm must be able to exercise some control over its frequency of production, its output rate, and its installed capacity during the production period. When the firm has choices in any of these decision dimensions, the firm in effect has the ability to choose among a set of opportunity vectors, each of which is associated with a feasible locus in the decision space of the firm and each of which represents a specific implementation of the option to produce new product $P_i$.

Let $OV_{i,k,t}$ represent an opportunity vector that defines the $k$th specific implementation available to the firm for exercising a new product initiative option. Now define $I_{i,k,t}$ as the value of the implementation option represented by this $k$th opportunity vector. Symbolically, we can define $I_{i,k,t}$ as

$$I_{i,k,t} = OV_{i,k,t} \times C_{i,t}$$  \hspace{1cm} \text{Equation 5-1}$$

where "$\times$" denotes the mapping of $OV_{i,k,t}$ onto a value function which gives the value of the initiative option $C_{i,t}$ if implemented in the manner defined by $OV_{i,k,t}$.

A basic strategic problem which the firm must solve is to determine which of the $k$ implementation options available to it will maximize the value of a new product opportunity. For convenience, let $OV_{i,m,t}$ be the implementation of product initiative option $C_{i,t}$ that maximizes the value of the new product opportunity for a general approach to producing $P_i$ (e.g., an approach characterized by a given production technology). Also let $I_{i,m,t}$ indicate the value of the value-maximizing $m$th implementation of $C_{i,t}$.

Sections 5.3 and 5.4 will give examples which illustrate how $I_{i,m,t}$ might be determined. Suppose for now that the firm knows how to determine the
value-maximizing implementation option $I_{i,m,t}$. Also suppose that, either as a result of some fortuitous change in the firm's environment or as a result of some intentional action by the firm, the firm can choose a new position along one or more decision dimensions and thus has a new implementation option $I_{i,n,t}$ made available to it. This new production approach may offer the firm an opportunity to increase the value of its product initiative option by switching to a different approach to producing product $P_i$. The marginal benefit to the firm of having the option to pursue this new approach to implementing $C_{i,t}$ can be stated as

$$\Delta I_{i,m\rightarrow n,t} = \text{Max} \left[ 0, I_{i,n,t} - I_{i,m,t} \right]$$

Equation 5-2

As Equation 5-2 indicates, when a new implementation option does not yield an increase in the value of the new product opportunity, the marginal value of the implementation option to the firm is zero, since the firm is not obligated to exercise a less valuable implementation option.

5.2 Some Sources of Implementation Option Value

With Equation 5-1's definition of an implementation option in mind, let us now consider some possible sources of implementation options. A firm's product development and production decision space may include an ability to influence input or output prices, to remove or relax constraints, and to make a number of choices about production technologies -- all of which can affect the value of the firm's product initiative options. The firm's value-maximizing position along each of these dimensions in the firm's decision space will be determined by the answers to the following questions:

(1) Is the firm a price-taker in inputs and outputs, or does the firm have some degree of monopsony or monopoly power which causes its choices of input or output levels to affect prices of the firm's inputs or output?

(2) Is the firm unconstrained, or is it constrained in its access to or utilization of critical inputs or in its ability to sell output?

(3) What is the nature of each production technology available to the firm, including such characteristics as:

(a) Is the capital (plant and equipment) the firm needs to install perfectly
reversible, or is it partially or completely irreversible?

(b) Can the firm install the capacity it needs quickly, or is there a significant "time to build" needed before the necessary capacity can be installed?

(c) Does the technology have a high ratio of variable to fixed costs, or a high ratio of fixed to variable costs?

(d) Is the capital perfectly divisible, or is capacity lumpy?

(e) Does the technology have high input efficiency (where input efficiency is defined as the amount of each input needed to produce each unit of output), or is input efficiency low?

Figure 5-1 summarizes these typical decision dimensions and the polar positions in each dimension. In most situations, a firm's implementation options would occupy intermediate positions along many or all of these decision dimensions. However, as a device for bringing into sharp focus the possible effects of each of these decision dimensions on the firm's production implementation options, the following discussion will intentionally evaluate the impact on implementation options value of occupying the polar positions along each dimension. As the discussion below will bring out, occupying the left-hand side of each decision dimension illustrated in Figure 5-1 allows the firm the greatest freedom to maximize the value of a new product opportunity. By contrast, occupying the right-hand side of each decision dimension in Figure 5-1 acts to limit the firm's freedom of choice and thus restricts the firm's ability to maximize the value of its new product opportunity.

If the firm is a price-taker, for example, it may select any level of output with no penalty in the form of rising input prices or falling output prices. If its choice of input or output level affects prices, however, there will be a single optimal level of production which would maximize the value of the product initiative option for any specified converging input and output price functions. Similarly, an unconstrained firm is free to choose any level of output, while the constrained firm will face caps on its choices of input or output levels, which in turn limit the maximum value of any given production opportunity. Within the dimensions of production technologies, for example, the firm with perfectly reversible capital can freely install or
remove capacity as desired, while the firm installing irreversible capital will be unable to disinvest once capacity is installed. The high opportunity cost of committing to irreversible capital acts to limit optimal capacity and optimal output levels, and thus limits the maximum value of a product initiative option.

Since intermediate or rightward positions in Figure 5-1 limit the firm's optimal production frequency, output, or capacity levels, a firm whose current maximum-value implementation option occupies such intermediate or rightward positions could have an opportunity to increase the value of its product initiative option whenever it can relocate to a more leftward position along one or more decision dimensions. If the marginal benefit $\Delta I_i,m \rightarrow n,t$ which the firm can gain from increased implementation option value exceeds the cost of relocating to the new opportunity vector, the firm will add to the net present value of its new product opportunity by choosing the new implementation option.

Sections 5.2.1 to 5.2.3 will discuss how limitations on the firm's freedom to choose its positions along key decision dimensions can limit the value of the firm's initiative options and how having choices that relax those limitations may create valuable new implementation options. To simplify the exposition, the effect of occupying an intermediate position along each decision variable is evaluated under the assumption that the other decision variables occupy the most favorable (i.e., most leftward) positions.

5.2.1 Changes in Input and Output Price Functions as Sources of Implementation Option Value

Imagine a firm that is unconstrained and has a single production technology characterized by capital that is perfectly reversible and efficient, infinitely divisible, and instantaneously installable and removable. Suppose, however, that the firm faces either an upward-sloping supply function, a downward-sloping demand function, or both, with moment-to-moment input and/or output prices being stochastic. In other words, the firm's demand for inputs is sufficient to cause expected input prices to rise if the firm increases its input level, or the firm's output is sufficient to cause expected output
prices to fall if the firm increases its output, or both.

Because the firm’s capital is perfectly reversible, divisible, and instantly installable or removable, after any interval of production, the firm’s capacity can be instantly and costlessly adjusted to equal the optimal level of production implied by the next interval’s stochastic price. In this case, the cost of capacity can be treated as a simple variable cost equal to the opportunity cost of the required capital equipment for one production interval.

Under these conditions, there will be a finite optimal level of output, \( q^* \), for any small production interval \( \Delta t \), where \( q^* \) will be the solution to the profit maximization problem,

\[
\pi^* = \text{Maximize } [q(p(q) - vc(q))] \quad \text{Equation 5-3}
\]

where \( p(q) \) is the observable price which the firm can get for its product during the production interval if produced at output level \( q \), and \( vc(q) \) is the average variable costs which apply at output level \( q \) (time notations are suppressed). In this setting, the firm’s optimal capacity choice, \( K^* \), will always exactly equal the optimal output quantity, \( K^* = q^* \), because capital can instantly and costlessly be adjusted to the optimal output level.

Now consider how a change in the fundamental input or output price functions would affect the firm’s optimal production and capacity levels — and thus the maximum value of the product initiative option. As Figure 5-2 shows, a rightward shift in the expected input price curve from \( S-S \) to \( S'-S' \) lowers optimal average input prices, and a rightward shift in the expected output price curve from \( D-D \) to \( D'-D' \) raises expected output prices. These two price function changes create a new and higher maximum profit level, \( \pi^{**} \), based on a new, higher optimal output level \( q^{**} \) and therefore a higher optimal capacity level \( K^{**} \):

\[
\pi^{**} = \text{Maximize } [q(p(q) - vc(q))] = q^{**}(p(q^{**}) - vc(q^{**})) \quad \text{Equation 5-4}
\]

Thus, when a favorable shift in a supply price function, output price function, or both creates the opportunity for the firm to profitably relocate from one optimal output and capacity level to another, the shifts in price functions would create a valuable new implementation option. The value of
this new implementation option comes partly from an increase in expected unit profit margins, partly from an increased level of output when production does occur, and partly from an expected increase in production frequency because unit prices are more likely to exceed variable unit costs.

Purposefully shifting an input or output price curve may sometimes be beyond the capability of a firm, in which case new implementation options may simply become available from time to time as the result of random shifts in supply or demand curves. New suppliers of an input may appear in the marketplace, for example, and begin to drive down prices for the input. Such an occurrence could be purely fortuitous from the perspective of the firm, but it would nonetheless give the firm the option to relocate to a new, more valuable implementation option based on a higher level of production and capacity.

In some cases, however, it may be possible for the firm to exercise some control over input or output price functions and thereby to create new implementation options by its own efforts. It may be possible, for example, for the firm itself to invest in creating a new source of an input which could offer the firm a lower cost for the input or which could drive down market prices by increasing supply. If the value of the new implementation option which the firm could create by expanding the supply of inputs exceeds the cost of the investment needed to create the new supply of inputs, the firm can increase the value of its initiative option by investing in expanding input supply and exercising its new implementation option. Similarly, a firm may be able to shift its effective demand curve by investing in advertising and marketing or expanding its sales into new geographic areas. If the value of the implementation option created by the opportunity to serve an expanded market exceeds the investment needed to enter the new market, the firm can add to the value of its initiative option by exercising its implementation option based on expanded marketing.

5.2.2 Relaxing Constraints as a Source of Implementation Option Value

Now suppose that the firm returns to being a price-taker and again that capital is perfectly reversible and efficient, infinitely divisible, and instantly installable and removable. In the absence of constraints, at \( t = t^* \) the firm will
install either zero or unlimited capacity, depending on whether producing
the new product would be a negative or positive NPV undertaking. Assuming
the firm does exercise its production option, a finite optimal capacity will
result if the firm's output level is limited by constraints on its supply of an
essential input, by constraints on its ability to utilize inputs (for example, by a
bottleneck in the available production system or by an environmental
protection regulation limiting the total amount of the firm's emissions), or by
constraints on its ability to sell its output. As shown in Figure 5-3, when it is
profitable to produce during a given production interval, the firm's optimal
output level q* will be the output level that requires exactly the maximum
amount of the constrained input, that equals the maximum constrained
utilization rate, or that produces the maximum level of saleable output, as
indicated by the constraint level L. When the firm faces a constraint that
limits output, any possible relaxation of the constraint, say from L to L' in
Figure 5-3, will offer the firm a potentially valuable new implementation
option based on increased output.

Implementation options may result from fortuitous changes in
constraints beyond the control of the firm. If a firm's production has been
limited by a supplier's allocation of a scarce input, for example, the entrance
of a new supplier into the market place may make more of the input available
to the firm and lift the constraint on the firm's output level. In some cases,
the firm itself may be able to take actions which can lift constraints limiting
the firm's output -- for example, by searching out new suppliers, eliminating
production bottlenecks, or adding new markets. The costs which the firm
may have to incur to obtain a new implementation option in this way may be
in the form of a pay-as-you-go premium or may require a significant up-front
payment. The mode of payment required to create the new implementation
option directly affects the value of the implementation option.

Consider first the pay-as-you-go premium. For example, a new source of
supply for a limited number of input units may become available, but at
higher unit prices; or the firm may be able to contract for additional capacity
at a bottleneck, but at higher unit processing charges; or the firm may be able
to identify a new market for its product, but will have to pay higher shipping
charges to serve the new market. An implementation option which can be
created in this manner -- one which requires no irreversible up-front payment -- *always* has some positive value if prices are uncertain and if the firm can exercise its implementation option whenever it wishes to do so. An implementation option with this cost mode gives the firm an option to produce at a higher than normal level of output whenever prices exceed the higher cost basis the firm will face for the incremental output made possible by the pay-as-you-go implementation option. The option costs the firm nothing, however, when prices are less than costs and the option is not utilized.

Alternatively, if the firm must incur an up-front cost (e.g., the cost of modifying its production system to accept a slightly different grade of input from a new supplier) or if the firm must accept a period of fixed costs by committing to a supply, processing, or sales contract at higher unit costs, the value of the option to produce the incremental amount of output may or may not be worth more than the present value of the irreversible up-front payment or the required commitment to extra costs. For implementation options of this latter type, the firm may or may not find it value-maximizing to create the new implementation option, and the marginal value of the new implementation option to the firm \( \Delta I_{t,m} \rightarrow n,t \) could effectively be zero.

### 5.2.3 Changes in Production Technology as Sources of Implementation Option Value

Five characteristics of production technologies were mentioned earlier in this section as being limiting conditions whose relaxation could create valuable new implementation options: capital irreversibility, a long time-to-build (non-instantaneous installability and removability of capital), a high ratio of fixed to variable costs, limited capital divisibility ("lumpy" capacity), and input inefficiency. The following discussion will examine how relaxing limitations imposed on the firm's production by each of these production technology characteristics can create implementation options. To begin this discussion, assume that the firm has a single production technology whose capital is perfectly reversible and efficient, infinitely divisible, and instantly installable and removable. We then invert each of
these technology characteristics one at a time (for example, changing capital from reversible to irreversible) and note how a rightward position along each technology characteristic (from Figure 5-1) acts to limit production implementation options value. We then show how relaxing each individual production technology characteristic (i.e., allowing a leftward shift in Figure 5-1) can create a valuable implementation option.

As the following discussion will show, in conjunction with converging price functions or with constraints on output, limitations in any of the five technology characteristics will reduce optimal output levels. Therefore relaxing those limitations can add to the value of a product initiative option by increasing optimal production levels. This section concludes with a few examples of how technology characteristics can interact to magnify the potential of each as a source of valuable implementation options.

**Changes in Capital Reversibility.** Let us assume that the firm is a price-taker, is unconstrained in inputs and outputs, and has a technology whose capital is instantly installable and removable and infinitely divisible. However, let the firm's capital be perfectly irreversible, so that the firm must pay or commit to pay the full cost of capital equipment in order to begin production. Also, once the production equipment is installed, the firm's perfectly irreversible capital will have no alternative uses and thus zero salvage value.

The benefit of installing an incremental unit of irreversible capacity may come from either of two sources of increased implementation option value. If the incremental of capacity will be put into production immediately, the value of the incremental unit of capacity is the value of the option to produce one additional unit of product $P_1$ during each interval of the production period for which prices exceed variable costs (assuming that the physical life of the capital is at least equal to the production period). On the other hand, if the incremental unit of capacity will be idle when installed, the benefit of installing the incremental unit of capacity is the value of the option to produce another unit of $P_1$ in the future by paying variable costs. To determine whether adding another unit of capacity would be
value-maximizing, the value-maximizing firm must weigh the benefit of adding one unit of active or idle capacity against the cost of installing that unit of capacity plus the value of the forfeited option to wait to install the incremental unit of capacity.

If input and output prices are unaffected by the firm's output level, then the incremental net gain to the firm from installing the first or the nth unit of capital is identical, even as \( n \to \infty \). Thus, in the absence of rising input price functions, falling output price functions, and output constraints, the firm will seek to install either zero or (if price is sufficient to induce investment at all) infinite capacity and to produce accordingly. Thus, irreversibility of capital per se does not limit optimal output or capacity levels whenever it is optimal to invest and produce during a given production interval, and relaxing capital irreversibility under these ideal supply and demand conditions would therefore not be a source of implementation options value.

However, irreversibility of capital does act to limit the frequency of production -- and thus limits the number of intervals in the production period within the firm will want to produce. Making capital irreversible increases the value of the option to wait to install capacity. Since the firm must forfeit the option to wait when it installs capacity, capital irreversibility raises the opportunity cost to the firm of installing capacity. Thus, the firm will wait until unit prices are higher before installing and utilizing irreversible capacity, compared to the unit prices at which reversible capacity could be installed and production begun or expanded.

Making capital irreversible also reduces the relative value of the production option which the firm receives when it installs capacity, because when capital is irreversible it creates an irreversible up-front cost, while perfectly reversible capital can be installed and removed as needed and thus treated like a variable cost which is incurred only as needed.

Since making capital irreversible raises the opportunity cost and lowers the benefit of installing a unit of capacity, the value of the revenue stream which the firm can claim by installing capacity must be higher when capacity is irreversible in order to make the installation of any amount of
capacity a value-maximizing undertaking. Thus, the result of making capital irreversible is that prices must reach higher levels before it is value-maximizing to install any capacity. This requirement reduces the likelihood that capital will be installed at all, thereby reducing the likelihood of production during the available production period for new product P_i. (Note again that if capacity is installed at all under these ideal conditions, it will be installed in unlimited amounts if prices do not converge and the firm is unconstrained.)

Since irreversibility of capital reduces the likelihood that capacity will be installed and production initiated, relaxing capital irreversibility can lead to increased expectations of output and revenue and thus can be a source of increased implementation options value.

**Changes in Time-to-Build.** Assume now that the firm is a price-taker, is unconstrained in inputs and output, and has a technology whose capital is perfectly reversible and efficient and infinitely divisible. However, let the firm’s technology require capital that has a "time to build" -- i.e., a time lapse between the decision to install capacity and the availability of that capacity for production.

Suppose that the firm is considering the production possibilities for new product P_i at t = t*. The initiative option to produce P_i can have three sources of value: the option to wait to invest in capacity to produce P_i, the option value of installed but idle capacity, and the option value of installed and active capacity. Imposing a time to build T_B > 0 will always decrease the value of the product initiative option, although which component of initiative option value will be reduced if T_B > 0 will depend on whether the imposed time to build extends beyond t = t^-, the expected optimal exercise time for the production option i.e., on whether t^* + T_B > t^-.

First consider how T_B > 0 affects the option to wait. If t^* + T_B > t^-, the firm will not be able to begin to install capacity or to begin production until after the expected time when it would be optimal to do so, with the result that
the option to wait will decrease in value. Even if \( t^* + T_B \leq t^- \), the option to wait will decrease in value because there will always be some probability that prices will rise more rapidly than expected, with the result that the firm would find it optimal to have capacity and produce at some time \( t^* \leq t < t^* + T_B \), but would be prevented from doing so by the required time to build.

Now consider the impact of time to build on the option value of idle capacity and the option value of active capacity. If \( t^- = t^* \), so that it would be optimal for the firm to have at least some installed capacity at \( t^* \), then adding a time to build forces the firm to bring capacity on line at a later-than-optimal date \( t = t^* + T_B \). Having capacity available only at a time \( t > t^* \) means that the active and idle components of initiative option value have zero value at \( t = t^* \) when otherwise they would have some positive value. Thus, having a time-to-build requirement can decrease the decrease the options value of both active and idle capacity.

**Changes in the Ratio of Variable to Fixed Costs.** Assume now that the firm is a price-taker, is unconstrained, and has a technology whose capital is perfectly efficient, instantly installable and removable, and infinitely divisible. Consider the impact on the product initiative option value of having a high ratio of variable to fixed costs versus a high ratio of fixed to variable costs. For example, consider the effect of paying labor costs by a piece rate (a fixed amount per piece produced) versus hiring salaried workers with guaranteed employment. Assume that the labor time and cost required to produce one unit of output would be the same under either employment system.

Because the firm need not commit to any fixed labor costs under the piece rate system, the lack of fixed labor costs gives the firm a valuable option to shut down production if unit prices fall below variable costs. Thus, a shift towards a variable cost structure and away from a fixed cost structure can increase the value of a product initiative option by adding the value of an option to shut down production.

**Changes in Capital Divisibility.** Assume now that the firm is a
price-taker, is unconstrained, and has a single technology whose capital is perfectly efficient, perfectly reversible, and instantly installable and removable.

If capital is infinitely divisible, the firm can install exactly the amount of capacity it wants during any production interval. If capital is imperfectly divisible or "lumpy," capacity can only be added in substantial increments, and as a result the firm may face a choice of adding more capacity than it wants to have or doing with less capacity than it would like to have. As Figure 5-4 indicates, having either too much or too little capacity is inefficient, forcing the firm to add costs for capacity $c_K(K - q^*)$ that it would not add otherwise, or to forego revenue $p_{t,t}(q^* - K)$ from units it cannot produce because of insufficient capacity during any given production interval. Through either effect, lumpiness of capital reduces the value of a production opportunity relative to the value the opportunity would have if capital were more finely divisible.

Relaxing the lumpiness of capital brings a benefit whose value is the difference in the implementation option values based on the relative efficiencies of capital or opportunity costs of foregone revenues which would result from production technologies with two different degrees of capital divisibility.

**Changes in Input Efficiency.** Assume that the firm is a price-taker, is unconstrained, and has a single technology whose capital is perfectly divisible, perfectly reversible, and instantly installable and removable.

Let the firm have a production technology whose efficiency in utilizing one or more inputs could be improved, and suppose that the firm discovers a way to change its production technology to make more efficient use of an input. Making more efficient use of an input lets the firm reduce its input cost per unit of output. Lowering variable costs per unit reduces the value of the option to wait, but increases by a greater amount the value of the idle-capacity and active-capacity components of initiative option value. Reducing input (variable) costs also increases the likelihood that production will occur in any production interval, and thereby raises the expected total

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output level over the production period. Thus, a chance to improve a firm's efficiency in utilizing an input creates a potentially valuable implementation option based on increased frequency of production and thus increased expectations of total output.

If the firm is a price-taker, improving input efficiency will not affect the optimal level of output during any interval when production would be undertaken. However, improving the efficiency of a production technology can become a source of implementation options based on increasing output when the firm faces converging input and output price functions or constraints on output. First consider the effect of improvements in input efficiency when the unconstrained firm faces converging price functions. In this case, improving input efficiency is equivalent to shifting rightward the input's supply curve expressed in terms of input cost per unit of output, as shown in Figure 5-5, with the results that all components of product initiative option value increase, that frequency of production will increase, and that optimal output will rise to a new, higher output level \( q^{**} > q^* \). At this higher optimal output level, the firm will also realize greater marginal profits during each period of active production. Thus, improving input efficiency in the face of converging price functions creates a valuable implementation option based on increased frequency of production, expanded output, and greater profitability.

Now consider the constrained price-taker. Improving input efficiency is comparable to lowering the variable cost per unit of output from \( v_c \) to \( v_{c'} \), as shown in Figure 5-6. As above, a reduction in variable costs has the effect of increasing the frequency of production. If the improved efficiency is in the use of the constraining input, the improved efficiency also has the effect of shifting the imposed constraint from \( L \) to \( L' \), thereby increasing the optimal output level of the firm. Thus, the constrained price-taker can also gain an implementation option based on increased frequency of production, expanded output, and greater profitability by making efficiency improvements in utilizing inputs which constrain the firm.

Thus, when prices are uncertain, the value of an implementation option which results from improvements in efficiency may be considerably greater than just the expected value of cost savings due to improved efficiency. In
fact, the resulting implementation option will also include the value of the option to produce profitably over a wider range of future unit prices.

**Effects of Interdependency of Technology Characteristics.** In general, as the location of the firm is more to the right along the dimensions of its production technology decision space, there is greater potential for interactions among the various technology dimensions to magnify the potential value of implementation options. For example, a high degree of capital irreversibility increases the opportunity cost of investing in capacity when there is a significant time to build, which reduces the value of the product initiative option. Thus, an opportunity to make capital more reversible can create an even more value implementation option when there is a significant time to build, compared to the potential of greater capital reversibility to create options value when capital can be installed quickly.

Similarly, a high degree of capital irreversibility occurring jointly with a significant time to build improves the potential for divisibility of capital to be an important source of valuable implementation options. With high capital irreversibility and significant time to build, lumpiness of capital decreases the return to the firm from investing in capacity and thus depresses capacity and output levels. From another perspective, capital irreversibility and lumpiness increase the depressing effect of a long time to build on production frequency. Lumpy, irreversible capital that takes time to build in turn increases the potential implementation option value of finding new ways to organize the firm's production so that the share of variable costs in total costs increases, especially if some capital costs can be shifted to variable costs (for example, by contracting for production).

### 5.3 The Option to Vary the implementation of Production

This section elaborates a general framework for valuing implementation options which result when a firm has the strategic flexibility to choose capacity levels and to vary output levels for a new product $P_j$. This section then applies this framework to the Pindyck (1988) model of the capacity choice.
of a value-maximizing firm when capital is perfectly irreversible and the firm faces converging price functions. The discussion shows that the general framework for valuing implementation options to vary capacity and output presented here accommodates the assumptions of the Pindyck model as a special case. Numerical examples adapted from the Pindyck analysis are also used to suggest the potential value of such implementation options.

5.3.1 General Framework for Valuing Implementation Options to Vary Capacity and Output

Suppose that a firm has just completed development of new product $P_i$ at $t = t^*$ and now must evaluate the impacts of its opportunity vectors on the product initiative option $C_{i,t}$ (see Equation 5-1) Also suppose that the firm has the strategic flexibility of all three timing options: the firm may wait to invest in installing capacity or to produce once capacity is installed; the firm may shut down production at will; and the firm may abandon the production project after beginning production. The objective of the firm is to find the initial capacity and output levels that will maximize the value of the product initiative option.

Each production opportunity vector $OV_{i,m,t}$ available to the firm has associated with it an implementation option $I_{i,m,t}$ that can have three possible sources of value. The first source of value is the value of producing $P_i$ when capacity has been installed and is producing. This source of opportunity vector value will be denoted by $[I_{i,m,t}]^{\text{produce}}$ or referred to as the production component of implementation options value. The second source is the value of capacity which has been installed but is currently idle. This source of value will be denoted by $[I_{i,m,t}]^{\text{wait to produce}}$ and referred to as the wait-to-produce component of implementation options value. The third value source is the value of the firm's option to install capacity and begin production at some future time, denoted by $[I_{i,m,t}]^{\text{wait to invest}}$ and referred to as the wait-to-invest component of implementation option value. Each of these components of the value of an implementation can be defined in terms...
of the underlying product initiative option and its attached timing options.

When a firm completes development of a new product, it must decide whether to put the new product into production, and if so, how much capacity to install and at what level to set initial output. Implicit in each approach to producing $P_i$ (e.g., using a specific production technology) is a capacity level and output level which will maximize the value of the product initiative option available through that approach. The value-maximizing capacity and output will be determined at any moment both by exogenous variables (the observed prices for inputs and output, by the assumed stochastic behavior of prices, by the risk-free interest rate, and by the market price of risk) and by a number of potentially endogenous variables. For the firm to realize the maximum implementation option value from a given approach, the firm must be able to determine the optimal capacity and output levels. Since there are three components of an implementation option's value, the optimal capacity and output levels for the value-maximizing implementation option $I_{i,m,t}$ are values which give the solution to the maximization problem:

$$I_{i,m,t} = \text{Maximize } \left[ [I_{i,m,t}]\text{wait to invest} + [I_{i,m,t}]\text{wait to produce} + [I_{i,m,t}]\text{produce} \right]$$

Equation 5-5

One method for solving this maximization problem will be discussed later in this section. For now we simply define the three components of opportunity vector value.

Suppose that the firm can instantly install capacity and begin producing in the initial interval of production. Then the production component of implementation option value is the expected present value of the revenue stream from producing new product $P_i$ when production can be abandoned and shut down ($((V_{i,m,t})^{SD,A}$, less the present value of costs to install utilized capacity ($c_K(K_U)$) and less the present value of any fixed costs of production other than costs of capacity ($C_{P,m,t}$):

$$[I_{i,m,t}]\text{produce} = (V_{i,m,t})^{SD,A} - c_K(K_U) - C_{P,m,t}$$

Equation 5-6

The wait-to-produce component of implementation option value in the initial production interval is the value of any capacity which is installed but
not used during the initial interval. In other words, \([I_{i,m,t}]_{\text{wait to produce}}\) is the value of idle capacity which could be put into production any time after the current production interval. A unit of currently idle capacity will be put into production whenever prices for \(P_i\) exceed variable costs in the future. Thus, a unit of idle capacity may be valued as an option on the current price for \(P_i\) during each production interval in the intended production period, exercisable by paying the variable costs of producing one unit of output. Let this production option be denoted by \((C'_{i,m,t})^{SD}\). To obtain this option, the firm must pay the present value of the cost of one unit of idle capacity, \(c_K(K_i)\). Thus, the value of the wait-to-produce component of implementation option value can be stated as

\[
[I_{i,m,t}]_{\text{wait to produce}} = (C'_{i,m,t})^{SD} - c_K(K_i)
\]

Equation 5-7

The wait-to-invest component of implementation option value is the expected present value of the capacity which the firm could install in the future. This is equivalent to having an option to wait to install capacity in any amount above the current level of utilized and idle capacity. Denote this option value as \((C_{i,m,t})^W\), where the option is on a maximum of \(K(t_n) \leq K \leq \infty\) units of capacity, where \(K(t_n)\) is the amount of capacity which will be installed at the beginning of the current production interval, and where the cost of each unit of capacity will be a constant \(c_K\). Then

\[
[I_{i,m,t}]_{\text{wait to invest}} = (C_{i,m,t})^W
\]

Equation 5-8

With these definitions of the value components of an opportunity vector, a detailed statement of the value-maximizing implementation option given in Equation 5-5 becomes

\[
I_{i,m,t} = \text{Maximize } [(C_{i,m,t})^W + (C'_{i,m,t})^{SD} + (V_{i,m,t})^{SD,A} - c_K(K) - C'_{P,m,t}]
\]

Equation 5-9

where \(c_K(K) = c_K(K_U) + c_K(K_i)\). (As it is written above, Equation 5-9 applies to the initial production interval, when no capacity has been previously installed. In a subsequent production interval, when capacity may have been installed previously, the cost of installed capacity is a sunk cost and
irrelevant to the capacity and output maximization problem for that interval. In that case, only incremental capacity would be included in Equation 5-9. This is discussed further below.)

Equation 5-9 says that the value of a given approach to producing a new product will depend directly on the firm's choice of capacity and the allocation of that capacity to active or idle status in a given production interval. Thus, capacity and output levels are fundamental decision variables that the firm must manage properly in order to maximize the value of each product initiative option.

Equation 5-9 also shows that the value of an opportunity to produce a newly developed product may be considerably in excess of \( V_{i,m,t} - c_K(K) - C_{P,m,t} = V_{i,m,t} - C_{P,m,t} \), which is the value that a conventional "no-option" discounted cash flow analysis would place on the production opportunity. Equation 5-8 makes clear that a no-option DCF analysis would ignore several components of implementation option value -- i.e., the value of the options to shut down or abandon ongoing production, the value of the option to use idle capacity in the future, and the value of the option to install additional capacity in the future.

To maximize the right-hand side of Equation 5-9, it is necessary to develop expressions for the incremental changes in each term which would result from incremental changes in capacity and output levels. The maximum value \( I_{i,m,t} \) and the optimal capacity and output levels can be solved for jointly by letting capacity and output levels increase incrementally until a further incremental change in either capacity or output results in a zero or negative incremental change in \( I_{i,m,t} \) -- i.e., \( \Delta I_{i,m \rightarrow n,t} \leq 0 \). Adding an incremental unit of capacity directly affects the wait-to-invest and wait-to-produce components, \( [I_{i,m,t}]^{\text{wait to invest}} \) and \( [I_{i,m,t}]^{\text{wait to produce}} \), while adding a unit of output affects only the production component of the opportunity vector, \( [I_{i,m,t}]^{\text{produce}} \). This procedure is subject to the condition that output cannot exceed capacity, \( q \leq K \).

From Equation 5-9 it follows that the effect of adding one more unit of
capacity $\Delta K$ to the wait-to-invest component of implementation option value is to change the value of the option to wait to invest by an amount $\Delta (C_{i,m,t}^W)$:

$$\Delta I_{i,m,t}^{\text{wait to invest}} = \Delta (C_{i,m,t}^W) \quad \text{Equation 5-10}$$

Adding an incremental unit of capacity forfeits the option to wait to invest in that unit of capacity, and accordingly $\Delta (C_{i,m,t}^W) \leq 0$. (One approach to calculating this amount is illustrated in the Pindyck example.)

Next consider how adding an incremental unit of idle capacity affects the component $[I_{i,m,t}^{\text{wait to produce}}$. Equation 5-7 for $[OV_{i,m,t}^{\text{wait to produce}}$ leads to this change in the value of the wait-to-produce component of implementation option value which would result from adding an incremental unit of idle capacity:

$$\Delta I_{i,m,t}^{\text{wait to produce}} = \Delta (C'_{i,m,t}^{SD}) - c_K(\Delta K) \quad \text{Equation 5-11}$$

Equation 5-11 says that the incremental increase in the value of the wait-to-produce component $[I_{i,m,t}^{\text{wait to produce}}$ from adding an incremental unit of capacity equals the call option (with options to wait, shut down, and abandon) on the incremental unit of output during the production period $(\Delta (C'_{i,m,t}^{SD}))$, less the present value of the cost of adding one more unit of capacity ($c_K(\Delta K)$).

Adding an incremental unit of capacity $\Delta K$ directly affects the production component of an implementation option if it allows the firm to increase its output level by one unit, $\Delta q$. To find the effect on the production component of an incremental increase in output $\Delta q$, restate Equation 5-6 to give the change in the value of the production component which would result from initially producing one additional unit of output:

$$\Delta I_{i,m,t}^{\text{produce}} = \Delta (V_{i,m,t}^{SD,A}) - c_K(\Delta K) - \Delta C'_{P,m,t} \quad \text{Equation 5-12}$$

This equation says that the incremental increase in the value of the production component of implementation option value from increasing the
firm's initial production level by an incremental unit of output $\Delta q$ equals the present value of the net revenue stream expected from producing the incremental unit (with options to shut down and abandon) during the production period, less the cost of installing an incremental unit of utilized capacity, less the present value of any fixed costs (other than for capacity) which the firm must commit to to produce the incremental unit of output.

Maximization of $I_{i,m,t}$ is accomplished by jointly and incrementally varying capacity and output levels until no further increases can be found for the sum of the changes in the value components:

$\Delta[I_{i,m,t}]^{\text{wait to invest}} + \Delta[I_{i,m,t}]^{\text{wait to produce}} + \Delta[I_{i,m,t}]^{\text{produce}} \leq 0$

$\Delta(C_{i,m,t})^{W} + \Delta(C'_{i,m,t})^{SD} + \Delta(V_{i,m,t})^{SD,A} - c_K(\Delta K) - \Delta C'_{p,m,t} \leq 0$

Equation 5-13

The capacity and output values which satisfy Equation 5-13 yield the value of the implementation option $I_{i,m,t}$ which would maximize the value of a product initiative option achievable through the approach of which $I_{i,m,t}$ is representative. Once the maximum value implementation option is determined for each of the firm's feasible approaches to producing product $P_i$, the maximum achievable value of the product initiative option can be found such that

$\Delta I_{i,m \rightarrow n,t} = 0$

Equation 5-14

5.3.2 Pindyck's Model of Optimal Capacity Choice Interpreted as an Implementation Option Maximization Problem

Within the general framework for determining implementation option values discussed above, let us now consider the Pindyck (1988) model of optimal capacity choice, which will be shown here to be a special case of the general framework for valuing implementation options. The following discussion reviews the general assumptions of the Pindyck model and their consequences for the implementation option maximization problem to be
solved. This section also shows how Pindyck’s solution contains valuations for each of the components of implementation option value discussed in the general framework.

In constructing his model of optimal capacity choice, Pindyck makes assumptions which impose certain limitations on the firm’s choice of optimal capacity and output levels. As a result, relaxing these imposed limitations become potential sources implementation option value. To understand how the imposed limitations on capacity and output in the Pindyck model become potential sources of implementation options value, it is necessary to understand more about both the general premises of the model, its detailed specifications, and its solution procedure.

The limitations imposed in the Pindyck model whose relaxation could create implementation options are (1) that the firm faces converging price functions and (2) that capital is perfectly irreversible. In Pindyck’s model, output prices are stochastic, but expected output prices are a downward-sloping function. Input prices are deterministic and upward sloping. The convergence of price functions assures that optimal output will be finite, which creates the potential for an expansion of the firm’s control over endogenous variables to increase optimal output and thus to generate a valuable new implementation option. The irreversibility of capital also acts to limit expected total output by raising the price levels at which investing and producing would have a positive net present value.

Pindyck also makes a number of simplifying assumptions that reduce somewhat the complexity of the analysis of the optimal capacity choice. Capital is characterized as being infinitely divisible, instantly installable, and unchangeable in its efficiency. There are no fixed costs other than those related to capacity. If and when the firm begins production, it will produce ad infinitum. The simplifications in the analysis of capacity choice which follow from these assumptions deserve clarification.

The perfect irreversibility of capital and the lack of fixed costs -- plus an implicit assumption that there are no organizational costs of abandoning production -- reduces the value of the option to abandon to zero, allowing it to be ignored. Thus, the operating option to abandon production, indicated by
the superscript \((\cdot)^A\) in Equation 5-9, is dropped from the Pindyck analysis.

Also, without fixed costs, \(C'_{P,m,t} = 0\) in Equation 5-6 and \(\Delta C'_{P,m,t} = 0\) in Equation 5-13.

Production, once begun, will continue *ad infinitum*, except that production may be shut down temporarily when output prices fall below variable costs. Thus, the value of the wait-to-produce component is the value \((C'_{i,m,t})^{SD}\) of idle capacity which, once put into production, could be shut down whenever output prices fall below variable costs, less the cost \(c_K(K_I)\) of idle capacity to be installed. The value of the production component of value then includes the value of the option to shut down production, \((V_{i,m,t})^{SD}\), less the cost \(c_K(K_U)\) of installing utilized capacity.

Also, in the Pindyck model capital does not depreciate and unit costs of capital are constant at \(c_K\).

With these simplifying assumptions, the problem of choosing the optimal capacity as posed by the Pindyck model reduces to the problem of solving the maximization problem

\[
I_{i,m,t} = \text{Maximize} \left[ [I_{i,m,t}]^{\text{wait to invest}} + [I_{i,m,t}]^{\text{wait to produce}} + [I_{i,m,t}]^{\text{produce}} \right]
\]

\[
= \text{Maximize} \left[ (C_{i,m,t})^W + (C'_{i,m,t})^{SD} + (V_{i,m,t})^{SD} - c_K(K) \right]
\]

Equation 5-14

where

\[
[I_{i,m,t}]^{\text{wait to invest}} = (C_{i,m,t})^W \quad \text{[Equation 5-8]}
\]

\[
[I_{i,m,t}]^{\text{wait to produce}} = (C'_{i,m,t})^{SD} - C_K(K_I) \quad \text{[Equation 5-7]}
\]

\[
[I_{i,m,t}]^{\text{produce}} = (V_{i,m,t})^{SD} - c_K(K_U) \quad \text{[Equation 5-6]}
\]

and \(c_K(K) = c_K(K_I) + c_K(K_U)\). To find the maximum value of \(I_{i,m,t}\), the incremental difference equation which must be solved for optimal capacity and output is

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\[ \Delta[I_{i,m,t}] = \Delta(C_{i,m,t})^{W} + \Delta(C'_{i,m,t})^{SD} + \Delta(V_{i,m,t})^{SD} - c_K(\Delta K) \leq 0 \]

Equation 5-15

Appendix A5 explains the Pindyck model specifications and solution procedure for Equation 5-15 in more detail. The following section interprets an example from the Pindyck analysis in the context of this thesis' model of product initiative options.

5.3.3 Implementation Options Values in the Setting of the Pindyck Model

One objective of Pindyck's analysis of capacity choice is to show the depressing effect of uncertainty on capacity choice when capital is irreversible. A corollary objective is to investigate the impact of uncertainty on the magnitude and composition of firm value when capital is irreversible. The two objectives are served by the device of evaluating a one-product firm. If the firm produces only one product, the market value of the firm will consist of the present value of expected returns from the production assets the firm has in place, plus the value of the firm's growth options to add capacity. In terms of the general framework of the preceding section for valuing implementation options to choose capacity and output levels, the value of the one-product firm is the maximized sum of the value components \([I_{i,m,t}]_{\text{wait to produce}}, [I_{i,m,t}]_{\text{produce}}, \) and the value of the firm's growth options to add capacity given by \([I_{i,m,t}]_{\text{wait to invest}}\).

Pindyck gives a numerical example of the magnitude and composition of the value of the firm which can be used to illustrate how the value components of an implementation option and the value-maximizing capacity might vary across different levels of uncertainty under conditions of competitive value erosion. Figures 5-7 to 5-10 adapt Pindyck's numerical example (1988, Table 2) to show how optimal capacity and the resulting implementation option value will vary when uncertainty increases from \(\sigma_0 = 0\) to 0.1, 0.2, and 0.4. (The assumed values of exogenous variables in the figures are: \(c_1 = c_2 = 0, \gamma = 0.5, r = \delta' = 0.05, \) and \(c_K = 10.\))

In Figures 5-7 to 5-10, it can be seen that the total value of the implementation option increases with increasing uncertainty for all price
levels, but that the component values change significantly with increasing uncertainty. In the deterministic case, \( \sigma_0 = 0 \), all of the value of an opportunity vector would come from the value of utilized capacity, \([I_i,m,t]\) produce, because with no uncertainty there is no value in waiting to invest or produce. As uncertainty increases, the value of capacity in place decreases because increasing \( \sigma_0 \) implies increasing \( \delta \) in the Pindyck model, which in the context of this thesis' model implies competitive value erosion of the new product opportunity over time. At the same time the value of the option to wait to invest increases rapidly, so that the net change in the implementation option with increasing uncertainty is strongly positive. Thus, as uncertainty increases, not only does the implementation option increase in value, but more and more of the value of the implementation option will reside in the option to wait to invest. At \( \sigma_0 = 0.4 \) over 80% of the value of the opportunity to produce new product \( P_i \) would be attributable to the value of the option to wait to install capacity and produce.

Figures 5-7 to 5-10 also show the effect of increasing uncertainty on optimal capacity \( K^* \). As uncertainty increases, the optimal capacity level decreases across all price levels. This is consistent with the noted shift in the source of implementation option value as uncertainty increases from value components based on installed capacity to the value component based on waiting to invest in capacity. As the value of waiting to invest in an incremental unit of capacity increases and the value of an incremental unit of installed capacity decreases, the number of incremental units of capacity for which \( \Delta(C_i,m,t)^W < \Delta(C_i',m,t)^SD + \Delta(V_i,m,t)^SD_A - c_K(\Delta K) \) will decrease, lowering the optimal amount of installed capacity.

The impact of increasing uncertainty on implementation options in the setting of the Pindyck model is also evident from the increasing share of the wait-to-invest component of value and from the declining optimal capacity as uncertainty grows. Since increasing uncertainty increases the value of implementation options, it is possible (though not necessary) that increasing uncertainty can make the chance to relocate from one implementation option
to another even more valuable. Whether a given implementation option increases in value or not, increasing uncertainty will lead to reduced output levels as a consequence of decreasing optimal capacity levels.

Frequency of production may increase or decrease with increasing uncertainty. As Figure 5-11 shows, for an expected price greater than variable costs, $E[p_{i,t}] > vc_1$, the greater uncertainty of distribution B compared to distribution A, where $\sigma_B > \sigma_A$, will increase the probability that a realized price will be less than variable costs, as indicated by a comparison of the areas under the two distributions to the left of $vc_1$. When the expected price is less than variable costs, $E[p_{i,t}] < vc_2$, increasing uncertainty increases the probability that the realized price will exceed variable costs, as indicated by a comparison of the areas under the two distributions to the right of $vc_2$. Since production by the value-maximizing firm will occur only when price exceeds variable costs, increasing uncertainty may lead to more frequent production (when $E[p_{i,t}] < vc_2$) or to less frequent production (when $E[p_{i,t}] > vc_2$).

Pindyck's analysis also suggests two other implications for implementation option values that are consistent with and add to the discussions of technology choices in Section 5.2.3.

When the firm is a price-taker, irreversibility of capital decreases the frequency of production (Section 5.2.3). Pindyck's analysis (1988, page 981) shows that irreversibility of capital can also limit optimal capacity and thus output when the firm faces converging input and output price functions.

Pindyck's analysis also confirms (as discussed in Section 5.2.3) that lumpiness of capacity combined with capital irreversibility will raise the price $\theta(t)$ at which it is optimal to add capacity, thereby depressing optimal capacity levels $K^*$ and maximum output levels. In addition, Pindyck notes (1988, page 982) that with converging price functions, lumpiness of capacity decreases the value of the firm (or, equivalently, of an opportunity vector).
5.4 Implementation Options to Vary the Speed of Development: Lockheed 1011 Tristar Re-visited

Majd and Pindyck (1987) have studied the option to invest in a development project when investments are made sequentially over a period of time and no payoff to the project is obtained until development is complete. The Majd and Pindyck model is applied to the model of product initiative options and summarized in Appendix A6. The appendix includes an adaptation of Majd and Pindyck's numerical example to illustrate the potential implementation option value of increasing the speed of development. The appendix also shows that the assumptions of the Majd and Pindyck model make it a special case within the general framework for valuing implementation options proposed in this chapter.

To illustrate the implementation options value which may be realized by increasing the speed of product development, the example of the Lockheed 1011 Tristar development project introduced in Chapter 2 is re-evaluated here when the required development period is allowed to vary from 12 to 48 months. (in the Chapter 2 example, the development period was fixed at 42 months.)

**Figure 5-12** shows the change in the options value of the 1011 Tristar project (evaluated as a European call option) over a range of development times. The options are evaluated for a production level of 4 aircraft per month, a competitive rate of value erosion $\delta = 0.06$ per year, and for two levels of project value uncertainty $\sigma = 0.20$ and $\sigma = 0.40$. Accelerating development increases the value of the product initiative option for both levels of uncertainty, but the relative benefit of increasing development speed varies inversely with the level of uncertainty about project value. Accelerating development from 42 to 36 months would have increased the options value of the project by 24.4% (from $149.0$ to $185.3$ million) for an uncertainty level of $\sigma = 0.20$, but by only 9.3% (from $487.9$ to $533.2$ million) for $\sigma = 0.40$.

Whether accelerating product development would be a value-maximizing implementation option will depend not just on available increases in
initiative options value, but also on the total costs of development if the
development period is compressed. If accelerating development increases the
present value of total development costs by an amount greater than the gain
from increased initiative option value, accelerating development would not be
desirable even in a context of competitive value erosion. The optimal speed of
development will be the development period for which the initiative options
value exceeds the total development cost by the greatest amount.
Figure 5-1: Some Decision Variables Which Define Implementation Options and Affect the Maximum Value of a Product Initiative Option
Figure 5-2: Rightward Shifts in Supply and Demand Curves

Figure 5-3: Constraints on Output
Figure 5-4: Effects of Lumpy Capacity on Capacity Costs or Revenue
Figure 5-5: Improved Input Efficiency Shifts Supply Curve to Right

Figure 5-6: Effect of Improved Efficiency on Input Constrained Firm

Firm receives benefit of (A) lowered variable costs and possibly (B) an increase in output.
Figure 5-7: Implementation Option Value and Optimal Capacity for $\sigma_\theta = 0$

Figure 5-8: Implementation Option Value and Optimal Capacity for $\sigma_\theta = 0.1$
Figure 5-9: Implementation Option Value and Optimal Capacity for $\sigma_\theta = 0.2$

Figure 5-10: Implementation Option Value and Optimal Capacity for $\sigma_\theta = 0.4$
Figure 5-11: Effect of Price Uncertainty on Frequency of Production
Figure 5-12: Change in Options Value of Lockheed 1011 Tristar with Changes in Development Time
Part III

Real Options in Product Strategies
6. Strategies for Component Design

This chapter describes several approaches to designing components now being followed in the development of assembled products as diverse as dishwashers, electronics products, and jumbo jets. Five component design strategies are discussed: use of "off-the-shelf" components, re-use of pre-existing components, commonality of components among a group of related products, design of components for re-usability, and "black box" component design by suppliers. The advantages which can be obtained from these strategies include reduced costs of development and manufacturing, shortened development periods, and improved component reliability. However, these component strategies also have potential weaknesses, which are briefly discussed. The chapter concludes with an assessment of how each advantage or disadvantage of pursuing these competitive strategies might affect the options value of a firm's new product development opportunity.

6.1 Component Strategies

Across a spectrum of markets for assembled products, many firms have begun to use a number of strategies for developing various components which collectively make up an assembled product. In diverse markets, five strategies for component design have emerged which appear to offer specific strategic benefits to firms in competitive product markets.

Design with "Off-the-Shelf" Components. In many product markets, certain kinds of components can be widely used in various product models. In such cases, components manufacturers often offer a range of "standard" components which can readily be incorporated into a range of designs for assembled products. Examples of such standardized components range from hard disks for personal computers to shock absorbers for cars.

When a new product design can incorporate at least some "off the shelf" components, several advantages may be realized by the developing firm. Usually the total development cost for a new product can be reduced by using a standard component instead of designing a new component. Development time can also be shortened. The costs of manufacturing the new product can
also be lowered if unit costs for a standard component are less than those for a custom-designed component, which is often the case if the standard component is produced in large volume. Finally, a standard component that has been in use for some time may often offer greater reliability than a new component design, thereby contributing to greater reliability of the assembled product which incorporates the component.

Although use of standard components may involve some compromise of overall product performance, the resulting development and manufacturing costs savings can be substantial compared to the value of the compromised performance of the assembled product. The *Economist* (1991) has suggested that extensive use of off-the-shelf components (which the *Economist* terms "catalogue design") by Japanese firms results in "a product that is 90% as good as a product designed from scratch might be -- but only half the price of a completely original version."

**Re-use of Existing Components.** Development of a new version of an existing assembled product need not require re-design of every part or component used in the assembled product. Often at least some existing components in current models can be incorporated into a new model design. The potential benefits of re-using existing components are similar to those obtained by using off-the-shelf components: reduced development and/or manufacturing costs, reduced development time, and improved reliability relative to new component designs.

US automakers are among the leading practitioners of re-using existing components. Figure 6.1 summarizes a comparative study by Clark and Fujimoto (1991) of U.S., European, and Japanese auto development projects. The figure shows that U.S. automakers typically had both a significantly lower ratio of newly designed parts (implying a higher ratio of re-used parts) than Japanese car makers and a much greater preference for in-house engineering of components. Clark and Fujimoto (1991, p 151-152) explain the greater reliance of U.S. car makers on re-using components as being motivated by a desire to economize on tooling costs for parts and components in order to concentrate development resources on periodic "great-leaps-forward" in which virtually completely new product models are
introduced every 12-15 years. Reuse of existing parts lowers the cost of introducing "refreshed" or moderately redesigned models every 3 or 4 years between major product reden
designs.

**Parts Commonality.** In some cases, a family of related new products may be designed which make extensive use of common parts. A high level of parts commonality across product models can lower the costs of both developing and manufacturing each new product model in the family. Two examples illustrate the use of parts commonality to reduce costs in development or manufacturing.

The development of airframes for commercial jets is engineering-intensive and can be both lengthy and expensive. To reduce the cost of developing new aircraft models, all major airframe builders now make extensive use of common parts and components in designing a family of related models of a new jet. **Figure 6-2** shows the commonality of components among various derivatives of the McDonnell-Douglas MD-80 and MD-90 midrange passenger jets. **Figure 6-3** shows a similar degree of parts commonality for the Airbus A-330 and A 340-200 models.

The use of parts commonality to reduce manufacturing costs (as opposed to development costs) can be observed in markets for products which are relatively simple in design, but which are produced in large volume. General Electric Company’s redesign of its dishwasher line to exploit the manufacturing economies of parts commonality is a case in point. GE marketing strategy requires a full line of dishwashers, and GE usually offers five or six models of dishwashers incorporating different levels of features at different price points. Before being redesigned, each model in GE’s dishwasher line was made from a number of basic components unique to that model or shared with just one or two other models. Cheaper models, for example, were made with coated metal interiors which were cheaper (in material cost) than the molded plastic interiors used in top-of-the-line GE models. GE’s study of its production processes found, however, that production and assembly of several different grades (and hence configurations) of the same basic component was more costly than simply producing the highest quality component for use in all models. Thus, in the
strategic redesign of the dishwasher line, the high-quality molded plastic interiors were specified for all models in GE's new line of dishwashers. **Figure 6-4** illustrates GE's use of parts commonality among several models to reduce manufacturing costs and to contain variety among product models to the dishwasher door panels.

**Design for Re-usability.** By their nature, certain kinds of assembled products are able to incorporate modular components with relative ease and efficiency. In such cases, a firm may be able to design modular components with the intention of re-using them in many future products. The ability to incorporate re-usable components in future products lowers the costs of developing future new products. Because re-usable components are often "de-bugged" in earlier uses, they can often offer greater reliability than new components.

Design of components for re-usability can be observed in product markets as diverse as farm equipment and computer software. Christian (1987) has described the rationalization of the John Deere tractor products line by making extensive re-use of a number of components specifically designed for re-use, such as hydraulic cylinders and transfer gear cases. In computer software, Cusumano (1989) has documented the reduced time to develop software applications realized by Toshiba and other Japanese software firms as a result of writing program routines as modules which can be reused in future programs. In the Cusumano study, Toshiba was able to achieve as much as 80% re-usable modules in its new software, with substantial gains in productivity (i.e., a reduction in development or manufacturing costs/unit).

"Black-Box" **Component Development.** Japanese automakers have evolved a supplier-based approach to developing components that has come to be known as the "black-box" strategy for component development. Originally constrained by limited engineering resources which had to be focussed on overall model design development, Japanese car makers in the 1950s and 1960s turned responsibility for development of many components over to their suppliers (Clark and Fujimoto, 1991, p 152). In developing new car models,
Japanese car makers now typically provide their suppliers with only a "black-box" specification of size and functionality of the required component and leave the actual design and development of the component up to the supplier.

Following this approach to component development allows Japanese car manufacturers to concentrate their limited engineering resources on frequent overall product redesigns, leading to shortened product development cycles and a greater variety of product models introduced to the market. Figure 6-5 shows the success of Japanese automakers in shortening product development cycles and increasing the number of product models relative to U.S. and European car companies. The use of black-box component development has reduced the product development task of the Japanese car companies and contributed to their capabilities in accelerating the product development cycle.

6.2 Some Caveats

The previous section identified several advantages which can result from the successful application of the five component strategies discussed above. Some potential pitfalls of these strategies also deserve mention.

As mentioned earlier, using a standard, pre-existing, or shared component in a new product design may require some compromise of the performance obtained for the new product, relative to the performance that could be obtained from a custom-designed component. A further danger is that overly extensive use of common components across product models could reduce the ability to differentiate each product model from its related models in the marketplace. (Perhaps the extreme example of the danger of loss of differentiation is the GM line of "X-Cars" -- Chevy Citation, Oldsmobile Cutlass, Pontiac Phoenix, and Buick Skylark-- which had a very high degree of parts commonality, but which were virtually indistinguishable in appearance and, as a result, sold poorly.) Finally, repeated re-use of components in successive designs forecloses the opportunity to make incremental improvements to components whenever a new product model is introduced (what Clark and Fujimoto have termed the "rapid inch-up" approach to technological improvement).
The potential effect of any of these possible pitfalls in component strategies is the development of a lower-performing, less competitive new product which cannot command as high a price and/or achieve a large a sales volume as it might otherwise. Thus to avoid diminishing the value of a new product design, the users of these component strategies must be sensitive to ways in which applying one or more of these component strategies might negatively affect the market's perception of the value of the assembled product.

### 6.3 Impact on Real Options Values

The potential impact of these component strategies on the real options value of a product development opportunity can be illustrated by use of Equation 2-10 for the value of a simple new product initiative option:

\[
C_{i,0} = V_{i,0} e^{-\delta t^*} N(h) - C_P e^{r t^*} N(h - \sigma \sqrt{t^*}) 
\]  

[Equation 2-10]

Recall also Equation 2-6 for the net present value of a product development opportunity:

\[
NPV_{i,0} = C_{i,0} - C_D
\]  

[Equation 2-6]

Following components strategies that reduce the cost of developing a new product -- e.g., by using off-the-shelf or pre-existing components -- reduces \( C_D \) in Equation 2-6 and thus may increase the net present value of a product development opportunity.

Reducing manufacturing costs by using standard, pre-existing, or shared components reduces \( C_P \), the exercise price of the production option, and thereby increases \( C_{i,0} \), the value of the product initiative option.

Reducing the time required to complete development of a new assembled product by re-using components or by allowing suppliers to develop "black-box" components may increase the value of \( C_{i,0} \) whenever the rate of competitive value erosion \( \delta \) of the new product is sufficient to make early exercise of the product initiative option desirable (see Section 4.1). Since many assembled products are sold in highly competitive ("high-delta") markets exposed to competitive value erosion, accelerating product
development through component strategies may lead to significant increases in the options value of a product development opportunity.

To the extent that re-use of components or a component supplier's special expertise leads to high product reliability or performance, the value of $V_{i,t}$, the revenue stream which can be obtained from the sales of the new product, may increase, with resulting enhancement in the value of $C_{i,t}$. On the other hand, injudicious use of these component strategies which results in reduced product differentiation, excessively compromised product performance, or lagging technological progress, may drastically reduce the value of $V_{i,t}$.

To illustrate the potential impact of these component strategies on the options value of a product development opportunity, consider a simple product initiative option in a highly competitive (high-delta) product market. In Equation 2-10, let the present market value of the revenue stream from new product $P_i$ be $V_{i,0} = 100$ million, production costs $C_P = 60$ million, variance of the revenue stream $\sigma = 0.20$ per year, time to develop $t^* = 1$ year, the rate of competitive value erosion $\delta = 0.15$, and the risk-free interest rate $r = 0.03$. Then the net present value of this product development opportunity is given by

$$\text{NPV}_{i,0} = C_{i,0} - C_D$$

Equation 6-1

$$= (100) e^{-0.15(1)} N(h) - (60) e^{-0.03(1)} N(h - (0.20)(1)) - C_D$$

$$= 28.0 \text{ million} - C_D$$

Thus, if the firm can develop this new product for costs of development with present value less than $28$ million, developing this product would be a positive net present value undertaking. Suppose that the firm can develop the product for $C_D = 20$ million, so the net present value of the development project would be $8$ million.

Now suppose that the Economist's estimate is correct that using off-the-shelf components can yield a product 90% as good at 50% the cost of development, and suppose this means that $V_{i,0} = 90\% \times 100 \text{ million} = 90\% \times 100$ million = $90$
million and \( C_D = 50\% \times \$20\) million = \$10 million. Then

\[
\text{NPV}_{i,0} = C_{i,0} - C_D
\]

\[
= (90) e^{-(0.15)(1)} N(h) - (60) e^{-(0.03)(1)} N(h - (0.20)(1)) \times 10
\]

\[= \$9.7\text{ million}\]

If the \textit{Economist's} estimates of the trade-offs of development cost and product value are correct, the firm would increase the options value of its product development opportunity by \$8.0 million to \$9.7 million by following an off-the-shelf components strategy.

Finally, let us suppose that the use of off-the-shelf components also reduces total development time by half, so that \( t^* = 0.5 \) (but the present value of development costs using component design remain the same at \( C_D = \$10 \) million). Then

\[
\text{NPV}_{i,0} = C_{i,0} - C_D
\]

\[
= (90) e^{-(0.15)(0.5)} N(h) - (60) e^{-(0.03)(0.5)} N(h - (0.20)(0.5)) \times 10
\]

\[= \$14.4\text{ million}\]

In this case, the increase in project value from faster product development through use of off-the-shelf components is \$14.4 - \$8.0 million = \$6.4 million.

Thus, in an environment of high competitive value erosion, components strategies which can reduce the costs of development and the required time for product development may provide an implementation option which can increase substantially the value which can be extracted from a firm's new product development opportunity.

\textbf{6.4 Contribution to Strategic Flexibility}

The foregoing example quantifies the contribution which a components strategy might make to the strategic flexibility of the firm. Investing in developing a new product will give the firm the strategic flexibility of having an option to produce the new product one year later. Equation 6-1 shows that the strategic flexibility of having that product initiative option would be worth more than its cost of development. Thus, developing the new product could help to optimize the strategic flexibility of the firm.

If the firm has design and engineering skills which let it use \textit{off-the-shelf}
or pre-existing components, the firm may be able to derive even more net benefit from the products it develops. In addition, having this kind of skill enables the firm to create more positive value product initiative options from its product development opportunities, because more product development opportunities will prove to have a positive net present value. Thus, having skills in using components can increase the strategic flexibility of the firm by increasing the number of product initiative options it can proceed to develop. A similar result follows when the firm's skills in using components let it decrease the time required for product development in a competitive market.
Figure 6-1: Ratio of Newly Designed Parts in New Car Models
by U.S., European, and Japanese Auto Makers

(Source: Clark and Fujimoto 1991, Figure 6.8, page 151)
Figure 6-2: Commonality of Components in McDonnell-Douglas MD-80 and MD-90 Commercial Aircraft Models

(Source: Air Transport World, January 1990)
By designing different models with common features, Airbus cuts down on production costs.

Figure 6-3: Commonality of Components in Airbus A330 and A340-200 Models

(Source: A. March, 1990)
Figure 6-4: Parts Commonality Among General Electric Dishwashers
Figure 6-5: Number of Car Models in Production and Average Age of Current Models for U.S., European, and Japanese Auto Makers, 1982 to 1990

Source: Womack, Jones, and Roos 1991, Figure 5.2, page 120)
7. Product Strategy: Designing Products as Platforms for Change

This chapter investigates the strategy of intentionally designing products to facilitate evolution of future derived from changes to the basic product design. Within the framework of product initiative options, this approach to product design can be characterized as an effort to create a design which has \textit{designed-in compound options} on modified versions of the basic product, which the firm can exercise in the future. Two strategic uses of this design regime are discussed. The first strategic use is to design-in options on low-cost product changes which can extend the competitive lifetime (or product life cycle) of a new product. The Porsche 911 design is discussed as a notable example of this strategy of designing-in options for change. The second strategic use of the platform-for-change design approach is to design-in options which support rapid product evolution by facilitating the introduction of successive, upgraded product models. The Sony Handycam is presented as an example of a design strategy focused on achieving rapid product evolution. The chapter concludes by suggesting how rapid product evolution in its ultimate expression, can dynamically pre-empt competition in a given product market, thereby converting a context of competitive value erosion by imitation to a context of competitive immunity.

7.1 Options Perspective on Designing a Product as a Platform for Change

The designer of a new product which will be sold in a market characterized by uncertain changes in technologies and market preferences has to make a fundamental decision at the beginning of the design process whether to design a "one-off" or single-model product, or to design a product which will be easy (\textit{i.e.}, cheap and/or fast) to modify in the future in response to changes in available technologies or market preferences. A decision to pursue the latter approach leads to a design regime which has come to be known as designing a product as a \textit{platform for change}. Designing a product as a platform for change may take more time and have a higher initial development cost than developing a one-off design, but it brings a benefit to the firm by making it relatively less costly and time-consuming to introduce
later models of the new product, compared to developing completely new one-off designs in the future.

Within the real options framework developed in Part II, designing a product as a platform for change can be characterized as creating a product initiative option with compound options on later versions of the original product, as suggested by Figure 7-1. Later versions of the product will be compound options because their availability is usually contingent on the firm's exercise of prior options -- i.e. later versions will not be produced unless earlier models are produced.

The firm may have to incur a higher initial cost of development $C_D$ over a longer development period $T_D$ to develop a platform design, but the firm can gain not only $C_{i,0}$, the options value of the first product introduced, but also $\sum C C_{i,0}^j, j = 1...N$, the value of all the compound options on later versions of the product which are embedded in the original platform design. Each of these compound options can be exercised later at a reduced cost of development. To the extend that learning curve economies carry over from one version of the product to a later version, reduced costs of manufacturing may also be realized from a platform design.

The decision to design a one-off product versus a platform for change can be described as a choice between $\text{NPV}_{i,0} = C_{i,0} - C_D$, which gives the options value of a one-off design, and

$$[\text{NPV}_{i,0}]_{\text{platform}} = C_{i,0} + \sum C C_{i,0}^j - C_{PD} \quad j = 1.....N \quad \text{Equation 7-1}$$

which gives the net present options value of the platform design approach to implementing the product initiative option at a platform development cost of $C_{PD}$. If $\text{NPV}_{i,0} > [\text{NPV}_{i,0}]_{\text{platform}}$, the value of the strategic flexibility the platform design would bring to the firm would not be worth it's cost of development. If $[\text{NPV}_{i,0}]_{\text{platform}} > \text{NPV}_{i,0}$, however, then the strategic flexibility the firm obtains by investing in creating a platform design is worth more than the extra cost of the platform design, and the firm will optimize its strategic flexibility by designing its new product as a platform for change. The following two sections describe product markets in which the strategic
flexibility conferred by platform design appears to have been highly advantageous and possibly value-maximizing implementation option.

7.2 Design to Extend the Product Life Cycle: Porsche 911

One strategic use of the platform-for-change design regime is to create a product platform which has designed-in a low-cost adaptability to market changes, so that the product can be modified at relatively low cost to meet a range of possible changes in available technologies or market preferences in the future. The platform design's ready adaptability to change enables a platform design to have a longer life as a competitive product in its markets. Especially for a firm that is constrained in development resources, skillful platform design may give the firm a succession of options on modified versions of the original product that will allow it to keep up with changes in its markets.

As a notably successful example of a long-lived platform design, the design of the Porsche 911 automobile in 1962 to 1964 was explicitly conceived as a platform design intended to accomodate a succession of expected product changes leading to incrementally improved models. As a result of Porsche's constrained resources for development at that time, the original goal of the product designers was to develop a design which could accomodate expected changes over a 10-year product life cycle, plus be robust enough to accomodate as much unanticipated change as possible. As a result of the unusual level of adaptability designed-in to the 911, the 911 platform design served as the basis for a succession of 911 models from 1964 well beyond the designers' goal of 1974 until its retirement in 1990 -- a product lifetime of 26 years in a product market subject to very high rates of technological obsolescence. The succession of new 911 models introduced in the USA from 1964 to 1990 is shown in Figure 7-2. The product changes which supported those new models and were accomodated within the original 911 platform design are shown in Figures 7-3.

In the 24-year evolution of the 911 portrayed in Figure 7-3, the original design was largely unchanged from 1964 to 1968, but major adaptations of the design occurred in 1969, 1974, and 1978. These adaptations included increasing the wheelbase and tread dimensions, changing the body
dimensions to accommodate the increases in wheelbase and tread dimensions, and especially incorporating larger, more powerful engines. Each of these adaptations was a response to significant changes in market preferences or regulatory requirements. The changes incorporated in the 1969-1973 model were primarily intended to make the ride of the 911 smoother and thereby to serve the tastes of U.S. buyers of sports cars, whose tastes were shifting away from the stiff ride epitomized by British sports cars of the 1950s and 1960s and towards a more comfortable ride better suited to daily use of the automobile. The 1974-1977 Porsche model further catered to the market's continuing preference for a comfortable ride, but also included the fitting of larger displacement engines designed both to serve the market's growing preference for more horsepower and to meet U.S. government mandated exhaust emissions regulations. The post-1978 model incorporated further changes in suspension and engine size designed to serve the continued strengthening of the market's preference for increased comfort combined with even higher horsepower. Before and after each of these major adaptations, a number of minor product variations were also offered to extend the 911's penetration into the market for sports cars.

(References for this discussion are Boschen and Barth 1977, Langworth 1983, Porsche Audi Division 1982, Schutz and Cook 1986, and Road & Track 1988.)

7.3 Design for Rapid Product Evolution: SONY HandyCam Video Camera

When a firm has an original product idea that can be imitated by competitors once the product is introduced to market -- i.e. when the firm's product faces a competitive context of value erosion by imitation, as described in Chapter 2 -- one strategy the firm may pursue in an effort to capture as much benefit as possible from its original product idea is to introduce a succession of improved version product models soon after imitators' copy-cat products appear in the market. This product strategy is suggested in Figures 7-4 and 7-5. If the firm can develop successive product versions which offer significant improvements over their predecessors, it may be able to introduce improved versions at some time after imitators have brought their products to market and prices for current versions have begun to fall, as shown in
Figure 7-4. (In this case, the firm must be careful to try to select the time for introducing a successor product that maximizes the value of the sum of all the firm's compound initiative options.)

If the firm has the capability to develop improved versions of its product quickly, before imitators can introduce their copy-cat products, the firm may be able to engage in a form of dynamic market preemption illustrated in Figure 7-5. In this strategy, after the firm introduces its original new product, the firm quickly develops an improved product version #1, before imitators can introduce their copy-cat products at t'. As soon as the first imitator's copy-cat product appears in the marketplace, the firm promptly introduces improved product version #1, which eliminates or substantially reduces demand for the now inferior original product version and thereby denies an imitator firm the chance to profitably sell their copy-cat versions of the original product. If the originator firm can repeat this scenario with an improved version #2 and so on, the originator firm may be able to deny imitators the chance to profit from their imitating, and profitable imitation may be effectively foreclosed in that product market. Thus, a strategy of rapid product evolution launched from a platform design may be able to dynamically preempt competition in a new product market. If the firm succeeds in foreclosing imitation in this way, it may effectively be able to restore its products to competitive immunity and capture the full potential value of its product initiative options.

Designing a product as a platform for rapid product evolution involves designing in compound options to quickly develop and introduce future improved models based on the original product design. SONY Corporation is a firm which has a history of being first to market with original products like mini-TVs, compact disc players, and the 8mm cassette "HandyCam" video camera. To capture as much value as possible from its original product ideas before imitators introduce their me-too products, SONY has developed a high level of skill in designing introductory products as platforms which can quickly be upgraded to incorporate a range of planned improvements and features. In effect, SONY has learned how to create platforms designs with design-in options for rapid technological evolution.
The remainder of this section discusses the development of the SONY HandyCam Video Camera and documents how SONY conceived the product design as a platform for rapid technological evolution and designed into the platform design a number of options on planned improved versions which it quickly exercised after introducing the original M-8 HandyCam platform design.

Sony's development of the HandyCam was undertaken in 1985 to 1988 with the goals of (1) being first to market with a compact, lightweight video camera based on the use of a small 8mm video cassette instead of the standard VHS-format video cassette, and (2) offering a succession of technologically upgraded models based on the same platform design. Although Kodak beat Sony to the market by introducing its compact video camera a few weeks before Sony introduced the HandyCam, the original HandyCam platform design and its subsequent upgraded models have been notable commercial successes.

**Figure 7-6** shows pattern of rapid product evolution based on the M-8 platform design from 1985 to 1988. **figure 7-7** shows the rapid technological evolution of the HandyCam in the 26 months from its introduction in December 1985 through January 1988. The original HandyCam model, the M-8, incorporated the platform design which defined the basic arrangement of the camera's components and specified the interfaces between its major functional subsystems. At the time of the M-8's development, Sony's design and manufacturing staff projected a reduction in the cost of manufacture of the M-8's circuit boards (the greatest single component of cost in the M-8 design) as a result of learning curve effects. Consequently, concurrent with the introduction of the M-8, the Sony marketing department planned the release of a lower priced M-10 model to occur as soon as Sony engineers could simplify the M-8 circuit board design, improve its manufacturability, and achieve lower manufacturing costs per board. The M-10 was actually released in July 1986, eight months after the M-8's introduction. The M-10 incorporated the redesigned circuit board and a slightly different exterior case to distinguish it in appearance from the M-8. The actual functionality of the M-10, however, was identical to that of the M-8.

Also immediately after the release of the original M-8 platform design,
however, Sony’s design engineers began work on the first intended technological upgrade of the platform, which was scheduled to follow the introduction of the M-10 if the M-8 was successful in the market. While the purpose of the M-10 was to offer a less expensive model to help Sony penetrate the video camera market, the first technologically upgraded product, named the V-30, was intended to maintain Sony’s technological and market leadership by offering significantly improved performance over the basic M-8 or M-10 models. Accordingly, the V-30 was planned to incorporate an electronic viewfinder, an autofocus zoom lens, and a videotape playback feature, all supported by a new circuit board component and packaged in a sleek new exterior case. However, the basic arrangement of the M-8 design, the definition of interfaces between its components, and a number of actual components in the original M-8 design were carried through to the V-30 model.

The next HandyCam model, the V-50, was introduced in October 1987, six months after the V-30, and continued Sony’s strategy to continually upgrade the HandyCam product line by adding new models with enhanced performance. Sony’s marketing staff identified three product features which they felt would add significantly to the consumer’s perception of the performance of the V-30 HandyCam, and the Sony design staff accordingly incorporated into the V-50 an extended range zoom lens, a modification to the circuit board to allow a "picture insert" feature, and a more powerful battery pack.

The next model of the HandyCam, the V-90, was positioned by Sony as a "semi-pro" model at the top end of the price and performance range for video cameras targeted at the consumer market. The V-90 incorporated major technological improvements in virtually all key components affecting the performance of the camera as perceived by the consumer. Particularly important was the improvement in the quality of the video image recorded by the V-90. A higher resolution charge coupled device (CCD) -- the component responsible for the sharpness of the video image -- had been under development by Sony since the introduction of the original M-8 model. The design work for the V-90 was undertaken immediately after the launch of the V-30 model in anticipation of the successful development of the new 380,000
pixel CCD, and the manufacture of the V-90 began as soon as Sony could begin producing the new CCD. The V-90 model was officially announced in January 1988. In spite of its greatly improved performance and distinctive exterior case, however, the V-90 was a continuation the general design arrangement and interface specifications established by the M-8 platform and shares some important components in common with prior models.

(I am indebted to Mr. Takuya Kumagai, design engineer for Sony on the HandyCam project, for invaluable information on the development of the HandyCam. Mr. Kumagai was a Master's degree student at MIT Sloan School 1987-1989. Additional references for this discussion are Sony DigiC 1987 and Sony product brochures on the V-30, V-50, and V-90 HandyCam models.)
Figure 7-1: Compound Option Product Models Derived from Original Platform Design

Figure 7-2: Evolution of Porsche 911 Models from Platform Design
**Figure 7-3: Product Changes to Porsche 911 Platform**
Figure 7-4: Introduction of Improved Versions of Product After Imitators Introduce Their Copy-Cat Products

Figure 7-5: Rapid Introduction of Improved Product Versions May Pre-empt Market by Denying Profits to Imitators
Figure 7-6: Evolution of Sony HandyCam Models from M-8 Platform Design
### Figure 7-7: Evolution of the Sony HandyCam Video Camera from M-8 Platform

<table>
<thead>
<tr>
<th>Model</th>
<th>Date Introduced</th>
<th>Optical Image Gathering</th>
<th>Conversion of Optical Image to Electronic Signals</th>
<th>Recording of Signals</th>
<th>Sound Gathering</th>
<th>Power Supply/Conversion</th>
<th>Exterior Case* and Controls**</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-8</td>
<td>12/85</td>
<td>Optical View Finder</td>
<td>2/3 inch CCD 250,000 pixels</td>
<td>M-series Circuit Boards</td>
<td>Omnidirectional Electret Condenser Type</td>
<td>NP-22</td>
<td>M-series Configuration with Variants for Japan, USA, and Europe</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15mm Fixed Lens</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slight Modification to M-8 Case and Controls (No Variants for Europe)</td>
</tr>
<tr>
<td>M-10</td>
<td>7/86</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**V-30** 4/87
- 0.7 inch Black and White CRT
- 12-30mm Autofocus Zoom Lens
- New V-series Circuit Boards
- Playback Feature Added
- V-30 Circuit Boards
- Changed to Allow Picture Invert

**V-50** 10/87
- 12-72mm Autofocus Zoom Lens
- New V-90 Circuit Boards
- 8mm triple-head recorder

**V-90** 1/88
- 12-72mm Autofocus Zoom Lens (Smaller than V-50 Lens)
- 2/3 inch CCD 380,000 pixels
- New V-90 Circuit Boards
- Tape Cassette

* Outsourced components
** Optical lenses only outsourced
1. European variants required modified circuitry in all models.

* Iteration Initiated by
** TECHNICAL DEPARTMENT
* ** Iteration Initiated by
** MARKETING DEPARTMENT

* New Component Design
* Modification to Existing Component Design
8. Product Strategy: Leveraging Product Variety from System Designs

This chapter explains the product strategy of creating a system design from which a number of varied but related products can readily be derived or "leveraged." This product strategy undertakes to create a system design for a product which can accommodate a range of possible product models. Within the real options framework of this thesis, creation of a successful system design is characterized as giving the firm a number of simple or compound options on each of the product models that can be accommodated within the system design. Two examples of strategic uses of system designs to leverage a variety of product models are discussed. First, Boeing's use of product leveraging is discussed and shown to create options on a family of related aircraft models which fill the major niches in important market segments. To illustrate the potential economic benefit of leveraging multiple products from a system design, the development of the Lockheed 1011 Tristar is reconsidered with the addition of two leveraged models, the 1011-ER extended range model and a 1011-SH a short haul model derived from the basic 1011 Tristar system design. Second, Sony's strategic use of system designs to proliferate Walkman model options to saturate product space is discussed.

8.1 Options Interpretation of Leveraging Products from System Designs

Just as an individual component can be designed to be readily incorporated into a number of different assembled products, it may also be possible to create an overall product design that can accommodate a number of intended product variations. A design that can serve as the basis for leveraging a potentially large number of product versions is called a system design. The basic concerns in creating a system design are (1) to define and design the functionality of a product as a system of interrelated functional subsystems and components and (2) to define the interrelationships between functional subsystems and between components within subsystems so that one version of a subsystem or component can be replaced by a subsequent version without requiring reworking of the overall product design.
When a new product has been conceived as a system design, the functional parts of the design become modular and can be changed easily. When the functional parts of a product design can be changed without reworking the overall product design, the marginal cost of developing another variation on a new product can become very low. In the lowest cost case, a new product version may be developed at negligible cost by simply specifying a new combination of existing components that can be accommodated within the system design. In this way, creating a system design is, in effect, a process of designing-in a potentially large number of options on product versions which can be obtained at low costs of development. If economies of learning carry over from one leveraged design to another, production costs which constitute the exercise price for the product version will also be reduced. In particular for the development-constrained firm, a strategy of leveraging product variety from system designs may offer significant potential for creating multiple product initiative options with limited product development resources.

The product options which a firm can create by leveraging product models from a system design can be either simple or compound options. If a firm makes a commitment at $t = 0$ to develop a number of leveraged product models, each leveraged model represents an independent development project and can be evaluated as a simple product initiative option. Figure 8-1(a) shows the contingency structure for an unconstrained firm creating product model options through a system design, while Figure 8-1(b) shows the contingency structure that a firm constrained to develop a single product at a time would have in leveraging product models. In both cases, the firm would be creating simple product initiative options if it commits to development of all product models at $t = 0$.

If the firm commits only to the creation of the system design but not necessarily to full development of any individual product model, the firm would be creating compound-option product models, because full development of each product model would be contingent on passing the hurdle of a second evaluation after completion of the system design. In this case, which is probably more common than a commitment at $t = 0$ to full development of all models, the contingency structure for the unconstrained
firm is given in Figure 8-2(a) and for the firm constrained to develop a single product at a time in Figure 8-2(b).

(Note that all the figures assume the earliest possible exercise of simple or compound product options -- an assumption which would be reasonable for a product market with a high rate of competitive value erosion.)

8.2 Leveraging a Family of Related Products: Boeing Airframe Development

In recent years the costs of developing some engineering-intensive products has reached unprecedented levels. The cost of developing a new commercial airframe, for example, is now $2 to $4 billion, requiring sales of at least 500 aircraft to recover development costs (A. March, 1989). Given such high costs of development, large airframe manufacturers have adopted a product strategy of using leveraged products to gain the broadest possible market coverage within a targeted market segment in an effort to hedge huge development costs over the widest possible base. (Alternatively, from an ex post perspective, once the major development costs are sunk, the marginal benefit of developing a new niche product within the market segment is likely to be high relative to its marginal development cost, so developing new products for every feasible market niche is likely to be a source of highly positive net present value projects.)

In developing a new airframe, the largest part of the engineering cost is in the design of the wings, empennage (tail), and nose of the aircraft, which together with the control systems and landing gear comprise the system design of the aircraft. Once the airframe system design is developed, creating model variety based on passenger capacity and cruising range is largely a matter of adding or removing fuselage sections and fitting engines in the required thrust range. Figure 8-3 shows how Boeing has leveraged families of several related airframe models from system designs for basic product types like the 737, 747, and 767.

As long as engines of appropriate thrust are available for each new size of aircraft desired, leveraging a new aircraft model from an existing airframe system design is relatively low in cost. Boeing, McDonnell-Douglas, and Airbus all now use a new airframe design as a platform for developing a
whole family of aircraft clustered in the range of sizes the airframe system
design was intended to accommodate. Boeing's next major airframe, the 777,
also continues this design regime, with a moderate range 777-A model
planned for release in 1995, a long range model 777-B in 1997, and an
extended range model 777-C in 1999.

From an options perspective, if initial development costs for a system
design are high, the best way to increase the net present value of the firm's
set of leverageable product opportunities is to make sure the system design
can accommodate a large number of leveraged products, each of which will
add to the number of product options the firm will have when the airframe
development is completed. Airframe developers seem to have recognized this
and now routinely develop airframes explicitly designed to accommodate a
range of aircraft sizes.

From the options perspective, creating a system design gives the firm a
number of embedded options on product models which can be leveraged from
the system design. If the sum of the value of all the embedded options is
greater than the total cost of the system design plus the further development
of each leveraged model, pursuing a leveraged design strategy could be
value-maximizing, and a firm's skill in leveraging product models from
system designs could become an important means of adding positive-value
strategic flexibility to the firm. The next section illustrates how significant
this contribution might be by re-evaluating the Lockheed 1011 Tristar
development project with two additional leveraged models.

8.3 What Leveraging Might Have Done for the Lockheed 1011 Tristar

Chapter 2 analyzed the Lockheed 1011 Tristar development project based
on the assumption that only one model of the 1011 would be produced. In
actuality, at the time of the project evaluation in April 1968, there is evidence
that Lockheed also had plans to develop a stretched, extended-range 1011-ER
version of the Tristar, which it estimated it could develop for an additional
$70 million (Rheinhart 1973, Appendix B). In addition, it is conceivable that
Lockheed could also have leveraged a third, "short-haul" version of the 1011
from the Tristar system design in much the same manner that McDonnell-Douglas leveraged their three DC-10 versions (DC-10-10, DC-10-20, and DC-10-30) from the DC-10 system design.

To illustrate the impact on the total 1011 Tristar development project that leveraging 3 product models from the Tristar system design might have had, the options valuation of the project is revised here to account for the possible leveraging of two additional 1011 models. For simplicity, the two new model options -- the 1011-ER and the 1011-SH -- are treated as simple options whose final development Lockheed could commit to at any time after $t = 0$ (April 1968). Assuming that Lockheed committed to full development of the basic 1011 model, each of the two new model option is assumed to add $70$ million in additional development costs. Each leveraged model is assumed to have a unit sales price of $15$ million. In this new example, one unit of each of the two leveraged models is assumed to be put into production one year after introduction of the basic 1011 Tristar model, so that monthly production rises from $N = 4$ to $N = 6$ units per month, beginning at $t = 42 + 13 = 55$ and continuing until month $t = 162$. Also, the new project value is evaluated for both one and two new leveraged products and at two rates of competitive value erosion, $\delta = 0.03$ and $\delta = 0.06$. (Appendix A-7 gives the Theorist program used to analyze this new project value.)

Figure 8-4 shows how the options value of the 1011 Tristar product development opportunity increases over a range of project value uncertainties ($\sigma = 0.10$ to $0.50$). Comparison of Figure 8-4 with Figure 2-9 for the original single-model project value shows that product leveraging could have substantially increased the value of Lockheed's 1011 Tristar product development opportunity and would have made the project a positive net-present-value undertaking under a much wider range of uncertainty about future outcomes.

8.4 Saturating Product Space by Proliferating Product Models: the Sony Walkman

When competing products constitute packages or bundles of attributes
that are perceived as different by the market, it is often possible to rank these
products by their principal attributes and to array the products in a "product
space" that is dimensioned by the important attributes of the products.

Hotelling (1929) first introduced this notion of spatial competition. In
Hotelling's model, the need to achieve a minimum level of revenue in a retail
store would act to limit the number of competing stores which could occupy a
given stretch of commercial street frontage. This concept was extended by
Lancaster (1966) to suggest that products form a product space of graduated
product characteristics. Because each product needs to attract a minimum
level of purchases, the product space can accommodate only a limited number
of products.

A basic insight from the spatial models of competition is that, under
certain conditions (usually including high entry costs -- like product
development costs -- or high exit costs), the first products to fully occupy a
product space will act as disincentives against new entrants who might want
to enter the market. In particular, if a firm can saturate a product space
with various models of its product, it may be able to foreclose competition and
collect monopoly rents in segments of the market it controls, because
potential competitors will find it too costly to enter the saturated product
space relative to the revenues they could hope to obtain. In addition, another
disincentive to new entrants is added when an incumbent firm has lower
costs of developing and producing a new product. If a firm has low total
product costs, it can afford to occupy (or credibly threaten to occupy) a
smaller section of product space than that which the potential entrant would
need in order to cover its higher development or production costs. Thus, an
incumbent with lower development costs could credibly foreclose product
space by threatening to deny any new entrant adequate product space to cover
costs.

When a firm can leverage products and its competitors cannot, or when a
firm is better at leveraging products than its competitors, it can fill more
product space at lower cost than its competitors. As the spatial models
suggest, the firm that is skillful in leveraging product models from a system
design may be able to use product leveraging to enhance the value of its
product initiative options, because it may be able to foreclose competition in
certain segments of market space and collect monopoly profits for its products in those segments.

A study of the development of the Sony Walkman by Sanderson and Uzumeri (1990) provides evidence which suggests that Sony has used product leveraging very effectively to pre-empt product space and to establish early domination of the market for Walkman-like products. Following introduction of its first Walkman model in mid-1980, Sony quickly proliferated a large number of product variations. Figure 8-5 is taken from the Sanderson and Uzumeri (1990) study and shows the pattern of product introduction in the U.S. market of Sony Walkman models in various price positions from mid-1980 to early 1990. By 1990 a cumulative total of more than 130 Sony Walkman models had been introduced into the U.S. market, and in early 1990 more than 20 Sony Walkman models spanning a range of price levels were available in the U.S.

Sanderson and Uzumeri show that these 130+ Sony Walkman models were developed from one initial and four subsequent system designs, each of which was leveraged to create a large number of models that consisted of "rearrangements of existing, well understood components" (Sanderson and Uzumeri 1990, p. 7). In most cases, the circuitry linking the components together required only minor modification to accommodate the entire range of product model variations. Figure 8-5, also from Sanderson and Uzumeri (1990), tracks the introduction of the five system designs and the coverage of price positions of the product models leveraged from each system design.

By skillful proliferation of products from a few system designs, between 1980 and 1990 Sony was able to introduce nearly as many Walkman models as its four competitors (Aiwa, Panasonic, Toshiba, and Sanyo) combined. Figure 8-6 shows the cumulative total of Sony Walkman model introductions in the U.S. compared to the cumulative totals for Aiwa, Panasonic, Toshiba, and Sanyo. In this context, it is interesting to note that Aiwa, the second best proliferator of Walkman-like product models, is a Sony subsidiary and often fills the strategic role of providing less expensive versions of products originally developed by Sony.

It is certainly seems possible that, as a result of saturating much of the Walkman product space, Sony has realized at least some monopoly rents
from its Walkman products, especially at the high-priced end of the product space where Sony models have well established positions and virtually no competitors. Moreover, Sony has been much more proficient than any of its competitors at leveraging a large number of distinctive new products from an existing system design, so there is reason to believe that Sony has also enjoyed lower marginal unit costs of development than its competitors. To the extent that Sony's lower marginal costs of development exist and are understood by Sony's competitors, Sony may also be capable of foreclosing product space without actually introducing enough products to saturate a product space, because Sony may be able to exert a credible threat that it can "squeeze" other maker's new products into unprofitability by (profitably) positioning new products near to any new models competitors might introduce into Sony's controlled product space. In sum, Sony appears to be pursuing a product strategy that makes skillful and extensive use of product leveraging to foreclose product space and thereby to enhance the value of its leveraged product options by endowing them with some degree of monopoly power in their product space.

If a firm can succeed in dominating a product market or market segment by intense proliferation of leveraged product models, as Sony appears to have done with the Walkman, then skillful leveraging of products may be able to add significant monopoly rents to the value of the firm's product development opportunities. In such cases, intense leveraging of products could not only generate more product options at lower costs of development and manufacture, but could also make the firm's leveraged product options more valuable than they would be in a more competitive market. Thus, a product strategy which can successfully use intensified product leveraging to dominate product markets may be able to increase both the number of positive net-present-value product development opportunities available to the firm and the value of the product initiative options the firm eventually develops.
Figure 8-1(a): Leveraging Product Initiative Options from a System Design (Unconstrained Firm)

Figure 8-1(b): Leveraging Product Initiative Options from a System Design (Firm Constrained to Develop a Single Product at a Time)
Figure 8-2(a): Leveraging Compound Product Initiative Options from a System Design (Unconstrained Firm)

Figure 8-2(b): Leveraging Compound Product Initiative Options from a System Design (Firm Constrained to Develop a Single Product at a Time)
Figure 8-3: Boeing Families of Airframes Based on Common Wing Design and Shared Components
Figure 8-4: Options Value of Developing Lockheed 1011 Tristar with One or Two Leveraged Models

Variable Values: Risk-free interest rate \( r = 0.03 \) year. Lockheed's monthly discount rate \( k' = 0.0094888 \). Initial unit production cost \( Y = $100 \) million. Expected sales price per plane \( = $15 \) million. Development period \( = A = 42 \) months. Production period \( = T = 120 \) months.
Figure 8-5: Sony Walkman Models Available in the U.S. Market, by Price (1980-1990)

(Source: Sanderson and Uzumeri 1990)
Figure 8-6: Cumulative Totals of Sony Walkman Models and Walkman Clones Introduced in the U.S. Market (1980-1990)

(Source: Sanderson and Uzumeri 1990)
Part IV

Product-Based Strategy
9. The Strategic Flexibility Framework and Product-Based Strategy

This chapter undertakes to close a conceptual loop connecting the optimal strategic flexibility framework of Chapter 1, the options analysis of product opportunities in Chapters 2 to 5, and the options-driven product strategies of Chapters 6 to 8. The goal is to show that the strategic flexibility framework, supported by options analysis of the sources of a firm's strategic flexibility, can provide a useful theoretical foundation on which to base the formulation of firm strategy.

9.1 Optimal Strategic Flexibility and the Value of the Firm

The preceding chapters of this thesis have provided a framework for valuing the initiative, timing, and implementation options which are the sources of strategic flexibility available to the firm whose products face technological and market uncertainty. For a given product development opportunity, the firm achieves optimal strategic flexibility when the firm acquires the package of initiative, timing, and implementation options that maximizes the net present value of the firm's product development opportunity. Because the firm's overall development and production opportunities may be interrelated and interdependent, to maximize the total value of the firm, the options analysis of preceding chapters has also tried to make clear that the firm must choose the packages of real options that jointly maximize the total value of all production and development opportunities available to the firm. (Examples of interdependent product options are products that can be leveraged from a common system design or manufactured on a shared production line.) When the firm does choose its new product development opportunities and production options so that the total value of the firm is maximized, the firm will achieve the strategic flexibility that is optimal for the technological and market uncertainties the firm faces.

From the strategy perspective, a firm may in essence be viewed as an entity that creates and provides products, where the term product denotes
both physical products and services and includes all the technical,
perceptual, and service attributes of products. Thus, a strategically useful
centralization of the value of the firm is one focused on the value of the
firm's product development and production opportunities. The real options
framework presented in Chapters 2 through 5 provides the means to
correctly value the firm's product development and production opportunities
under technological and market uncertainty, and thus to determine the
economic value of the strategic flexibility each product opportunity can bring
to the firm.

Within this value framework, each product which the firm can now
produce can be valued as a product initiative option, plus any attached timing
and implementation options. Of a firm's available approaches to
implementing a given product initiative option, one implementation option
will maximize the value of the initiative option. Let $C_{i,m^*,t}$ denote the present
value of the value-maximizing ($m$th) implementation of the initiative option
to produce product $P_j$. Similarly, let $PDO_{j,n^*,t}$ denote the present value of the
opportunity to develop a new product $P_j$ using the value-maximizing $n$th
implementation for developing and producing the product. Since the objective
of the firm's strategy is to maximize the total value of the firm, the
options-equivalent statement of the objective of firm strategy is select the $m$th
and $n$th implementatons so as to jointly maximize the value of both $C_{i,m^*,t}$
for all the firm's product initiative options and $PDO_{j,n^*,t}$ for all the firm's
product development opportunities.

When the firm can correctly determine the options value of its
product opportunities and select the combination that maximizes the value of
the firm, it will have implicitly also determined the bundle of initiative,
timing, and implementation options that define the optimal strategic
flexibility for the firm. Thus, under uncertainty, a key component of the
economic value of the firm is the economic value of the strategic flexibility
which the firm possesses.

The optimal strategic flexibility achievable by the firm at any point in
time can be expressed as
$$SF^* = \sum PDO_{j,n^*,t} + \sum C_{i,m^*,t} \text{ for all } i \text{ and } j \quad \text{Equation 9-1}$$

In Equation 9-1, $SF^*$ can be achieved by selecting the package of initiative, timing, and implementation options that define the value-maximizing implementations of the product development opportunities available to the firm.

The optimal strategic flexibility $SF^*$ of Equation 9-1 is a primary source of the value of the firm, but it is not the only source of firm value or the only component of firm value demanding strategic management. Another component of firm value not included in Equation 9-1 is the strategic core of the firm, by which is meant the core competencies and strategic capabilities and resources the firm can apply to developing and producing products not yet conceived of by the firm. These strategic capabilities and resources can be used to identify and exploit future development and production projects, but their value is not specifically included in projects included in $SF^*$. The strategic core of a firm includes capabilities like research and development and market knowledge by which the firm generates new product ideas, as well as the product design, manufacturing, and marketing skills which the firm can bring to bear on future development and production opportunities.

In addition to the options that make up its strategic flexibility and the capabilities in its strategic core, a firm is likely to have at least some residual assets (buildings, patents, skills, etc.) which the firm currently possesses, but which are unlikely to find further use in exploiting existing or future product opportunities.

If we denote by SC the value of the firm's strategic core of product generating and producing resources and capabilities and by $R_A$ the market value of the residual assets of the firm, then a comprehensive statement of the maximum obtainable firm value at any point in time is given by

$$V^* = SF^* + RC_{OV} + R_A$$

$$= \sum PDO_{j,n^*,t} + \sum C_{i,m^*,t} + RC_{OV} + R_A \quad \text{Equation 9-2}$$

Since the ultimate source of the value of the firm is the ability of the firm to generate and provide products to markets, Equation 9-2 provides a product-focused statement of what the value of the firm can be if the firm is strategically well managed.
To the extent that the firm chooses its product options suboptimally, the current value of the firm will be less than $V^*$. The task of strategic management therefore is to maintain the actual value of the firm as close as possible to $V^*$. The firm's strategic managers can carry out this task in three basic ways. First, the firm's managers must correctly identify, evaluate, and select the product development opportunities and production options that optimize the strategic flexibility of the firm. In this effort, methods for valuing initiative, timing, and intensity options such as those presented in Chapters 3, 4, and 5 are essential strategic management tools.

Second, the firm's managers must attend to building the value of SC, the firm's strategic core of technological and organizational capabilities which are the sources of future product development opportunities and production options. In managing SC, the firm's managers must be guided by a clear personal understanding of how specific technological capabilities and organizational skills can contribute to the creation and enhancement of the firm's new product opportunities in the product markets in which the firm competes.

Third, the firm's strategic managers must be able to perceive and exploit synergistic linkages among the existing firm's capabilities and resources -- and also between the firm's existing capabilities and those it could acquire.

### 9.2 Managing the Strategic Flexibility Value Chain

The strategic flexibility framework proposes that in environments characterized by uncertainty about technologies and market preferences, strategic management adds value to the organization by identifying, acquiring, and strengthening the strategic capabilities and resources that optimize the strategic flexibility of the firm in its product markets. This value-adding activity of strategic management can be thought of as a process of managing the firm's strategic flexibility value chain.

The following discussion elaborates on the nature of the strategic flexibility value chain, using as an example four strategic capabilities that appear to be essential components of a strategic flexibility chain in many dynamic, competitive markets for manufactured goods. Each of these four strategic capabilities is shown to be derived from certain core competencies
which enable the firm to continually adapt its development and production activities to new opportunities created by changes in its environment. The ongoing development of these strategic capabilities and their underlying core competencies is asserted here to be a primary task of strategic managers, along with the recognition and exploitation of synergistic linkages among the firm's strategic capabilities and core competencies.

The basic premise of this thesis is that the proper objective of firm strategy is to maximize the value of the firm. Equation 9-2's statement of the maximum value of a firm identified the components of firm value as its optimized development and production opportunities, its strategic core of capabilities and resources which can be brought to bear on future product opportunities, and its residual assets which are no longer useful in exploiting the firm's present or future opportunities. These components of firm value form, in effect, a strategic flexibility value chain, illustrated in Figure 9-1, through which the firm can respond to new opportunities created by technological and market change and can transform those opportunities into new products and new cash flows.

The first link in the strategic flexibility value chain, SC, is the strategic core of the firm: the strategic capabilities and resources which enable the firm to identify and fully exploit new product development opportunities and product initiative options. The exercise of the firm's new product initiative options creates new cash flows, which can be reinvested in strengthening the capabilities and resources of the firm, as well as paid out to various stakeholders in the firm.

In the process of developing and producing products, the firm can learn how to improve its development and production techniques and can adopt new techniques from outside the firm. This learning process further adds to the strategic resources and capabilities the firm can bring to bear on development and production opportunities. At the same time, as an inevitable consequence of changes in technologies and market preferences, some of the resources and capabilities of the firm will become obsolete and highly unlikely ever again to be useful in exploiting present or future opportunities. These obsolete resources and capabilities become, in effect, residual assets of the firm which contribute nothing to the value-creating
activities of the firm. To the extent that maintaining these residual assets constitutes a drain on the firm's management resources, the firm should seek to convert these residual assets into cash which can be reinvested in strategically useful capabilities or assets.

To maximize the value of the firm, strategic managers must be able to correctly identify the strategic resources and capabilities the firm must have to acquire the value-maximizing number and kind of development opportunities and production options. The firm's strategic managers must also be able to lead the firm in acquiring the strategic capabilities it needs and in continuously strengthening the strategic capabilities it already possesses. Thus, under technological and market uncertainty, the firm's strategic managers can make their uniquely important contribution to increasing the value of the firm (1) by understanding which resources and capabilities contribute most critically to improving the strategic flexibility of the firm to identify and fully exploit new opportunities created by technological and market changes, and (2) by facilitating the ongoing acquisition and further development of those strategic capabilities by the firm.

To lend specificity to this general prescription for the task of strategic managers, the next section discusses four specific core competencies and strategic capabilities the firm must have in order to fully exploit new opportunities in dynamic, competitive markets for many manufactured goods.

9.3 Achieving Strategic Flexibility Through Core Competencies and Strategic Capabilities

In recent years, an active line of strategy research has sought to identify the key success factors which seem to be associated with firms that have achieved sustained competitive success in their markets. A related body of strategy research has begun to focus on specific resources and capabilities which appear to characterize firms which achieve sustained success in competitive product markets subject to frequent changes in technologies and market preferences. Most recently, within this body of research there is growing recognition that the resources and capabilities of these successful
firms spring, in turn, from certain core competencies which these firms appear to have developed (Prahalad and Hamel 1990). It is further suggested here that these core competencies in fact form the core of a successful firm's strategic flexibility to consistently and fully exploit new product opportunities.

This section examines four strategic capabilities which appear to be essential for competitive success in many manufactured goods markets, the ways in which they contribute to the real option value of the firm, and the core competencies from which they appear to spring. Most of these strategic capabilities seem to be fairly well recognized in recent strategy literature, but a fourth -- competitive product design -- is now just beginning to gain the recognition it deserves.

The four strategic capabilities and the core competencies which underlie each capability are summarized in Figure 9-2.

### 9.3.1 Fast-Cycle Product Development

When a firm has a fast-cycle development capability, it can respond to new product opportunities before its competitors. As discussed in Sections 9.2 and 9.3, an ability to respond to new product opportunities more quickly than competitors can give the firm a period of competitive immunity which may considerably enhance the value of the firm's production options. As a vice president of product development for AT&T recently observed, "We came to the realization that if you get to market sooner with new technology, you can charge a premium until the others follow" (*Fortune*, 2/13/89, page 57). Principal reasons cited by other firms for accelerating product development are "...increased domestic and global competitive pressures and rapid technological change" (Gupta and Wilemon 1990, page 28). In the extreme case considered in Section 9.4, the firm that can become consistently faster at product development than its competitors may be able to foreclose competition in a given product market by exploiting a growing share of new product opportunities, leaving fewer opportunities than less capable competitors will need to exploit in order to remain competitive in the long run.

The core competencies which underlie fast-cycle product development are an ability to organize and manage overlapping product development and
an ability to achieve quasi-integration with suppliers who can assume major responsibilities for component or materials development. The need to abandon sequential development practices and to compress development into overlapping development phases was emphasized by Takeuchi and Nonaka (1986) in their widely read article on "The New New Product Development Game." Subsequently, the effectiveness of overlapping problem-solving in shortening the development cycles of Japanese auto makers was documented by Clark and Fujimoto (1988). Most recently, firms seeking to compress the development cycle even further are developing techniques for simultaneous engineering utilizing computer-assisted design (CAD) programs. To realize the benefit of fast development, however, the rapid generation of new products must be accompanied by a production system that can quickly accommodate new products. As an example of this capability, Bower and Hout (1988) attribute Seiko's dominant position in the global watch market in part to the ability of Seiko's automated production line to be re-programmed to produce a number of new product models every day.

The second needed core competency -- the ability to achieve quasi-integration with suppliers -- requires that the firm have skills in establishing and maintaining an incentive structure for its suppliers which at the same motivates the suppliers to lower costs and provides adequate funds for continued supplier investments in developing the technologies on which their components are based. Moreover, when firms co-venture in an effort to exploit complementarities in their technologies or market access, an ability to devise durable incentive schemes and efficient shared management structures becomes even more critical to achieving fast-cycle development capability (Astley and Brahm 1989). Achieving quasi-integration also requires an ability to create a free flow of information between the firm and its suppliers or partners. To facilitate the exchange of information, Japanese firms typically place some of their best staff in supplier firms until the design parameters for a new component are well specified (The Economist, 1/12/91, page 61). Many American firms, on the other hand, are still trying to overcome decades of arm's-length relationships with suppliers which have blocked the flow of information and degraded both the speed and the quality of the product development process.
9.3.2 Ability to Define Appropriate New Products

Fundamental to the creation of positive-value product opportunities is the ability of the firm to identify the kinds of products, the packages of product features, and the product performance levels its market will value most. In particular, an ability to define correctly the kinds of products which different target groups within a product market will want most -- and pay a premium price for -- is a key to increasing the value of each new product option the firm develops.

The core competencies which appear to underlie this capability are an acute awareness of changing market preferences, an ability to translate identified market preferences into appropriate product design and engineering parameters, and skills in phasing development so that the firm's development effort can be continually tuned to market preferences.

In highly dynamic product markets, many firms that have been successful in identifying changes in market preferences and translating those new preferences into new product ideas appear to have created alternatives to traditional marketing methods for discovering consumers preferences. Sony, for example, has preferred to hire engineers who are themselves what Erik von Hippel has termed lead users of electronics products who generate new ideas for the next generation of products. In addition, Sony sends its engineers around the world to observe consumers for the sole purpose of trying to imagine what kinds of products its target consumers would want next. In bypassing the traditional separation between marketing and product design, Sony has had notable success in defining entirely new kinds of products (e.g., miniature televisions and portable Walkman stereos) to serve new market preferences.

Other firms have sought to wire consumer preferences directly into the product design process by perfecting less novel but nonetheless effective approaches. The House of Quality is one method for identifying consumer tastes and translating them into design parameters that has been used with great effectiveness by Japanese auto makers and is now being adopted by Ford and other companies in the U.S. Essentially a schematic device for linking product qualities as perceived by consumers to engineering design parameters, the House of Quality helps a firm to determine what something
like "a luxurious, comfortable interior" means in engineering terms (Clausing 1988). Skill in using the House of Quality or related means for integrating consumer preferences directly into product definition and design appear to have become core competencies in product development that enable some firms to consistently achieve a profitable match between the products they produce and the products their markets want.

Some firms have also achieved an ability to achieve a high level of correspondence between market preferences and product designs by using multi-functional development teams composed of marketing, sales, service, and manufacturing staff as well as design engineers. This approach to developing products has been most widely used in Japan and is now being adopted by some U.S. firms.

Skills in phasing product development also constitute a core competency critical to achieving appropriate products, because phased development enables the firm to focus its development resources on continuing development of products that match changing customer preferences during the development cycle, and to drop those products that don't. As discussed in Chapter 3, phased development allows the firm to structure development as a series of nested or compound options exercisable at the beginning of each development phase. When each phase of development is completed, the firm can assess the option value of continuing development of a given product through the next phase (which is a function of the price consumers would pay for the product) and can drop any product which no longer offers option value in excess of its remaining cost of development. Terminating development of products which prove to be inferior in light of ongoing changes in technologies and market preferences allows the firm to concentrate its development efforts on initiating or accelerating development of its most appropriate new products. Phasing development requires organizational flexibility and an ability to redeploy the firm's development resources to development projects that will create the most valuable new product options.

9.3.3 Ability to Produce High Quality Products at Low Cost.
When a firm can offer high quality products to its markets, it may be able
to build a reputation for quality, to collect premium prices for its products, and thereby to enhance the value of its product options. For an increasing number of products, however, an ability to offer high quality has become a minimum qualification for participation in the product market, and only firms which can continually raise a superior standard of quality for their products can hope to receive premium prices. When a firm can collect premium prices while producing products at low cost, its product options become all the more valuable.

The core competencies in manufacturing which underlie an ability to offer high quality products while achieving low production costs have been studied in depth by Hayes, Wheelwright, and Clark (1988) and others. The key ability required to maintain and improve quality in manufacturing while lowering costs is an ability to gain control of a manufacturing process by advancing to the highest possible level the firm's knowledge of how process variables affect the output of the process. (For a classification of levels of manufacturing process knowledge, see Bohn 1987). To accomplish this requires a genuine organizational commitment to learning about and improving the firm's processes, plus the skillful use of diagnostic tools like statistical process control which enable meaningful experiments and learning to take place. In addition, the organization must be capable of adopting improvements to production processes developed outside the firm.

The pivotal role of product design as a core competency in achieving high quality products at low cost has received little attention in the United States until recently. Dixon and Duffey (1990) quote Dr. Barry Beeb of Xerox in asserting that lack of understanding by American managers and engineers of evolving product-design methodologies has frustrated the ability of U.S. firms to learn from the successes of Japanese manufacturers in producing high quality products at low cost:

The implications of many of the "experts" about Japanese processes that success is due to manufacturing effectiveness and management practices is dangerously misleading. A primary factor in Japan's success is development and
utilization of new engineering design methodologies that are not yet broadly understood by U.S. engineers, much less by U.S. corporate management.

(Dixon and Duffey 1990, page 19)

Recent efforts to improve product "design for manufacture" at Ford, IBM, NCR, Xerox, and other manufacturing firms attest to the fact that "high quality and low cost cannot be manufactured-in unless they are first designed-in" (Dixon and Duffey 1990). Effective engineering design for high quality and low cost requires interrelated skills in designing for functionality, structural integrity, manufacturability, ease of use, and economy of maintenance and repair. In addition, the styling, fit, and finish of the product must be suggestive of high quality, but producible at low cost.

9.3.4 Ability to Proliferate a Large Number of New Product Models at Low Cost of Development

In competitive product markets characterized by rapid product imitation or diffused product technologies, a firm which can field a large number of new product models positioned at different points in the product space may be able, in effect, to multiply the option value of a new product idea. When the firm can develop multiple product models at a low cost of development, it increases both the value of each new product development opportunity and the number of product models which will have a positive net present value. When the firm can consistently do all of this quickly, before competitors bring their products to market, the firm may also be able to foreclose effective competition in its product market and create a highly profitable context of competitive immunity for its multiple new product options. Alternatively, a firm may want to generate a succession of improved products models over time, while minimizing development costs.

The core competency behind the ability to produce a number of new products at low development costs -- whether in the form of a rapid, simultaneous proliferation of a number of new product models or of a succession of new product models over time -- is a skill in leveraging multiple product designs from a platform design, a common system design,
and/or shared components. These design regimes are discussed in Chapters 6, 7, and 8.

This method of product development and the benefits which it can bring in competitive product markets have only recently been detected and studied by a few researchers. In a pioneering study, Sanderson and Uzumeri (1990) analyzed the Sony Walkman models introduced in the U.S. since 1980 and traced the proliferation of dozens of Walkman models from five basic system designs or "platforms." Imitators have followed Sony with multiple product model introductions, but without achieving the multitude of product models and near-saturation of product space accomplished by Sony. In a related product design study, Wheelwright and Sasser (1989) have suggested how product models can be leveraged from a "core" consumer product design to produce "enhanced," "customized," "cost-reduced," and "hybrid" models to maintain the competitiveness of a product line over an extended period of time.

Producing a range of product models at low cost from a common system design requires skill in designing components which can be reused in a range of models or in using readily available, "off-the-shelf" components. Only a few successful uses of this design regime have been reported in the United States. In preparing to automate production in its electrical circuit box business in 1989, General Electric redesigned its product line and reduced the number of standard parts from over 28,000 to 1275, from which GE was able to leverage about 40,000 different circuit box models (Fortune, 2/13/89, page 56). There is ample evidence that this skill in designing different combinations of re-usable components to generate product variety has been highly developed by a number of Japanese manufacturing firms. A 1990 English-language translation of two books by Suzue and Kohdate (1990), originally published in Japan in 1984 and 1988, offers a detailed explanation of how a reduction in the variety of parts can form an intergral element in a strategy for product diversification based on modularity of parts.

9.4 Enhancing Strategic Flexibility By Exploiting Synergistic Linkages Among Core Competencies

The strategic capabilities and resources (and the core competencies
which underlie those capabilities) which seem to be necessary to achieve a sustainable competitive advantage in dynamic, competitive markets for manufactured consumer products were identified in the preceding section. Other kinds of product markets -- for example, markets for industrial equipment, financial services, or construction -- will have different strategic resources and capabilities and different underlying core competencies. In the strategic flexibility framework, the task of a firm's strategic managers is (1) to correctly identify the strategic capabilities needed to fully exploit product opportunities in the markets in which the firm competes, and (2) to acquire and strengthen any needed strategic capabilities by building the firm's core competencies from which those strategic resources and capabilities spring. If the firm's strategic managers are successful in this task, they will assure that the firm has the strategic flexibility to respond strongly and quickly to changes in technologies and market preferences, effectively endowing the firm with "the core competencies that spawn unanticipated products" (Prahalad and Hamel 1990, page 81).

Once appropriate core competencies are built up within a firm, a second but equally crucial task of strategic managers is to search out and exploit synergies among the firm's existing capabilities or core competencies and between capabilities or competencies the firm has now and those the firm can acquire. Finding synergistic linkages between core competencies can open up major new product possibilities and opportunities for growth, greatly enhancing the strategic flexibility of the firm. Prahalad and Hamel (1990) describe, for example, how in the early 1980s NEC's managers' correctly identified synergies among semiconductor and computer technologies (in which NEC possessed core competencies) and digital signal technology (in which it did not) and NEC's subsequent strategic move to acquire and further develop digital transmission technology. The synergistic linkages which NEC's strategic managers were able to achieve among its core competencies in these three technologies enabled NEC to become a producer of a broad spectrum of information processing and transmission products. In effect, NEC's strategic managers' perceptiveness and actions significantly expanded the number of product development opportunities available to the firm and enabled the firm to increase its share of value-added in the product
initiative options it subsequently exercised.

In an especially interesting recent example of the search for synergies between strategic resources and capabilities, Sony's acquisition of Columbia's film and music businesses gives Sony access to a large inventory and an ongoing stream of entertainment "software" which it may be able to combine synergistically with its competencies in developing new entertainment hardware products. The primary synergy in this linkage may come from the possibility that Sony will be able to market new entertainment hardware using new formats for entertainment software, which it will now be able to provide in adequate quantities to reach a critical mass necessary for consumer acceptance. If successful, this synergistic linking of new kinds of hardware with a critical mass of available software could enable Sony to create and sustain new, proprietary formats for entertainment software. By controlling new software formats for which it can provide new hardware products, Sony may be able to enjoy significant periods of competitive immunity from competing products and thereby to greatly increase the rewards from its new entertainment hardware development opportunities. Sony may also profit from creating new format markets for "recycling" Columbia's considerable software inventory, thus creating new initiative options from existing assets.

The search for synergies among a firm's resources and capabilities or among its core competencies requires that strategic managers grasp clearly the important technological and marketing capabilities of the firm and understand intimately the core competencies that underlie the firm's technological and marketing capabilities. To achieve enduring synergistic linkages, the firm's strategic managers must be able to see beyond superficial complementarities to ascertain the goodness of the strategic fit between fundamental core competencies. Efforts to derive synergies by combining two firm's regional marketing systems might appear promising on the surface, for example, but are likely to fail to achieve a workable arrangement between the two marketing organizations (much less synergistic linkages) if the core competencies which have made each firm successful in its region are fundamentally non-complementary. Thus, the strategic manager searching for synergistic linkages that will enhance the
strategic flexibility of the firm must necessarily have a keen perception of the competencies and capabilities which give the firm its strategic flexibility, and must perceive how other competencies and capabilities which the firm could acquire could contribute synergistically to the strategic flexibility of the firm.
Figure 9-1: The Strategic Flexibility Value Chain
**STRATEGIC CORE**

<table>
<thead>
<tr>
<th>Core Competencies</th>
<th>Strategic Capabilities</th>
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<tr>
<td>which underlie firm's strategic capabilities and endow firm with the strategic</td>
<td>which enable the firm to acquire and exploit new product development and production</td>
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<td>flexibility to respond changing technologies and market preferences</td>
<td>opportunities ($OV^D_{l,m,t}$ and $OV^P_{l,m,t}$)</td>
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<td></td>
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<tr>
<td>1A. Acute awareness of changing market preferences</td>
<td>1. Ability to Define Appropriate New Products</td>
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<td>1B. Ability to translate identified market preferences into product design and</td>
<td>2. Fast-Cycle Product Development</td>
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<td>engineering parameters</td>
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<td>1C. Skills in phasing development</td>
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<td></td>
<td>3. Ability to Produce High Quality Products at Low Cost</td>
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<tr>
<td>2A. Ability to organize and manage overlapping product development</td>
<td></td>
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<td>2B. Ability to achieve quasi-integration with suppliers who can assume major</td>
<td>4. Ability to Develop a Large Number of Product Models at Low Cost of Development</td>
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<td>responsibilities for component or materials development</td>
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<tr>
<td>3A. Ability to gain control of a manufacturing process</td>
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<td>3B. Ability to design products for low cost manufacture</td>
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<td>4A. Skill in leveraging multiple product designs from a common system design and</td>
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<td>shared components</td>
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*Figure 9-2: Strategic Capabilities and Underlying Core Competencies in Some Markets*
10. The Strategic Flexibility Framework and Strategy Theory

The evolution of strategy as a field of study may be described as springing from business policy studies in the general management tradition (see, for example, Learned et al. 1969), but striving for greater rigor and predictive ability. As strategy has evolved, three principal frameworks for analyzing competition between firms and for predicting competitive success have been advanced as providing the theoretical basis needed to transform strategy into a more rigorous discipline. These three frameworks have been characterized by Teece, Pisano, and Shuen (1990) as the competitive forces framework, the entry deterrence/strategic interaction framework, and the resource-based framework. Whether these frameworks are complementary or competitive to each other is now being debated within the strategy field. This section does not attempt to join that debate, but rather to comment on how the strategic objective of achieving optimal strategic flexibility developed in this thesis relates to the three frameworks now being considered as a unifying basis for strategy theory. The following discussion draws on the Teece, Pisano, and Shuen (1990) characterizations of the three strategy frameworks.

10.1 Strategic Flexibility and the Competitive Forces Framework

The competitive forces framework for strategy analysis and formulation descends from the industrial organization economics of Bain (1959) and is epitomized by Michael Porter's (1980 and 1985) work on competitive analysis of industries and ways in which firms can secure a competitive advantage within various industry structures. The normative theory advanced in the Porter work is that three internally consistent but mutually exclusive strategies constitute the feasible paths for achieving long-term competitive success: the low cost producer strategy, the product differentiation strategy, and the focus strategy. Competitive success is defined as the ability to earn an above-average rate of return for a given industry. To be successful, a business must concentrate on pursuing one of these three generic strategies and must avoid the trap of becoming "stuck in the middle" - i.e. of having insufficient
market share to use economies of scale and learning to become the low-cost producer, and of having insufficient product differentiation or market focus to command a premium price for the firm's products.

Three issues lie at the heart of the effort to relate a strategy dedicated to achieving optimal strategic flexibility to the competitive forces framework.

First, the presumption that low-cost production and high levels of product differentiation are mutually exclusive strategies may have been reasonable until the early 1980s, given the product development and production technologies generally available at that time. However, one of the critical features of currently used development and production technologies is that a firm may be able to develop and produce a potentially large number of different products by using a platform design, a common system design, and a pool of shared components (as discussed in Chapters 6, 7, and 8). These product design strategies may allow both development and manufacturing costs to be greatly reduced. When a firm knows how to develop and manufacture products in this way, it can create a large number of different products at low total costs of development and production. In this case, there is no logical reason why a firm may not pursue a strategy of offering differentiated products produced at low cost and priced as competitively as need be for a given market. Indeed, some firms are already pursuing this strategy with considerable apparent success (for example, see the discussion of the Sony Walkman in Chapter 8). Thus, a central difference between the strategic flexibility framework presented here and the competitive forces framework is that the discussion of strategic flexibility in this thesis reflects the last decade's advances in product design and manufacturing technologies, which have done much to overcome the dichotomy between product differentiation and low cost production which permeates the competitive forces framework.

A second issue in relating strategic flexibility to the competitive forces framework is the impact of technological and market uncertainty on the ability of each to reliably prescribe a strategy which will maximize the value of the firm in the long run. Given its emphasis on predating strategy on the structural features of an industry, the competitive forces framework seems most applicable to competitive environments characterized by stable
technologies and market preferences. When technologies are in flux and future market preferences uncertain, it is rather unclear in the competitive forces framework what the relative values of maintaining a low-cost, differentiation, or focus strategy might be, or when switching from one generic strategy to another might be value-maximizing for the firm. By contrast, the strategic flexibility framework not only explicitly recognizes technological and market uncertainty (as reflected in price uncertainty) as a natural feature of the firm's environment; it also explicitly values the impact of uncertainty on the firm's alternative courses of action. The largely deterministic setting of stable technologies and known market preferences, which is implicit in much competitive forces analysis, is simply a special case ($\sigma_v = 0$) in the strategic flexibility framework. When significant technological and market uncertainty exists, strategic flexibility analysis becomes essential to understanding how alternative courses of action can affect the value of the firm.

The third issue is the difference in the ways a firm creates value in the competitive forces and strategic flexibility frameworks. In the competitive forces framework, the firm creates value in one of three ways. By becoming a low-cost producer, the firm may be able to drive out competitors and charge monopoly prices, or at least may be able to discipline competitors to maintain a price umbrella well above its costs of production. Alternatively, by offering different customer groups a well differentiated product or by producing a bundle of appropriate products and service to a market niche the firm has focussed on, the firm may be able to charge a premium price (presumably in excess of its costs). By following one of these strategies, the firm increases its value by the value of the profit stream the firm generates if the strategy is successful. The competitive forces framework provides no mechanism for adjusting the expected value of a strategy by the probability that the strategy may turn out not to be successful.

In the strategic flexibility perspective, the firm creates value by creating initiative options to develop or produce products and timing or implementation options associated with those initiative options. Alternatively, the firm may occasionally add to its value by positively
responding to fortuitous changes in its environment which create new initiative, timing, or implementation options. In either case, the value of the strategic flexibility these options brings to the firm includes an assessment of the probability that a given product idea may prove to be unsuccessful in the future.

With the strategic flexibility mode of value creation, lowering costs creates real option value in several ways. Lowering development costs allows the firm to acquire more positive value production options and increases the value of any new product ideas (product development opportunities) the firm can imagine. Lowering production costs allows the firm to exercise more production options on completion of development and also adds to the value of each new product initiative option the firm creates, which also allows more new product ideas to be put into development. Lowering variable production costs also enables the firm to maintain production of a product at lower market prices for the product, which in turn increases the value of both development and production opportunities. Similarly, differentiated or focussed products which may command premium prices can add value to both development and production opportunities.

In sum, the strategic flexibility framework developed in this thesis differs from competitive forces strategy in that strategic flexibility (1) recognizes new development and production technologies which are breaking down the dichotomy between low cost production and differentiated products, and (2) explicitly incorporates technological and market uncertainty into the valuation of alternative courses of action. At the same time, the strategic flexibility perspective has in common with competitive forces analysis (1) a focus on the firm's products and production capabilities as important determinants of firm value, and (2) a recognition that low cost production, product differentiation, and product focussing are means to increase the value of the firm, although the valuation methods of the two frameworks differ significantly.

10.2 Strategic Flexibility and the Entry Deterrence/Strategic Interaction Framework

The entry deterrence/strategic interaction framework for strategy
(hereafter referred to simply as the strategic interaction framework) is premised on game theoretic analysis of competitor moves and countermoves in contests to capture markets and extract monopoly profits. Teece, Pisano, and Shuen (1990) suggest that the essential feature of this framework is a presumption that competition between firms will have "outcomes [that] are a function of the effectiveness with which firms keep their rivals off balance through strategic investments, pricing strategies, signalling, and control of information." Within this framework, a firm achieves competitive success by preventing other firms from participating in markets (pre-empting markets), which it accomplishes by making irreversible investments in capacity (Dixit 1980), research and development (Gilbert and Newberry 1982), advertising (Schmalensee 1983), or other assets which will give the firm a long-run cost advantage over other firms. The lower cost position of the firm enables it to drive out present competitors or to threaten potential entrants with losses if the they enter. By signalling that it is an unmatchable low cost producer or that it is willing and able to absorb losses to a greater degree than a potential entrant (which may be true or untrue), a firm may be able to monopolize a market and earn monopoly profits.

The intellectual parent of the strategic interaction framework is the "new" industrial organizational economics, which uses game theory to analyze competitor interactions in a context that is suggestive of many of the basic presumptions of the "old" industrial organizational economics. For example, capacity, once installed, is presumed to provide a durable cost advantage derived from economies of scale and experience. Technology, once developed, provides a means to achieve a durable low-cost advantage in production. Consumer preferences, once discovered or created by advertising, endure and can be served indefinitely by differentiated brand products which strategically populate a product space, because the high costs of creating consumer awareness for a new product, plus the prospect of inadequate returns from entering an already densely populated product space, combine to deter entry. To the extent that the strategic interaction framework shares the presumptions of stable technologies and market preferences which underlie the competitive forces framework, strategic flexibility differs in similar respects from the two frameworks.
In contrast to the special emphasis on pre-emption in the strategic interaction framework, the strategic flexibility framework developed here has not yet addressed the possibility that a firm may pre-empt a market or itself be pre-empted. However, the strategic flexibility framework provides the means to value pre-emption under uncertainty, in the following way. The strategic flexibility framework recognizes competition between firms in the form of competitive price erosion when competing firms can imitate a new product or when diffusion of technologies and market knowledge enables firms to introduce competing products which they have developed themselves. Competitive erosion of prices reduces the maximum value of the firm's opportunity vectors. This reduction in the value of the firm's product opportunities can be compared to the value those same product opportunities would have if the firm enjoyed competitive immunity from competition. The difference in the values of a product opportunity when it has competitive immunity versus when it is exposed to competitive price erosion is the maximum amount which the value-maximizing firm would invest to pre-empt a market for a new or existing product. (Equation 2-10 provides the point of departure for valuing the firm's product development opportunities and production options in different competitive contexts.)

A further difference between the strategic flexibility perspective and the strategic interaction framework is the assumed mechanism for creating value. In the strategic interaction framework, value is created by extracting monopoly rents which are possible because the firm achieved entry-deterring cost advantages by making irreversible investments. An implicit assumption in this value creation mechanism is that the cost advantages the firm creates by investing irreversibly are sufficiently enduring to deter entry, which in turn assumes relative stability of technologies and market preferences. When technological and market preferences are uncertain, however, the opportunities for creating value by making irreversible investments that effectively pre-empt markets for any significant time period may be rare or non-existent. By contrast, in the strategic flexibility framework, value is created by acquiring options for future action, which is the antithesis of making irreversible commitments. The goal of strategy founded on strategic flexibility is the firm which can
respond in a variety of ways to uncertain future events, not a firm which is irreversibly committed to one mode of production or to production of a fixed product or set of products. The ways in which one firm's ability to achieve superior strategic flexibility might act to deter entry is not analyzed formally here, but ways in which achieving superior strategic flexibility might act to pre-empt markets are suggested in Chapter 9.

10.3 Strategic Flexibility and the Resource-based/Dynamic Capabilities Framework

The third framework for strategy theory identified by Teece, Pisano, and Shuen (1990) is the resource-based framework. In contrast to the competitive forces and strategic interaction framework's emphasis on improving a firm's profits by reducing the threat of competition, the resource-based framework emphasizes the role of firm-specific capabilities which enable a firm to achieve low costs and/or high quality products in a dynamic market context. Rather than focussing on driving out competitors or frustrating potential entrants, the resource-based strategy is focussed on building distinctive competencies that enable the firm to succeed "against the opposition of circumstance or competition, whatever it sets out to do" (Learned et al. 1959). In an extension to the resources-based perspective, a number of researchers have emphasized that a firm's capabilities are dynamic in that they take time to acquire and depend on prior capabilities the firm has developed. Teece (1980, 1982) has also emphasized the critical role of a firm's complementary assets (like marketing skills, distribution networks, and sources of inputs) in exploiting new product opportunities.

Within the resource-based/dynamic-capabilities framework, the central concern in strategy formulation is to invest the firm's resources in ways that look beyond immediate returns to the long term enhancement of the resources and skills that promise to make the firm a strong, resilient, and profitable competitor in an environment in which technological and market change is likely. As Dierickx and Cool (1989) and Hayes, Wheelright, and Clark (1988) have argued, the objective of strategic management then becomes the development of firm-specific competencies (including relationships with customers and suppliers) that enable the firm to
outperform its competitors and which are difficult or impossible for the firm's competitors to duplicate. In his recent work on global competition, Porter (1990) adds to this perspective by advancing the view that indigenous resources and capabilities can contribute significantly to the ability of a nation's firms to compete in global product markets.

Of the three frameworks for a theory of strategy, the strategic flexibility framework presented in this thesis is clearly most closely allied with the resource-based/dynamic-capabilities framework. One source of compatibility is the shared presumption that technological and market preferences are dynamic and subject to uncertain change over time, and thus that the opportunities for entry deterrence or market pre-emption through strategic investments in capacity, etc., may be sufficiently rare that focusing on exploitation of such opportunities is not by itself an adequate or robust objective of strategy. Further, in the resource/dynamic-capabilities framework, the firm succeeds by acquiring specific resources and capabilities which let it compete effectively in the long run. Similarly, in the strategic flexibility framework suggested here, the value of the firm, as stated in Equation 9-2, is maximized when the firm's strategic core of capabilities (SC) to develop, produce, and market existing and future products is expanded and when the firm can effectively apply those resources and capabilities to optimizing the value of its development and production opportunities.

In this regard, although no analytic valuation of the strategic core of the firm is on the horizon, the real options valuations of product opportunities utilized in this thesis do indicate the best available approaches to correctly valuing identifiable product development or production opportunities under technological and market uncertainty. Thus, one hoped-for contribution of this thesis to the field of strategy is to demonstrate the potential of real options analysis to provide both a theoretical framework and an analytic capability which can guide a firm's strategic managers towards those strategic resources and capabilities which can make the greatest additions to firm value in the long run.
Conclusions

A fundamental premise of this thesis' research is that the proper objective of a firm's strategy is to maximize the present value of the firm. Equation 9-2 gives a statement of firm value that can guide the firm's strategic managers in formulating strategies that will optimize the strategic flexibility of the firm and maximize the value of the firm -- which are identical, indistinguishable objectives in the strategic flexibility framework. Equation 9-2 says that strategic managers should try to maximize the value of the firm's product development opportunities and product initiative options ($\sum PD_{ij,n_{ij}^*,t} + \sum C_{i,m_{i}^*,t}$), plus its strategic core of resources and capabilities (SC) which can generate and enhance future product development opportunities, plus any residual assets the firm may happen to have.

This perception of the task of strategic managers leads to three important conclusions about competitive strategy under uncertainty.

First, a firm's strategy, while likely to be complex and contextual, will be fundamentally different in character depending on whether it is conceived to be defensive, predatory, or opportunity exploitative. With significant levels of uncertainty about technologies and market preferences, the strategy posture that may have the best chance to maximize firm value in the long run is a strategy focussed on exploiting new opportunities created by changes in technologies and market preferences. Strategy premised on taking defensive measures to insulate the firm against competitive forces or on pre-empting markets through strategic investments in production capacity relies heavily on stability of technologies and market preferences to accomplish its goals. Uncertainty in technologies and market preferences greatly diminishes the predictability of securing long term competitive advantage through the actions that typically comprise such defensive or predatory strategies. With high uncertainty levels, a focus on building resources and capabilities to exploit new opportunities created by changes in technologies and markets is likely to offer the most sustainable means for the firm to achieve profitability and competitive success in the long run.
Second, to be effective, a strategy focused on exploiting technological and market change will have to be a multifaceted effort to identify, acquire, and strengthen a range of resources and capabilities which can enable the firm to fully exploit future opportunities in its product markets. These capabilities will include key skills in identifying, developing, producing, marketing, and distributing new products. If the firm can continually develop its resources and capabilities, it may be able to create a virtuous circle of rising profitability, leading to greater investments in resources and capabilities, leading to even greater profitability, leading to even more strategic investments, and so on. In the most successful cases, the opportunity exploitative firm may become so much more capable in identifying and fully exploiting new product opportunities than its less able competitors that it may effectively foreclose competition in its product markets by capturing such a large portion of new opportunities that competitors will be unable to continue trying to compete in exploiting opportunities. Thus, with high levels of technological and market uncertainty, the only feasible way to create competitive immunity in the long run may be to become much better at detecting and exploiting change than competitors. In other words, under significant technological and market uncertainty, the most sustainable strategy may be a highly capable offensive strategy.

Third, in seeking to understand which resources and capabilities the firm ought to build up, an opportunity-exploitative strategy must be guided by a clear understanding of which resources and capabilities can optimize the firm's strategic flexibility in its product markets. The multifaceted nature of any effective effort to maximize firm value has also been suggested by the options analysis of product opportunities in preceding chapters.

Chapter 6, 7, and 8 showed that skills in product design (such as leveraging product variety) and development management (such as phasing development) can enable the firm to increase the number of its new product initiative options, enhance the value of each new product option, and convert more product development opportunities into positive-value development projects. Chapter 4 showed that extracting maximum value from a product opportunity will depend on correctly timing the exercise of product development and production options, which in turn implies that the firm's
development speed must be well matched with the typical optimal exercise
time for the product markets in which the firm competes. Chapter 5 showed
that the value of a firm’s product initiative options -- and thus of its product
development opportunities -- will also depend on the ability of the firm to
expand the markets for its products, to expand its sources of inputs, to make
more efficient use of inputs, to install more reversible and more finely
divisible capacity, to reduce the time required to develop products or begin
production, etc. Thus, maximizing the value of the firm by fully exploiting
product opportunities and optimally implementing product initiative options
requires strategic management attention to the full spectrum of value chain
activities from development to marketing. Although some of these activities
may prove more critical than others to extracting as much value as possible
from various kinds of product opportunities, inattention to building firm
resources and capabilities needed at any step in the product value chain can
lead in the long run to a systematic inability of the firm to fully exploit its
product opportunities.

The strategic flexibility framework developed in this thesis has proposed
that under uncertainty about future available technologies and market
preferences, strategic managers will maximize firm value by optimizing the
strategic flexibility of the firm to fully exploit new opportunities made possible
by technological and market change. The firm’s strategic managers can
optimize the firm’s strategic flexibility by maximizing the net present value
of the real options the firm has or can create. This thesis has used options
analysis to investigate how decisions the firm makes about how it develops
and produces products can affect the firm’s real options values and thus the
strategic flexibility of the firm. Options analysis of a firm’s full value chain
could bring into clearer focus other specific capabilities that would help the
firm to optimize its strategic flexibility in specific product markets.
Appendices A1 to A7
Appendix A1

Relating A Time-Dependent Lognormal Distribution To The Uncertain Future Values of A Risky Asset

The dynamics for a risky asset $V_{i,t}$ can be derived from assumed dynamics for $\ln \left( \frac{V_{i,t+\Delta t}}{V_{i,t}} \right)$ such as those given in Equation 2-1 and illustrated in Figure 2-2(a). Begin by restating Equation 2-1:

$$\ln \left( \frac{V_{i,t+\Delta t}}{V_{i,t}} \right) = \mu \Delta t + \sigma Z \sqrt{\Delta t} \quad \text{Equation 2-1}$$

where

- $V_{i,t} =$ market equilibrium present value at time $t$ of the risky asset \{V_i\}
- $V_{i,t+\Delta t} =$ market equilibrium present value at time $t+\Delta t$ of the risky asset

$V_{i,t+\Delta t} / V_{i,t} =$ asset return over the interval $\Delta t$

- $\mu =$ the mean of the logarithm of the asset return per unit time
- $\sigma \sqrt{\Delta t} =$ the standard deviation of the logarithm of the asset return per unit time
- $Z =$ the standard normal random variable with mean $= 0$ and variance $= 1$

Then, generally following the transformations of Jarrow and Rudd (1983, pp 89-92), exponentiate and re-arrange Equation 2-1:

$$\ln(V_{i,t+\Delta t}) - \ln(V_{i,t}) = \mu \Delta t + \sigma Z \sqrt{\Delta t}$$

$$\ln(V_{i,t+\Delta t}) = \ln(V_{i,t}) + \mu \Delta t + \sigma Z \sqrt{\Delta t}$$

$$V_{i,t+\Delta t} = V_{i,t} e^{\mu \Delta t + \sigma Z \sqrt{\Delta t}} \quad \text{Equation A1-1}$$

Recalling that $e^x = \sum (x^n / n!)$ for all integer values of $n$, $0 \leq n \leq \infty$, expanding $e^{\mu \Delta t + \sigma Z \sqrt{\Delta t}}$ gives
\[ V_{i,t+\Delta t} = V_{i,t} \left[ 1 + (\mu \Delta t + \sigma Z \sqrt{\Delta t}) + (\mu \Delta t + \sigma Z \sqrt{\Delta t})^2 / 2 \right. \\
\left. + (\mu \Delta t + \sigma Z \sqrt{\Delta t})^3 / 6 \ldots \right] \]

Equation A1-2

For small intervals \( \Delta t \), terms of higher order than \( \Delta t \) can be ignored, so that
Equation A1-2 reduces to

\[ V_{i,t+\Delta t} = V_{i,t} \left[ 1 + \sigma Z \sqrt{\Delta t} + (\mu + (\sigma)^2 Z^2 / 2) \Delta t \right] \]

Equation A1-3

Defining \( \Delta V_{i,t} = V_{i,t+\Delta t} - V_{i,t} \) and rearranging Equation A1-3:

\[ \Delta V_{i,t} / V_{i,t} = \left[ \sigma Z \sqrt{\Delta t} + (\mu + (\sigma)^2 Z^2 / 2) \Delta t \right] - V_{i,t} \]

Equation A1-4

Equation A1-4 gives the rate of return on the risky asset \( V_{i,t} \) over the interval \( \Delta t \). Recalling that the expectations \( E[Z] = 0 \) and \( E[Z^2] = 1 \), taking the expectation of \( \Delta V_{i,t} / V_{i,t} \) gives the mean rate of return on asset \( V_{i,t} \):

\[ E \left[ \Delta V_{i,t} / V_{i,t} \right] = E \left[ 1 + \sigma Z \sqrt{\Delta t} + (\mu + (\sigma)^2 Z^2 / 2) \Delta t \right] \]

\[ = (\mu + (\sigma)^2 / 2) \Delta t \]

Equation A1-5

Now find the variance of \( \Delta V_{i,t} / V_{i,t} \). From the definition of variance,

\[ \text{Var} \left[ \Delta V_{i,t} / V_{i,t} \right] = E \left[ (\Delta V_{i,t} / V_{i,t})^2 \right] - E^2 \left[ (\Delta V_{i,t} / V_{i,t}) \right] \]

Substituting \( \Delta V_{i,t} / V_{i,t} \) from Equation A1-4 and \( E[\Delta V_{i,t} / V_{i,t}] \) from Equation A1-5 and ignoring all terms of higher order than \( \Delta t \) yields

\[ \text{Var} \left[ \Delta V_{i,t} / V_{i,t} \right] = E \left[ (\sigma)^2 Z^2 \Delta t \right] = (\sigma)^2 \Delta t \]

Equation A1-6

and from this result the standard deviation follows:

\[ \text{SD} \left[ \Delta V_{i,t} / V_{i,t} \right] = \sqrt{E \left[ (\sigma)^2 Z^2 \Delta t \right]} = \sigma \sqrt{\Delta t} \]

Equation A1-7

Now combining the expected change per unit time in \( \Delta V_{i,t} / V_{i,t} \) given by Equation A1-5 and the unanticipated change per unit time given by Equation A1-7, the dynamics for \( \Delta V_{i,t} / V_{i,t} \) can be stated:

\[ \Delta V_{i,t} / V_{i,t} = (\mu + (\sigma)^2 / 2) \Delta t + \sigma Z \sqrt{\Delta t} \]

Equation A1-8
(Equation A1-8 is also reproduced as Equation 2-2 in Chapter 2.) The lognormal distribution of $\Delta V_{i,t}/V_{i,t}$ which results from the dynamics of Equation A1-8 is shown in Figure 2-2(b).

When the risky asset $V_{i,t}$ follows the dynamics of Equation A1-8 over the interval $\Delta t$, the resulting random variable $V_{i,t+\Delta t}$ will be given by Equation A1-1:

$$V_{i,t+\Delta t} = V_{i,t} e^{\mu \Delta t + \sigma Z \sqrt{\Delta t}}$$

Equation A1-1

To specify the distribution of $V_{i,t+\Delta t}$, apply the moment generating function $\phi(x) = \exp(\mu_x t + (\sigma_x)^2 t^2 / 2)$ for a continuous normal distribution to the random variable $V_{i,t+\Delta t}$ as given in Equation 2-2 above (see Ross 1989, pp 60-69). The mean of the distribution $V_{i,t+\Delta t}$ is given by the first derivative $\phi'(V_{i,t+\Delta t}) = E[V_{i,t+\Delta t}]$, and the variance of the distribution $V_{i,t+\Delta t}$ is found by subtracting $E^2[V_{i,t+\Delta t}]$ from the expectation of the second moment of $V_{i,t+\Delta t}$, $\phi''(x) = E[(V_{i,t+\Delta t})^2]$. These steps yield the following results:

$$\text{Mean } [V_{i,t+\Delta t}] = E[V_{i,t+\Delta t}]$$

$$= E[V_{i,t} e^{\mu \Delta t + \sigma Z \sqrt{\Delta t}}]$$

$$= V_{i,t} E[e^{\mu \Delta t + \sigma Z \sqrt{\Delta t}}]$$

$$= V_{i,t} \exp[(\mu + (\sigma)^2 / 2) \Delta t]$$

$$= V_{i,t} e^{\alpha \Delta t}$$

Equation A1-9

where $\alpha_v = (\mu + (\sigma)^2 / 2)$ will be used to simplify notation. Equation 2-10 also gives the mean of a distribution $V_{i,t+\Delta t}$ subsequent to a realization $V_{i,t}$:

$$\text{Mean } [V_{i,t+\Delta t}] = V_{i,t} e^{\alpha \Delta t}$$

Equation A1-10

Similarly,

$$\text{Var } [V_{i,t+\Delta t}] = V_{i,t} (\exp((2\mu + \sigma^2) t) \exp[\sigma^2 t - 1]) \Delta t$$

$$= (V_{i,t})^2 (\sigma')^2 \Delta t$$

Equation A1-11
where \((\sigma')^2 = \exp[(2\mu + \sigma^2) t] \exp[\sigma^2 t - 1]\) will be used to simplify notation. Then

\[
\text{SD} \left[ V_{i,t+\Delta t} \right] = V_{i,t} \sigma' \sqrt{\Delta t}
\]

Equation A1-12

Thus, given the mean \(\alpha_v\) and the standard deviation \(\sigma'\) of the returns per unit time to the lognormally distributed risky asset \(V_{i,t}\), the distribution of \(V_{i,t}\) at any future time \(t + \Delta t\) can be fully specified from Equations A1-9 and A1-10 or A1-11, and the dynamics of \(V_{i,t+\Delta t}\) specified by

\[
V_{i,t+\Delta t} = V_{i,t} \alpha \Delta t + V_{i,t} \sigma' \sqrt{\Delta t} Z
\]

Equation A1-13
Appendix A2

Valuation Methodology for Real Options

A2.1 Assumptions

The following options analysis invokes assumptions that markets for risky assets like product development projects are perfect, efficient, frictionless, and complete. For further discussion of these and other assumptions usually made in options analysis, see Galai and Masulis 1976 and Merton 1982. Of all the assumptions that are applicable to real options analysis, the assumption that capital markets are complete will play a key role in the following options valuation of a product development project, and some comments on this assumption are in order.

The basic method used in options analysis to value the opportunity -- as distinct from the obligation -- to develop and produce new product $P_i$ as a call option is *valuation by duplication*. In this method of valuation, a "replicating security" is identified whose payoffs exactly duplicate those associated with the opportunity to develop and produce $P_i$ in all future states of the world. The replicating security may either be an individual security which is actually traded in the capital markets, or it may be a "synthetic security" consisting of a portfolio of traded securities such that the payoffs to the portfolio will match exactly those of the opportunity to develop $P_i$. Under the no arbitrage condition necessary for market equilibrium, if the replicating security and the product development opportunity have the the same payoffs in all states of the world, then they must have the same market value at all points in time. Thus, if one can determine the market value of the replicating security at any point in time, then by duplication one has determined the value of the non-traded product development opportunity at the same point in time.

Now identify $S_{i,t}$ as the replicating or "twin" security to the capital budgeting project to develop $P_i$, which has the value $V_{i,t}$. The existence of a traded twin security that replicates the payoffs to a non-traded capital budgeting project necessarily follows from the usual assumption in finance.
theory that capital markets are complete. The assumption that capital markets are complete stipulates that the existing set of traded securities (or synthetic securities composed of traded securities) fully spans the state-space of risk opportunities and therefore is unaltered by the firm's creation of the development project for $P_i$ (Myers 1979, pp 6-8; Copeland and Weston 1988, p. 125). Since the firm's creation of $V_{i,t}$ adds nothing new to the set of existing investment opportunities, it follows that it must be possible to find a traded twin security $S_{i,t}$ somewhere in the capital markets or to synthesize a twin security from existing traded securities. Thus, in principle at least, a traded twin security for $V_{i,t}$ must exist and be identifiable under the assumption of complete markets.

One might question whether, as a practical matter, a twin security can always be found for every non-traded capital budgeting project of every firm, and whether unique new investment opportunities are never created. Nevertheless, the assumption of completeness underlies all available financial valuation methods for capital budgeting analysis, in which values for non-traded firm projects are obtained by likening the projects to some kind of traded security. In conventional discounted cash flow valuation, for example, a net present value for $V_{i,0}$ actually cannot be determined directly, because at $t = 0$ the uncertain revenue stream ($V_i$) does not yet exist and thus cannot be observed to determine its mean, variance, and correlation with the portfolio of all risky assets -- all of which are required to determine the appropriate discount rate for calculating $V_{i,0}$.

The conventional DCF analysis moves forward, however, by assuming that there is a traded security whose distribution of payoffs in future states of the world will have the mean, variance, and correlation with the market portfolio that we believe ($V_i$) will have, and $V_{i,0}$ is obtained by discounting ($V_i$) by the same risk premium that the market would demand for holding the twin security to ($V_i$). In a similar manner, the options analysis of the development project for $P_i$ must move forward under the assumption that
even though $V_{i,t}$ is not a traded security, there does exist a twin security $S_{i,t}$ that is traded and that therefore will enable a valuation of $V_{i,t}$ under a condition of no arbitrage. (For a further discussion of twin securities, see Mason and Merton 1985, pp 38-39, and Trigeorgis and Mason 1987, pp 15-17.)

**A2.2 Forming a Perfectly Hedged Replicating Portfolio**

Since the twin security $S_{i,t}$ and the value $V_{i,t}$ of the project to develop $P_i$ have the same value at all points in time, the dynamics of the twin security $S_{i,t}$ must be the same as those for $V_{i,t}$, and thus Equation 2-2 (also Equation A1-8) for the movement of $V_{i,t}$ can be restated for $S_{i,t}$:

$$\frac{\Delta S_{i,t}}{S_{i,t}} = \alpha \Delta t + \sigma Z \sqrt{\Delta t}$$  \hspace{1cm} \text{Equation A2-1}

where $\alpha = (\mu + \sigma^2/2)$ and $\mu$ and $\sigma$ are the mean and standard deviation of the time-dependent distribution of $\ln(S_{i,t+\Delta t}/S_{i,t})$.

To bring Equation A2-1 into conformance with the standard notation in options analysis, the term $Z \sqrt{\Delta t}$ will be replaced with $\Delta Z_t$, where $\Delta Z_t = Z_{t+\Delta t} - Z_t$. The new term $Z_t$ is a *Weiner process*, which is defined as a process in which $\Delta Z_t$, changes in $Z_t$ over small increments of time $\Delta t$, are normally distributed with mean $E[\Delta Z_t] = 0$, variance $(\sigma_z)^2 = \Delta t$, standard deviation $\sigma_z = \sqrt{\Delta t}$, and covariance $\text{Cov}(\Delta Z_t, \Delta Z_{t'}) = 0$ where $t \neq t'$ (Jarrow and Rudd 1983, p.96). Since $\Delta Z_t$'s have zero mean and variance of $\Delta t$ and are serially independent, $\Delta Z_t$ is functionally the equivalent of $Z \sqrt{\Delta t}$, and substituting $\Delta Z_t$ for $Z \sqrt{\Delta t}$ and re-stating the dynamics for $\Delta S_{i,t}$ as Equation A2-2 below involves no change in the specification of the stochastic process for $\Delta S_{i,t}$:

$$\Delta S_{i,t} = \alpha S_{i,t} \Delta t + \sigma S_{i,t} \Delta Z_t$$  \hspace{1cm} \text{Equation A2-2}

To determine by duplication the value of the opportunity to develop and produce $P_i$ as a European call option on $\{V_j\}$, begin by constructing a
replicating security which is a continuously adjustable portfolio \( R_{i,t} \) consisting of a twin security \( S_{i,t} \) and a riskless security \( B_t \) which together will exactly duplicate the pattern of cash flows from the opportunity to develop and produce \( P_i \). Although the project's revenue and cost streams extend over the period \( 0 \leq t \leq t_f \), the cash flows associated with the opportunity to develop and produce \( P_i \) in the basic model of product development have been simplified and reduced to four present values: (1) \( C_D \), the present value at \( t = 0 \) of the total costs of development; (2) \( C_P \), the present value at \( t = t^* \) of the total costs of producing \( Q \) units of \( P_i \) over the interval \( t^* \leq t \leq t_f \), conditional on the firm's deciding to produce and sell \( P_i \) (i.e., conditional on \( V_{i,t^*} \geq C_P \)); (3) \( V_{i,t^*} \), the present value at \( t = t^* \) of the uncertain revenue stream \( \{V_i\} \), again conditional on the firm deciding to produce and sell \( P_i \) (i.e., conditional on \( V_{i,t^*} \geq C_P \)); and (4) a zero cash flow if the firm decides not to produce and sell \( P_i \) (i.e., conditional on \( V_{i,t^*} < C_P \)).

Now denote the value at time \( t \) of the European call option on \( V_{i,t} \) exercisable at \( t = t^* \) for an exercise price of \( C_P \) as \( C_{i,t} (V_{i,t^*}; C_P, t^*) \), or where unambiguous, simply \( C_{i,t} \). Since the call option \( C_{i,t} \) will be exercised only if \( V_{i,t^*} \geq C_P \) at \( t = t^* \), the value of \( C_{i,t^*} \) is given by

\[
C_{i,t^*} (V_{i,t^*}; C_P, t^*) = \text{Max} [0, V_{i,t^*} - C_P]
\]

Equation A2-3

If the replicating portfolio of the twin security \( S_{i,t^*} \) and a riskless security \( B_{t^*} \) can exactly replicate the payoff \( \text{Max} [0, V_{i,t^*} - C_P, 0] \) at \( t = t^* \), and if there are no net cash flows into or out of the replicating portfolio at any time \( 0 \leq t \leq t^* \), then in order to avoid arbitrage the value at \( t = 0 \) of the call option must be the same as the value of the replicating portfolio at \( t = 0 \). In other words, \( C_{i,0} \) must equal \( R_{i,0} \). Thus, if the value of the replicating portfolio \( R_{i,0} \) can be determined, the value of the call option \( C_{i,0} \) held by the firm is also determined.
The method of valuing $R_{i,0}$ to be used here generally follows Bergman 1981 and Jarrow and Rudd 1983, pp 98-111. To find the value of $R_{i,0}$, begin by specifying that the replicating portfolio consist of $n_{i,t}$ shares of the twin security $S_{i,t}$ and $m_{i,t}$ units of a zero-coupon riskless bond $B_t$ whose value at $t = t^*$ is one dollar ($B_{t^*} = $1), where $n_{i,t}$ and $m_{i,t}$ can be adjusted continuously over the period $0 \leq t \leq t^*$. The market value of the replicating portfolio at any time during $0 \leq t \leq t^*$ is given by

$$R_{i,t} = n_{i,t} S_{i,t} + m_{i,t} B_t$$  \hspace{1cm} \text{Equation A2-4}

The goal for this portfolio is to select $n_{i,t}$ and $m_{i,t}$ such that liquidating the portfolio at $t = t^*$ will produce a cash flow which in all states of the world at $t = t^*$ will equal Max $(V_{i,t^*} - C_P, 0)$. If $n_{i,t}$ and $m_{i,t}$ can be selected to give this payoff, and if no other net cash flows need occur during $0 \leq t \leq t^*$, then the cash flow needed at $t = 0$ to purchase $n_{i,t}$ shares of $S_{i,t}$ and $m_{i,t}$ units of $B_t$ gives the value of $R_{i,0} -- and therefore of C_{i,0} under the no arbitrage condition.

To assure that no cash flows other than that needed to set up the portfolio need occur during $0 \leq t \leq t^*$, we impose the condition that any adjustments in $n_{i,t}$ and $m_{i,t}$ must be self-financing. That is, any cash flow associated with increasing $n_{i,t}$ (purchasing shares of $S_{i,t}$) or decreasing $n_{i,t}$ (selling shares of $S_{i,t}$) must be exactly offset by, respectively, decreasing $m_{i,t}$ (selling units of $B_t$) or increasing $m_{i,t}$ (purchasing units of $B_t$).

The change in the value of the portfolio $\Delta R_{i,t}$ over a small interval of time $\Delta t$ is given by

$$\Delta R_{i,t} = R_{i,t+\Delta t} - R_{i,t}
= (n_{i,t+\Delta t}) (S_{i,t+\Delta t}) + (m_{i,t+\Delta t}) (B_{t+\Delta t}) - (n_{i,t} S_{i,t} + m_{i,t} B_t)$$

Since $n_{i,t+\Delta t} = n_{i,t} + \Delta n_{i,t}$ and $S_{i,t+\Delta t}$, $m_{i,t+\Delta t}$, and $B_{t+\Delta t}$ are similarly defined, substituting these expressions into the above equation yields
\[ \Delta R_{i,t} = n_{i,t} \Delta S_{i,t} + m_{i,t} \Delta B_t + \Delta n_{i,t} (S_{i,t} + \Delta S_{i,t}) + \Delta m_{i,t} (B_t + \Delta B_t) \]

Equation A2-5

The terms \( \Delta n_{i,t} (S_{i,t} + \Delta S_{i,t}) \) and \( \Delta m_{i,t} (B_t + \Delta B_t) \) give the part of \( \Delta R_{i,t} \) that results from adjustments in \( n_{i,t} \) and \( m_{i,t} \) which must equal zero under the self-financing condition. Thus,

\[ \Delta n_{i,t} (S_{i,t} + \Delta S_{i,t}) + \Delta m_{i,t} (B_t + \Delta B_t) = 0 \]

Equation A2-6

In this equation, \( \Delta B_t = r \Delta t \) as \( \Delta t \to 0 \), where \( r \) is the riskfree interest rate on \( B_t \). Making this substitution gives

\[ \Delta n_{i,t} S_{i,t} + \Delta m_{i,t} B_t + \Delta n_{i,t} \Delta S_{i,t} + \Delta m_{i,t} r \Delta t = 0 \]

Equation A2-7

This is the fundamental equation which governs any adjustments in the replicating portfolio which must be made during \( 0 \leq t \leq t^* \) under the self-financing constraint.

To use Equation A2-7 to solve for \( n_{i,t} \) and \( m_{i,t} \), we must first find expressions for \( \Delta n_{i,t} \), \( \Delta m_{i,t} \), \( \Delta n_{i,t} \Delta S_{i,t} \), and \( \Delta m_{i,t} r \Delta t \). Expressions for \( \Delta n_{i,t} \) and \( \Delta m_{i,t} \) can be found by a Taylor series expansion:

\[ \Delta n_{i,t} = \left( \frac{\partial n_{i,t}}{\partial t} \right) \Delta t + \left( \frac{\partial n_{i,t}}{\partial S_{i,t}} \right) \Delta S_{i,t} + \left( \frac{1}{2} \right) \left( \frac{\partial^2 n_{i,t}}{\partial S_{i,t}^2} \right) (\Delta S_{i,t})^2 + 0(\Delta t) \]

Equation A2-8

\[ \Delta m_{i,t} = \left( \frac{\partial m_{i,t}}{\partial t} \right) \Delta t + \left( \frac{\partial m_{i,t}}{\partial S_{i,t}} \right) \Delta S_{i,t} + \left( \frac{1}{2} \right) \left( \frac{\partial^2 m_{i,t}}{\partial S_{i,t}^2} \right) (\Delta S_{i,t})^2 + 0(\Delta t) \]

Equation A2-9

where \( 0(\Delta t) \) represents all the terms which can be ignored as \( \Delta t \to 0 \). From Equation A2-2 for the dynamics of \( \Delta S_{i,t} \),

\[ (\Delta S_{i,t})^2 = (\alpha S_{i,t} \Delta t + \sigma S_{i,t} \Delta Z_t)^2 \]

\[ = \alpha^2 (S_{i,t})^2 (\Delta t)^2 + 2 \alpha S_{i,t} \Delta t \sigma S_{i,t} \Delta Z_t + \sigma^2 (S_{i,t})^2 (\Delta Z_t)^2 \]

Since \( S_{i,t} \) is a random variable following a Markov diffusion process that depends only on \( S_{i,t} \) and time \( t \), Ito’s Lemma can be applied to reduce the
above equation to

\[(\Delta S_{i,t})^2 = \sigma^2(S_{i,t})^2 \Delta t + 0(\Delta t)\]  \hspace{1cm} \text{Equation A2-10}

since by Ito's Lemma all terms \(\Delta t \Delta Z = 0(\Delta t), (\Delta t)^2 = 0, \text{ and } (\Delta Z_t)^2 = \Delta t\) (see Merton 1982, pp 37-39). Substituting Equation A2-10 into Equations A2-8 and A2-9 gives

\[\Delta n_{i,t} = (\partial n_{i,t}/\partial t)\Delta t + (\partial n_{i,t}/\partial S_{i,t})\Delta S_{i,t} + (1/2)(\partial^2 n_{i,t}/\partial S_{i,t}^2) \sigma^2(S_{i,t})^2 \Delta t \]

+ 0(\Delta t) \hspace{1cm} \text{Equation A2-11}

\[\Delta m_{i,t} = (\partial m_{i,t}/\partial t)\Delta t + (\partial m_{i,t}/\partial S_{i,t})\Delta S_{i,t} + (1/2)(\partial^2 m_{i,t}/\partial S_{i,t}^2) \sigma^2(S_{i,t})^2 \Delta t \]

+ 0(\Delta t) \hspace{1cm} \text{Equation A2-12}

Using Equations A2-11 and A2-12 gives useful expressions for \(\Delta n_{i,t} \Delta S_{i,t}\) and \(\Delta m_{i,t} \Delta S_{i,t}\): 

\[\Delta n_{i,t} \Delta S_{i,t} = (\partial n_{i,t}/\partial S_{i,t})(\Delta S_{i,t})^2 + 0(\Delta t)\]  \hspace{1cm} \text{Equation A2-13}

\[\Delta m_{i,t} \Delta S_{i,t} = 0(\Delta t)\]  \hspace{1cm} \text{Equation A2-14}

Having derived the above expressions for every term in Equation A2-7, the fundamental equation governing adjustments in the replicating portfolio can now be stated as

\[[(\partial n_{i,t}/\partial t)\Delta t + (\partial n_{i,t}/\partial S_{i,t})\Delta S_{i,t} + (1/2)(\partial^2 n_{i,t}/\partial S_{i,t}^2) \sigma^2(S_{i,t})^2 \Delta t)] S_{i,t} \]

+ \[[(\partial m_{i,t}/\partial t)\Delta t + (\partial m_{i,t}/\partial S_{i,t})\Delta S_{i,t} + (1/2)(\partial^2 m_{i,t}/\partial S_{i,t}^2) \sigma^2(S_{i,t})^2 \Delta t)] B_t \]

+ (\partial n_{i,t}/\partial S_{i,t})(\Delta S_{i,t})^2 + 0(\Delta t) = 0 \hspace{1cm} \text{Equation A2-15}

Substitution of \(\Delta S_{i,t} = \alpha S_{i,t} \Delta t + \sigma S_{i,t} \Delta Z_t\) from Equation A2-2 into the above equation gives

\[X \Delta t + Y \sigma S_{i,t} \Delta Z_t = 0\]  \hspace{1cm} \text{Equation A2-16}

where
\[ X = \left( \frac{\partial n_{i,t}}{\partial t} + \frac{\partial n_{i,t}}{\partial S_{i,t}} \right) \alpha S_{i,t} + \frac{(1/2)(\partial^2 n_{i,t}/\partial S_{i,t}^2)}{\sigma^2 S_{i,t}} S_{i,t} + \left( \frac{\partial m_{i,t}}{\partial t} + \frac{\partial m_{i,t}}{\partial S_{i,t}} \right) \alpha S_{i,t} + \frac{(1/2)(\partial^2 m_{i,t}/\partial S_{i,t}^2)}{\sigma^2 S_{i,t}^2} \right] B_t \]

\text{Equation A2-16a}

and

\[ Y = \left( \frac{\partial n_{i,t}}{\partial S_{i,t}} \right) S_{i,t} + \left( \frac{\partial m_{i,t}}{\partial S_{i,t}} \right) B_t \]

\text{Equation A2-16b}

Since changes in the Y term in Equation A2-16 depend on \( \Delta Z_t \) (which is perfectly random) and thus are completely uncorrelated with changes in the X term, it must be the case that both

\[ X = 0 \]

\text{Equation A2-17}

and

\[ Y = 0 \]

\text{Equation A2-18}

in order for Equation A2-16 to hold. The conditions \( X = 0 \) and \( Y = 0 \) will implicitly determine the value of \( n_{i,t} \) and \( m_{i,t} \) in Equations A2-16a and A2-16b.

To solve for \( n_{i,t} \) and \( m_{i,t} \) in Equations A2-16a and A2-16b, the partial derivatives of \( n_{i,t} \) must be expressed in terms of \( m_{i,t}, S_{i,t} \) and \( B_t \), and those of \( m_{i,t} \) must be expressed in terms of \( n_{i,t}, S_{i,t} \) and \( B_t \), and then these new terms substituted back into Equations A2-17 and A2-18. Partial derivatives of this sort can be obtained by rearranging Equation A2-4:

\[ R_{i,t} = n_{i,t} S_{i,t} + m_{i,t} B_t \]

\[ m_{i,t} B_t = R_{i,t} - n_{i,t} S_{i,t} \]

\[ m_{i,t} = \left( \frac{1}{B_t} \right) \left( R_{i,t} - n_{i,t} S_{i,t} \right) \]

\text{Equation A2-19}

Since \( B_t = \$1 \) at \( t = t^* \), its value at any time \( t < t^* \) is \( \$1(e^{-\tau(t^*-t)}) = e^{-\tau t} \) where \( \tau = t^*-t \). Thus, Equation A2-19 becomes

\[ m_{i,t} = e^{\tau t} (R_{i,t} - n_{i,t} S_{i,t}) \]

\text{Equation A2-20}

Taking the partial derivatives \( \partial m_{i,t}/\partial t, \partial m_{i,t}/\partial S_{i,t}, \) and \( \partial^2 m_{i,t}/\partial S_{i,t}^2 \) from Equation A2-19 and substituting them into Equation A2-17 gives an expression
which simplifies to

\[ -r (R_{i,t} - n_{i,t} S_{i,t}) + \partial R_{i,t}/\partial t + (\partial R_{i,t}/\partial S_{i,t}) \alpha S_{i,t} \]

\[ + (1/2)(\partial^2 R_{i,t}/\partial S_{i,t}^2) \sigma^2(S_{i,t})^2 - n_{i,t} \alpha S_{i,t} = 0 \]

Equation A2-21

Then substituting the partial derivatives of \( m_{i,t} \) into Equation A2-18 gives the simple result for \( n_{i,t} \):

\[ n_{i,t} = \partial R_{i,t}/\partial S_{i,t} \]

Equation A2-22

Finally, substituting Equation A2-22 into Equation A2-21 gives this important partial differential equation governing the dynamics of changes in the value of the replicating portfolio:

\[ -rR_{i,t} + \partial R_{i,t}/\partial t + rS_{i,t}(\partial R_{i,t}/\partial S_{i,t}) + (1/2)(\partial^2 R_{i,t}/\partial S_{i,t}^2) \sigma^2(S_{i,t})^2 = 0 \]

Equation A2-23

This partial differential equation gives the dynamics which the value of the continuously adjusted (or hedged) portfolio \( R_{i,t} \) must follow under the self-financing condition. Given the conditions in the basic model that the firm must decide at \( t = t^* \) whether to exchange \( C_P \) for \( V_{i,t^*} \), to Equation A2-22 can be added these three boundary conditions:

\[ R_{i,t^*} = \text{Max} [0, V_{i,t^*} - C_P, 0] \]

\[ 0 \leq t \leq t^* \]

\[ 0 \leq V_{i,t^*} \leq +\infty \]

Given these boundary conditions, Equation A2-23 will have a unique solution (Gleit 1978, pp 71-87). Therefore, Equations A2-20 for \( m_{i,t} \) and Equation A2-22 for \( n_{i,t} \) will also have unique solutions. When the unique solutions for \( m_{i,t} \) and \( n_{i,t} \) are inserted into Equation A2-4 (\( R_{i,t} = n_{i,t} S_{i,t} + m_{i,t} B_t \)), the replicating portfolio that uniquely duplicates the cash flow of the product development project for \( P_1 \) is completely specified.

Since the portfolio \( R_{i,t} \) must have the same value in all states of the world as the development project for \( P_2 \) valued as the call option \( C_{i,t}(V_{i,t^*}; C_P, t^*) \), it must also be the case that \( C_{i,t} \) must conform to the same partial differential
equation as $R_{i,t}$. In other words,

$$-rC_{i,t} + \partial C_{i,t}/\partial t + rS_{i,t}(\partial C_{i,t}/\partial S_{i,t}) + (1/2)(\partial^2 C_{i,t}/\partial S_{i,t}^2)\sigma^2(S_{i,t})^2 = 0$$

Equation A2-24

Since $V_{i,t}$ also follows the same dynamics as its twin security $S_{i,t}$, we can substitute $V_{i,t}$ for $S_{i,t}$ in the above equation to obtain

$$-rC_{i,t} + \partial C_{i,t}/\partial t + rV_{i,t}(\partial C_{i,t}/\partial V_{i,t}) + (1/2)(\partial^2 C_{i,t}/\partial V_{i,t}^2)\sigma^2(V_{i,t})^2 = 0$$

Equation A2-25

where Equation A2-25 is also subject to the boundary conditions

$$C_{i,t^*} = \text{Max} [0, V_{i,t^*} - C_P]$$

$$0 \leq t \leq t^*$$

$$0 \leq V_{i,t^*} \leq +\infty$$

This partial differential equation can be solved for a unique value of $C_{i,t^*}$ by applying the Cox-Ross risk neutrality argument, discussed in the next section.

### A2.3 The Cox-Ross Risk Neutrality Argument

The Cox-Ross risk neutrality argument (Cox and Ross 1976) makes two telling observations about partial differential equations like Equation 4-24: The value of $C_{i,t}$ implicit in an equation like A2-25 does not depend on expected returns from the underlying security (either $S_{i,t}$ or $V_{i,t}$), nor does it depend on any assumptions about investor’s utility functions or resulting risk preferences. Given this insight, Cox and Ross then argue that a value of $C_{i,t}$ which does not depend on risk preferences can be evaluated as if it were a risky asset in a risk-neutral world. In a risk-neutral world, all assets would earn the same rate of return on their expected value -- namely, the risk-free rate $r$. Thus, in a risk neutral world,

$$C_{i,0} = e^{-rt^*} E [C_{i,t^*}]$$

$$= e^{-rt^*} E [\text{Max} (V_{i,t^*} - C_P, 0)]$$

Equation A2-26

In addition, under the risk-neutrality condition, the underlying securities $S_{i,t}$
or \( V_{i,t} \) must also earn the risk-free rate \( r \). In this case, \( \alpha S_{i,t} \Delta t \), the expected change in \( \Delta S_{i,t} \) in Equation A2-2, and \( \alpha V_{i,t} \Delta t \), the expected change in \( \Delta V_{i,t} \) in Equation 2-2 (also Equation A1-8), must equal \( r \Delta t \). Thus, in a risk-neutral world, Equation A2-2 for the dynamics of \( \Delta S_{i,t} \) becomes

\[
\Delta S_{i,t} = r S_{i,t} \Delta t + \sigma S_{i,t} \Delta Z_t
\]

Equation A2-27a

and similarly Equation 2-2 for becomes

\[
\Delta V_{i,t} = r V_{i,t} \Delta t + \sigma V_{i,t} \Delta Z_t
\]

Equation A2-27b

When \( \Delta S_{i,t} \) and \( \Delta V_{i,t} \) follow the dynamics of Equations A2-27a and A2-27b, the call option \( C_{i,0} \) can be valued as the expected value of \( C_{i,t^*} \), discounted back to \( t = 0 \) at the risk-free rate. Given this characterization of \( C_{i,0} \) under the risk-neutrality argument, an exact pricing formula for \( C_{i,0} \) can be obtained.

### A2.4 Pricing a Product Development Opportunity as a European Call Option

The finding of the two preceding sections that a suitably constructed and continuously adjusted (or dynamically hedged) replicating portfolio implies a risk-neutral expectation of returns from \( V_{i,t} \) reduces the valuation of \( C_{i,0} \) to an exercise in mathematics. (The derivation here generally follows Jarrow and Rudd 1983, pp 90-93.) Before proceeding with the valuation, note that Equation A2-27b requires that

\[
r = \alpha = (\mu + \sigma^2/2)
\]

Equation A2-28

where \( \alpha \) is the expected rate of change in \( V_{i,t} \) per \( \Delta t \) from Equation 2-2.

The value of \( C_{i,0} \) in Equation A2-26 can be re-stated as the sum of two conditional values

\[
C_{i,0} = (C_{i,0})_{CV1} + (C_{i,0})_{CV2}
\]

Equation A2-29

where

\[(C_{i,0})_{CV1} = \text{the value of } C_{i,0} \text{ conditional on } V_{i,t^*} < C_p \text{, in which case}\]
\[(C_{i,0})_{CV1} = 0\]  \hspace{1cm} \text{Equation A2-30}

and

\[\langle C_{i,0}\rangle_{CV2} = \text{the value of } C_{i,0} \text{ conditional on } V_{i,t^*} \geq C_P, \text{ in which case}\]

\[(C_{i,0})_{CV1} = e^{-rt^*} E [V_{i,t^*} - C_P] = e^{-rt^*} E [V_{i,t^*}] - e^{-rt^*} E [C_P] = e^{-rt^*} E [V_{i,t^*}] - e^{-rt^*} C_P \]  \hspace{1cm} \text{Equation A2-31}

Now let \( \phi \) be the probability that \( V_{i,t^*} \geq C_P \); then \( 1 - \phi \) will be the probability that \( V_{i,t^*} < C_P \). Also, let \( E [V_{i,t^*} \mid V_{i,t^*} \geq C_P] \) denote the expectation of \( E [V_{i,t^*}] \) conditional on \( V_{i,t^*} \geq C_P \). Then Equation A2-29 becomes

\[C_{i,0} = (1 - \phi) (C_{i,0})_{CV1} + \phi (C_{i,0})_{CV2} = (1 - \phi) (0) + \phi (e^{-rt^*} E [V_{i,t^*}] - e^{-rt^*} C_P) = e^{-rt^*} E [V_{i,t^*} \mid V_{i,t^*} \geq C_P] \phi - e^{-rt^*} C_P \phi \]  \hspace{1cm} \text{Equation A2-32}

To solve Equation A2-32, first evaluate \( \phi \) and then \( E [V_{i,t^*} \mid V_{i,t^*} \geq C_P] \phi \).

To evaluate \( \phi \), recall that when \( \Delta V_{i,t}/V_{i,t} \) follows the dynamics of Equation 2-2, \( V_{i,t+\Delta t} = V_{i,t} e^{\mu \Delta t} + \sigma Z \sqrt{\Delta t} \), as stated in Equation A1-1. Thus \( V_{i,t^*} \) can be stated as

\[V_{i,t^*} = V_{i,0} e^{\mu t^*} + \sigma Z \sqrt{t^*} \]  \hspace{1cm} \text{Equation A2-33}

Then

\[\phi = \text{Probability } [V_{i,t^*} \geq C_P] = \text{Probability } [V_{i,0} e^{\mu t^*} + \sigma Z \sqrt{t^*} \geq C_P] = \text{Probability } [\ln V_{i,0} + \mu t^* + \sigma Z \sqrt{t^*} \geq \ln C_P] = \text{Probability } [Z \geq (\ln C_P - \ln V_{i,0} - \mu t^*)/\sigma \sqrt{t^*}] = \text{Probability } [Z \geq (\ln(C_P/V_{i,0}) - \mu t^*)/\sigma \sqrt{t^*}] = \text{Probability } [Z \geq (-\ln(V_{i,0}/C_P) - \mu t^*)/\sigma \sqrt{t^*}] \]
\[ = \text{Probability } [Z < (\ln(V_{i,0} / C_P) + \mu t^*) / \sigma \sqrt{t^*}] \]

Equation A2-34

The last step follows because the standard normal distribution of \( Z \) is symmetric, so that \( \text{Probability } [Z > -x] = \text{Probability } [Z < +x] \). Also, \( \ln(C_P / V_{i,0}) - \mu t^*) / \sigma \sqrt{t^*} \) may be thought of as the value of \( C_P \) when the normal distribution of \( \ln(V_{i,t} / V_{i,0}) \) is standardized to a unit normal distribution, as shown in Figure A2-1.

Since the distribution of \( Z \) is a standard normal distribution, by definition its probability density function is given by

\[ N'(x) = (1/\sqrt{2\pi}) \exp(-x^2/2) \]

Equation A2-35

and its cumulative probability function by

\[ N(x) = \int N'(x) \, dx = \int (1/\sqrt{2\pi}) \exp(-x^2/2) \, dx \quad \text{for } -\infty \leq Z \leq x \]

Equation A2-36

(Cox and Rubinstein 1985, pp 201-204). Equation A2-37 gives the probability that the standard normal random variable \( Z \) will be less than \( x \) -- that is, \( N(x) = \text{Probability } [Z < x] \). Thus Equation A2-34 can be re-stated in terms of the standard normal distribution:

\[ \phi = \text{Probability } [Z < (\ln(V_{i,0} / C_P) + \mu t^*) / \sigma \sqrt{t^*}] \]

\[ = N(\ln(V_{i,0} / C_P) + \mu t^*) / \sigma \sqrt{t^*}) \]

Equation A2-37

Since under risk-neutrality \( r = \alpha = (\mu + \sigma^2/2) \), or equivalently \( \mu = r - \sigma^2/2 \), Equation A2-37 can be written as

\[ \phi = N(\ln(V_{i,0} / C_P) + (r \sigma^2/2) t^*) / \sigma \sqrt{t^*}) \]

Equation A2-38

For notational convenience, define

\[ h = [\ln(V_{i,0} / C_P) + rt^* + (\sigma^2/2)t^*] / \sigma \sqrt{t^*} \]

Equation A2-39

Then Equation A2-38 can be written in the simplified form

\[ \phi = N(h - \sigma \sqrt{t^*}) \]

Equation A2-40

Next evaluate \( E[V_{i,t^*} | V_{i,t^*} \geq C_P] \phi \) of Equation A2-32, which is the expected value of \( V_{i,t^*} \) at \( t = t^* \), conditional on \( V_{i,t^*} \geq C_P \). By definition (Ross 1989, pp 39-40), the expected value of a continuous random variable is given by
\[ E[X] = \int x N'(x) \, dx \quad \text{for } -\infty \leq x \leq +\infty \]  

Equation A2-41

where \( N'(x) \) is the probability density function of the random variable as defined in Equation A2-35. In this case, we will only calculate the expected value of the continuous random variable \( V_{i,t^*} \) over the range of possible outcomes \( C_P \leq V_{i,t^*} \leq +\infty \) at \( t = t^* \), since we already know from Equation A2-32 that \( (C_{i,0})_{CV2} = 0 \) for the case of \( V_{i,t^*} < C_P \). Integrating from \( C_P \) to \( +\infty \) (and completing the square in the fourth and fifth lines below),

\[ E[V_{i,t^*} \mid V_{i,t^*} \geq C_P] \phi = \int x N'(x) \, dx \quad \text{for } C_P \leq (x = V_{i,t^*}) \leq +\infty \]

\[ = \int V_{i,t^*} (1/\sqrt{2\pi}) \exp(-x^2/2) \, dx \]

\[ = \int (V_{i,0}) [\exp(\mu t^* + \sigma Z \sqrt{t^*})] (1/\sqrt{2\pi}) \exp(-x^2/2) \, dx \]

\[ = \int (V_{i,0}) [\exp(\mu t^* + \sigma Z \sqrt{t^*}) + (-\sigma Z \sqrt{t^*} + \sigma^2 t^*/2)] \times (1/\sqrt{2\pi}) [\exp(-x^2/2 + ((2\sigma \sqrt{t^*})/2 - \sigma t^*/2)] \, dx \]

\[ = \int (V_{i,0}) [\exp(\mu t^* + \sigma^2 t^*/2)] (1/\sqrt{2\pi}) [\exp(-\sigma \sqrt{t^*} - x)^2/2] \, dx \]

\[ = V_{i,0} [\exp(\mu t^* + \sigma^2 t^*/2)] \int (1/\sqrt{2\pi}) [\exp(-\sigma \sqrt{t^*} - x)^2/2] \, dx, \]

\[ (h-\sigma \sqrt{t}) \leq x \leq +\infty \]

Equation A2-42

Imposing the risk-neutrality condition and expressing the integral as the cumulative probability of a standard normal distribution by introducing

\[ y = \sigma \sqrt{t} - x, \] 

Equation A2-42 becomes

\[ E[V_{i,t^*} \mid V_{i,t^*} \geq C_P] \phi = V_{i,0} e^{rt^*} \int (1/\sqrt{2\pi}) [\exp(-y^2/2)] \, dy, \quad -\infty \leq x \leq h \]

\[ = V_{i,0} e^{rt^*} N(h) \]

Equation A2-43

Finally, substituting this result and that of Equation A2-40 into Equation A2-32 for \( C_{i,0} \) gives

\[ C_{i,0} = e^{-rt^*} E[V_{i,t^*} \mid V_{i,t^*} \geq C_P] \phi - e^{-rt^*} C_P \phi \]

270
\[ = e^{rt} V_{i,0} e^{rt} N(h) - e^{-rt} C_P N(h - \sigma\sqrt{t}*) \]

\[ = V_{i,0} N(h) - e^{-rt} C_P N(h - \sigma\sqrt{t}*) \]  \hspace{1cm} \text{Equation A2-44}

This result can be more generally stated to give the value of the product development option at any time \(0 \leq t \leq t^*:\)

\[ C_{i,t} = V_{i,t} N(h) - e^{-r(t-t^*)} C_P N(h - \sigma\sqrt{t-t^*}) \]  \hspace{1cm} \text{Equation A2-45}

where

\[ h = \left[ \ln\left(\frac{V_{i,t}}{C_P}\right) + r(t-t^*) + \left(\frac{\sigma^2}{2}\right)(t-t^*)\right] / \sigma\sqrt{t-t^*} \]  \hspace{1cm} \text{Equation A2-46}

(Equations A2-44 and A2-45 are also reproduced as Equations 2-3 and 2-4 in Chapter 2.)

The value of \(C_{i,t}\) given in Equation A2-45 corresponds to the Black-Scholes formula (Black and Scholes 1973) for valuing a European call option

\[ C_t = S_t N(h) - K e^{rt} N(h - \sigma\sqrt{t}*) \]

where

(1) \(V_{i,0}\), the present value at \(t = 0\) of the uncertain revenue stream \(\{V_i\}\) has replaced the current stock price \(S_t;\)

(2) \(C_P\), the present value at \(t = t^*\) of the costs of production, has replaced the exercise price \(K;\) and

(3) \(h\) and \(h - \sigma\sqrt{t^*}\), the limits of the integrals giving the cumulative probabilities \(N(h)\) and \(N(h - \sigma\sqrt{t^*})\), are obtained from the standardized distribution of \(V_{i,t}\) instead of \(S_t.\)

It may also be useful to note that forming a portfolio which can be perfectly hedged against changes in the value of \(V_{i,t}\) in effect transforms the probabilities of the possible outcomes of \(V_{i,t^*}.\) The cumulative probabilities \(N(h)\) and \(N(h - \sigma\sqrt{t^*})\) result from these transformed probability distributions, as illustrated in Figure A2-2. Imposing the risk-neutrality condition causes a "shift" in the original distribution of \(V_{i,t^*}\) with mean \(V_{i,0} e^{\alpha t^*} = V_{i,0} \exp(\mu + \sigma_t \sigma^2 / 2)\).
\( \sigma^{2/2}t^* \) to a distribution of \( V_{i,t^*} \) with mean \( V_{i0} e^{rt^*} \). This transformation of the distribution of \( V_{i,t^*} \) also implies a transformation of the normal distribution of \( \ln(V_{i,t^*}/V_{i0}) \) from a distribution with a mean of \( \mu t^* \) to a transformed normal distribution with a mean of \( (r - \sigma^2/2)t^* \). The probability \( N(h - \sigma \sqrt{t^*}) \) corresponds to the probability that \( V_{i,t^*} \geq C_P \) when \( C_P \) is standardized to the value \( \ln(C_P/V_{i0}) - rt^* + \sigma^2/2 t^* / \sigma \sqrt{t^*} \) on the transformed normal distribution. Similarly, the probability \( N(h) \) corresponds to the probability that \( V_{i,t^*} \geq C_P \) when \( C_P \) is standardized to the value \( \ln(V_{i0} / C_P) + rt^* + (\sigma^2/2)t^* / \sigma \sqrt{t^*} \) on the transformed standard normal distribution of \( y = \sigma \sqrt{t} - x \).
Normal Distribution of $\ln(V_{i,t^*} / V_{i,0})$

Mean = $\mu_t^*$  

SD = $\sigma \sqrt{\Delta t}$

Standardized Normal Distribution of $\ln(V_{i,t^*} / V_{i,0})$

Mean = 0  

SD = 1

$\frac{(\ln(C_P/V_{i,0}) - \mu_t^*)}{\sigma \sqrt{t^*}}$

Figure A2-1: Standardizing the Normal Distribution of $\ln(V_{i,t^*} / V_{i,0})$
Figure A2-2: Transformed Probability Distributions for $V_{i,t^*}$ and $\ln(V_{i,t^*} / V_{i,0})$
Appendix A3

Program for Options Valuation of Lockheed 1011 Tristar Development Project
Note: Programmed on Theorist, Version 1.0 (Prescience Corporation)

These are the formulas used to value a product development option as a European call option:

\[ C = \left( V_0 e^{-\delta \tau} \right) N_1 - Ke^{-r \tau} N_2 \]

\[ N_1 = 0.5 + w \left\{ 0.5 - \frac{e^{-d_1 \frac{d_1}{2}}}{c_1} \left[ y_1 (c_2 + y_1 (c_3 + y_1 [c_4 + y_1 (c_5 + y_1 c_6)]))] \right] \right\} \]

\[ N_2 = 0.5 + w \left\{ 0.5 - \frac{e^{-d_2 \frac{d_2}{2}}}{c_1} \left[ y_2 (c_2 + y_2 (c_3 + y_2 [c_4 + y_2 (c_5 + y_2 c_6)]))] \right] \right\} \]

\[ d_1 = \frac{1}{\sigma \sqrt{\tau}} \left( \ln \left[ \frac{V_0}{K} \right] + \left[ r - \delta + \frac{\sigma^2}{2} \right] \tau \right) \]

\[ d_2 = d_1 - \sigma \sqrt{\tau} \]

\[ w = 1 \]

\[ c_1 = 2.5066 \]

\[ c_2 = 0.31938 \]

\[ c_3 = -0.35656 \]

\[ c_4 = 1.7815 \]

\[ c_5 = -1.8213 \]

\[ c_6 = 1.3303 \]

\[ y_1 = \frac{1}{1 + 0.23165w d_1} \]

\[ y_2 = \frac{1}{1 + 0.23165w d_2} \]
Following are expressions to be used in formulas for Lockheed 1011 product development option values (Chapter 2):

- $Y = Y_1 G^{-b}$
- $V_A = \sum_{t=A+1}^{T} nP \frac{1}{(1+k)^{t-A}}$
- $V_0 = V_A \frac{1}{(1+k)^A}$
- $K = \sum_{t=43}^{162} Y_1 \frac{(n[t-A])^{1-b} - (n[t-A-1])^{1-b}}{(1+k)^{t-A}}$

These variable values are constant for all Lockheed 1011 option cases evaluated:

- $Y_1 = 100$
- $k = 0.12$
- $k' = (1+k)^{12} - 1$
- $0.0094888 = 0.0094888$
- $r = 0.03$
- $P = 15$

These variables will have different assumed values in evaluating different Lockheed 1011 option cases:

- $b = 0.369$
- $T = 162$
- $A = 42$
- $\tau = \frac{A}{12}$
- $\delta = 0$
- $n = 3$
Appendix A4

A Method for Valuing the Option to Choose the m Maxima of M Risky Assets (m < M)

In deciding which products to develop, a production-constrained firm may often have to choose a limited number of developed products to put into production. However, the firm may want to have the flexibility to choose from a set of developed products that is larger than the number of products it could produce. To decide how many products to develop -- or in other words, how many production options to invest in creating -- the firm will need to know the value of the option to choose the m most valuable of M risky assets, where m is the maximum number of products it could produce and M is the number of new products the firm could develop and have available for production at some time in the future (m < M). To date, no analytic method has been developed to value this option, denoted here as \( \text{MAX}_{m,M,t} \).

It is possible to determine the value of \( \text{MAX}_{m,M,t} \) by forming a portfolio of options which will duplicate the payoffs to \( \text{MAX}_{m,M,t} \) in all states of the world. This appendix explains a technique for forming a duplicating portfolio for \( \text{MAX}_{m,M,t} \) and gives equations that define the contents of duplicating portfolios up to \( m \leq M \leq 7 \). Note that the method given here assumes that all individual product options have the same exercise price \( K \) (i.e., the same costs of production).

Begin by noting that both \( \text{MAX}_{1,2,t} \) and \( \text{MIN}_{1,2,t} \) have been valued by Stulz (1982) and \( \text{MAX}_{1,M,t} \) and \( \text{MIN}_{1,M,t} \) by Johnson (1987), all using equal exercise prices \( K \). Using these options valuations as basic building blocks, the option on the maximum 2 of 3 new products A, B, and C can be found by forming the duplicating portfolio of options

\[
\text{MAX}_{2,3,t}(A,B,C) = \text{MAX}_{1,2,t}(A,B) + \text{MAX}_{1,2,t}(B,C) + \text{MAX}_{1,2,t}(A,C) - \text{MAX}_{1,3,t}(A,B,C)
\]

Equation A4-1

(A comparable portfolio gives the value of \( \text{MIN}_{2,3,t}(A,B,C) \).) Terms on the
right hand side of Equation A4-1 with a positive sign represent options that
are held in the portfolio. The negative term option (- MAX_{1,3:t}(A,B,C)) is the
value of a written call and thus decreases the value of the portfolio. At the
exercise date, this portfolio will yield (M - 1) = 2 most valuable options, plus
(M - 2) = 1 second most valuable option, less one most valuable option, so that
the total yield is one each of the first and second most valuable options. Since
all options have the same exercise price K, the portfolio on the right-hand
side of Equation A4-1 duplicates the payoffs to MAX_{2,3:t}(A,B,C) for every
possible outcome of A, B, and C.

The portfolio defined by Equation A4-1 suggests a method for forming a
duplicating portfolio for the option to choose the two most (or least) valuable of
M risky assets for any number M: Form a portfolio of M options to choose the
single maximum of each of M non-duplicating combinations of M - 1 assets.
For example, for the M = 4 risky assets A, B, C, and D, the M = 4
nondupliicating combinations of A, B, C, and D are (A,B,C), (A,B,D),
(A,C,D), and (B,C,D). The payoff to these M = 4 options to choose the single
maximum of each nonduplicating combination will be M - 1 = 3 most
valuable assets and M - 3 = 1 second most valuable asset. To reduce the payoff
from these M options to a single most valuable option and a single
second-most-valuable option, reduce the portfolio by writing M - 2 = 2 call
options on the most valuable product. The result will always be a payoff
equivalent to MAX_{2,M:t}(A,B,C,...M).

In other words, for MAX_{2,4:t}

\[
MAX_{2,4:t}(A,B,C,D) = MAX_{1,3:t}(A,B,C) + MAX_{1,3:t}(B,C,D) \\
+ MAX_{1,3:t}(A,C,D) + MAX_{1,3:t}(A,B,D) \\
- 2 MAX_{1,3:t}(A,B,C,D)
\]

Equation A4-2

Similarly, for MAX_{2,5:t}

\[
MAX_{2,5:t}(A,B,C,D,E) = MAX_{1,4:t}(A,B,C,D) + MAX_{1,4:t}(B,C,D,E) \\
+ MAX_{1,4:t}(A,C,D,E) + MAX_{1,4:t}(A,B,D,E) \\
+ MAX_{1,4:t}(A,B,C,E) - 3 MAX_{1,5:t}(A,B,C,D,E)
\]

Equation A4-3
A general statement of the method for valuing an option on \( m = 2 \) maxima of \( M \) products is as follows. Let \( P_{-i} \) denote the set of \( M - 1 \) products which does not include the product \( P_i \). Then

\[
\text{MAX}_{2,M; t}(P_1, ..., P_M) = \sum \text{MAX}_{1,M-1; t}(P_{-i}) - (M - 2)\text{MAX}_{1,M; t}(P_{-i} \cup P_1 \cup ..., P_M)
\]

for \( i = 1, ..., M \)  \hspace{1cm} \text{Equation A4-4}

Equation A4-4 and a comparable duplicating portfolio for \( \text{MIN}_{2,5; t} \) can now be used as building blocks, singly or in combination with Stulz' and Johnson's building blocks, to value options on \( m \) maxima of \( M \) products, where \( m \geq 3 \).

For example, the option on the \( m = 3 \) maxima of \( M = 5 \) products, \( \text{MAX}_{3,5; t}(A, B, C, D, E) \), can be duplicated with this portfolio:

\[
\text{MAX}_{3,5; t}(A, B, C, D, E) = \sum C_{i,t} - \text{MIN}_{2,5; t}(A, B, C, D, E) \hspace{1cm} \text{Equation A4-5}
\]

for \( i = 1, ..., 5 \)

where \( C_{i,t} \) is the simple (European) call option on the \( i \)th product.

The method for finding \( \text{MAX}_{3,5; t}(A, B, C, D, E) \) above, while straightforward for this case, cannot be extended to value \( \text{MAX}_{3,M; t} \) for \( M > 5 \) so this equation cannot become a building block for solving higher level options. However, the method used to obtain Equation A4-4 can be extended to obtain a general valuation for \( \text{MAX}_{3,M; t}(A, B, C, D, E ... M) \) for \( M > 5 \), in the following way.

Form the set of \( M(M - 1) \) options on the single maximum of \( M - 2 \) nonduplicating combinations of products \( P_1, ..., P_M \), denoted by \( (P_{i \neq j}) \). The \( M(M - 1) \) options on the maximum of \( M - 2 \) nonduplicating combinations \( (P_{i \neq j}) \) will yield \( (M - 1)(M - 2) \) units of the single most valuable product, plus \( 2(M - 2) \) units of the second most valuable product, plus \( 2 \) units of the third most valuable asset. This portfolio can be corrected to duplicate the yield of \( \text{MAX}_{3,M; t}(P_1, ..., P_M) \) by writing calls on \( 2(M - 3) \) units of \( \text{MAX}_{2,M; t}(P_1, ..., P_M) \) and \( (M^2 - 5M + 6) \) units of \( \text{MAX}_{1,M; t}(P_1, ..., P_M) \) and then dividing the value of the entire portfolio by 2. A general statement of this approach is
\[ \text{MAX}_{3,M;t}(P_1 \ldots P_M) = \frac{1}{2} \left[ \sum \sum \text{MAX}_{1,M-2;t}(P_{x_i:x_j}) \right. \\
- 2(M - 3) \text{MAX}_{2,M;t}(P_1 \ldots P_M) \\
- (M^2 - 5M + 6) \text{MAX}_{1,M;t}(P_1 \ldots P_M) \left. \right] \]

for \( i = 1 \ldots M, \ j = 1 \ldots M \) \hspace{1cm} \text{Equation A4-6}

A similar portfolio defines \( \text{MIN}_{3,M;t}(P_1 \ldots P_M) \).

Using Equation A4-6 as a building block in combination with Equation A4-4 and the Stulz and Johnson building blocks, it is straightforward to value the option on any number of \( m \) maxima among \( M \) products, where \( m \leq 7 \) and \( M \leq 7 \). By using the above equations for \( \text{MIN}_{m,M;t}(P_1 \ldots P_M) \) for \( m = 1, 2, \) or \( 3 \), it is also possible to value an option the \( M - m \) maxima of any number of \( M \) products as well, in the manner of Equation A4-5.
Appendix A5


In the Pindyck (1988) model of optimal capacity choice, the firm faces converging input and output price functions. The output demand function is stochastic and specified as

\[ p_{i,t} = \theta(t) - \gamma q \]  \hspace{1cm} \text{Equation A5-1}

where \( \theta(t) \) is stochastic component of output price and moment-to-moment changes in \( \theta(t) \) are given by

\[ d\theta(t)/\theta(t) = \alpha_0 \theta(t) \, dt + \sigma_0 \, dz \]  \hspace{1cm} \text{Equation A5-2}

The expected rate of change \( \alpha_0 \) is assumed to be less than \( \alpha_{eq} \), the required rate of return for holding the production opportunity, with the result that there is a positive rate of asset value depreciation, \( \delta' > 0 \). (This source of asset value depreciation has an effect on options value comparable to the rate of competitive value erosion used in the model of product initiative options.)

All costs (other than for capacity) are variable costs and are deterministic. Total costs at any level of output \( q \) are given by

\[ C(q) = c_1 q + 1/2 c_2 q^2 \]  \hspace{1cm} \text{Equation A5-3}

Values of \( \gamma \) and \( c_2 \) are restricted to \( c_2 > 0 \) if \( \gamma = 0 \) and to \( \gamma > 0 \) if \( c_2 = 0 \). These restrictions assure that the input price function will be upward-sloping \( (c_2 > 0) \) if the firm is a price taker in output markets \( (\gamma = 0) \) and that the output price function will be downward-sloping \( (\gamma > 0) \) if the firm is a price-taker in input markets \( (c_2 = 0) \). Thus, the firm will always face converging input and output price functions, which in turn assures that there will always be a finite profit-maximizing output level for any random price which the firm observes.
To provide a reference case, the optimal capacity and output problem is first solved for the case of deterministic output price ($\sigma_0 = 0$). Let $c_K$ be the cost now of a unit of capacity, and let the risk-free interest rate for one production interval be $r'$. Because capital does not depreciate, the one-interval cost of having a unit of installed capacity is $r'c_K$. Since capacity is instantly installable and infinitely divisible, optimal capacity and optimal output will be identical, $q^* = K^*$, in the case of deterministic prices. The optimal initial capacity and (identical) optimal output level are the values $q^* = K^*$ that solve the maximization equation

$$\pi^* = \text{Maximize } [p_{i,t} q - C(q) - r'c_K K]$$

$$= \text{Maximize } [(\theta(t) - \gamma q)q - (c_1 q + 1/2 c_2 q^2) - r'c_K K]$$

$$= \text{Maximize } [\theta(t) q - \gamma q^2 - c_1 q - 1/2 c_2 q^2 - r'c_K K]$$

$$= \theta(t) q^* - \gamma q^*^2 - c_1 q^* - 1/2 c_2 q^*^2 - r'c_K q^*$$  \text{ Equation A5-4}

At the optimal capacity and output value $q^*$, $\partial \pi^*/\partial q = 0$ for infinitely divisible capital, so that

$$\theta(t) - 2 \gamma q^* - c_1 - c_2 q^* - r'c_K = 0$$

from which it follows that

$$q^* = (\theta(t) - c_1 - r'c_K)/(2 \gamma + c_2)$$  \text{ Equation A5-5}

After installing capacity $K^*$ and producing at optimal output level $q^*$ for one production interval, the firm will utilize its installed capacity to produce the optimal output $q^{**}$ appropriate to the next interval's price, so long as $q^{**} \leq K^*$. If the desired output level $q^{**}$ is greater than the installed capacity $K^*$, the firm must again decide whether to increase its capacity. If the firm's influence on output prices, represented by the factor $\gamma$, is treated as a component of variable cost, then from Equation A5-5 it follows that the firm's capacity decision for the next interval is to add capacity if and only if the new observed price

$$\theta(t + \Delta t) > q^{**} (2 \gamma + c_2) + c_1 + r'c_K$$  \text{ Equation A5-6}

Capacity should then be increased to $K^{**} = q^{**}$, where $K^{**}$ is determined by
the new observed price level,

$$K^{**} = (\theta(t + \Delta t) - c_1 - r'c_K) / (2 \gamma + c_2)$$  \hspace{1cm} \text{Equation A5-7}$$

The values of $q^*$ and $K^*$ for any deterministic $\theta(t)$, given by Equation 7-19, can now serve as reference values for assessing the impact on optimal output and capacity of introducing output price uncertainty.

The fundamental consequence of introducing uncertainty ($\sigma_0 > 0$) to the problem of optimal capacity choice when capital is irreversible is that the firm will now have a positive valuable option to wait to install capacity. The firm's value-maximization problem now is more involved than just maximizing the next period's profits, because with uncertainty installing a unit of capacity forfeits the potentially valuable option to wait to install capacity. Thus, with uncertainty the maximization problem is that given by Equation 5-14:

$$\text{Maximize } [(C_{i,m,t})^W + (C'_{i,m,t})^SD + (V_{i,m,t})^SD - C_K(K)].$$

Pindyck solves this maximization problem by first determining the two incremental component values $\Delta[I_{i,m,t}]^{\text{wait to produce}}$ and $\Delta[I_{i,m,t}]^{\text{produce}}$ which an installed unit of capacity would have. To make the result general and not just limited to capacity and output choice in the initial production interval, let the firm have previously installed capacity $K$, $0 < K < \infty$, and let the (undiscounted) net revenue expected from the incremental unit of capacity $(K + 1)$ during the production interval beginning at time $t = t_n$ be $\pi(t_n, K + 1)$. Since $r'c_KK$ is the fixed one-interval cost of installed non-depreciating capacity, the variable costs faced by the firm in using the $(K + 1)$th unit of installed capacity are just $(K + 1)(2 \gamma + c_2) + c_1$ (see Equation A5-6). Because the firm has the option to shut down whenever prices fall below variable costs, the (undiscounted) net payoff from the incremental unit of capacity $(K + 1)$ during the production interval beginning at time $t = t_n$ is

$$\pi(t_n, K + 1) = \text{Max } [0, \theta(t_n) - (K + 1)(2 \gamma + c_2) + c_1]$$  \hspace{1cm} \text{Equation A5-8}$$

The (undiscounted) expected value of the incremental unit of capacity over...
the life of the production project with the shut down option is therefore

\[ \sum \pi(t_n, K + 1) = \sum \text{Max} \left[ 0, \theta(t_n) - (K + 1) (2 \gamma + c_2) + c_1 \right] \quad \text{for } 0 \leq n \to \infty \]

Equation A5-9

When each interval’s payoff is discounted at the equilibrium rate of appreciation \( \delta' \),

\[ \Delta(V_{i,m,t})^{SD} = \sum \pi(t_n, K + 1) e^{-\delta'(t_n-t^*)} \quad \text{for } 0 \leq n \to \infty \]

Equation A5-10

With this statement of the payoff to having the \((K + 1)\)th incremental unit of capacity, Pindyck uses dynamic programming (see Pindyck 1988, Appendix) to solve for \((C'_{i,m,t})^{SD}\) and \((V_{i,m,t})^{SD}\). The value the \((K + 1)\)th unit of installed capacity will have depends on whether or not the capacity will be idle or utilized during the current production interval, which in turn depends on whether the stochastic price \(\theta(t)\) exceeds variable costs. If \(\theta(t) < q^*(2 \gamma + c_2) + c_1\), the \((K + 1)\)th unit of capacity will be idle and will contribute incremental value to the wait-to-produce component of the opportunity vector, \(\Delta(C'_{i,m,t})^{SD}\). When \(\theta(t) > q^*(2 \gamma + c_2) + c_1\), the unit of capacity will be utilized and will contribute incremental value to the production component, \(\Delta(V_{i,m,t})^{SD}\). When \(\theta(t) = q^*(2 \gamma + c_2) + c_1\), the two values will be identical:

\[ \Delta(C'_{i,m,t})^{SD} = \Delta(V_{i,m,t})^{SD} \]

The values of \(\Delta(C'_{i,m,t})^{SD}\) and \(\Delta(V_{i,m,t})^{SD}\) derived by Pindyck are

\[ \Delta(C'_{i,m,t})^{SD} = b_1[\theta(t)]^{\beta_1} \quad \text{for } \theta(t) \leq (K + 1) (2 \gamma + c_2) + c_1 \]

Equation A5-11

\[ \Delta(V_{i,m,t})^{SD} = b_2[\theta(t)]^{\beta_2} + \theta(t)/\delta' - [(K + 1)(2 \gamma + c_2) + c_1]/r \]

\[ \quad \text{for } \theta(t) \geq (K + 1) (2 \gamma + c_2) + c_1 \]

Equation A5-12

where
\[ \beta_1 = \frac{(r - \delta - \sigma_0^2/2)/\sigma_0^2 + (1/\sigma_0^2)\left[(r - \delta - \sigma_0^2/2)^2 + 2r\sigma_0^2\right]^{1/2}}{\sigma_0^2} > 1 \]

Equation A5-13

\[ \beta_2 = \frac{(r - \delta - \sigma_0^2/2)/\sigma_0^2 - (1/\sigma_0^2)\left[(r - \delta - \sigma_0^2/2)^2 + 2r\sigma_0^2\right]^{1/2}}{\sigma_0^2} < 0 \]

Equation A5-14

\[ b_1 = \frac{\left[(r - \beta_2 (r - \delta')) / (r\delta'\beta_1 - \beta_2)\right]}{(2 \gamma + c_2)K + c_1} \left[(2 \gamma + c_2)K + c_1\right]^{-\beta_1} > 0 \]

Equation A5-15

\[ b_2 = \frac{\left[(r - \beta_1 (r - \delta')) / (r\delta'\beta_1 - \beta_2)\right]}{(2 \gamma + c_2)K + c_1} \left[(2 \gamma + c_2)K + c_1\right]^{-\beta_2} > 0 \]

Equation A5-16

Under the assumption that production will proceed *ad infinitum*, Pindyck values revenue and cost cash flows as perpetuities in Equation A5-12 discounting the cost stream at the riskless rate \( r \) and revenue stream at the equilibrium rate of appreciation \( \delta' \). When the revenue stream and cost stream from the \((K + 1)\)th unit of capacity are valued as if they are never interrupted (*i.e.*, as perpetuities), the expression \( \theta(t)/\delta' - [(K + 1) (2 \gamma + c_2) + c_1]/r \) is the present value of a production project which will continue to produce whether prices exceed variable costs or not. Thus, the expression \( b_2[\theta(t)]^{\beta_2} \) in Equation A5-12 gives the value of the option to shut down production of the \((K + 1)\)th unit of capacity whenever prices fall below variable costs. Similarly, the expression \( b_1[\theta(t)]^{\beta_1} \) in Equation A5-11 gives the value of the option to put an idle \((K + 1)\)th unit of capacity into production whenever prices exceed variable costs.

Pindyck next values the incremental value of the uninstalled \((K + 1)\)th unit of capacity, \( \Delta(C_{i,m,t})^W \). The \((K + 1)\)th unit of capacity will remain uninstalled until the observed price \( \theta(t) \) reaches a critical value \( \theta^*(t,K) \) at which the value-maximizing firm will install the \((K + 1)\)th unit of capacity. Thus, for \( \theta(t) < \theta^*(t,K) \),

\[ \Delta(C_{i,m,t})^W = a[\theta(t)]^{\beta_1} \quad \text{for} \; \theta(t) < \theta^*(t,K) \]

Equation A5-17
where
\[
a = [\beta_2 b_2 (\theta^*(t,K) (\beta_2 \cdot \beta_1)) / \beta_1 + [(\theta^*(t,K)(1- \beta_1) / \delta \beta_1)] > 0
\]
Equation A5-18

and \(\theta^*(t,K)\) is the solution to
\[
[b_2 (\beta_1 - \beta_2) (\theta^*(t,K)^{\beta_2}) / \beta_2 + [(\beta_1 - 1) (\theta^*(t,K))] / \delta \beta_1
- [(2 \gamma + c_2)K + c_1] / r - c_K = 0
\]
Equation A5-19

When \(\theta(t) \geq \theta^*(t,K)\), it will be optimal for the firm to install the \((K + 1)\)th unit of capacity by paying the cost of the \((K + 1)\)th unit of capacity and converting the option to install to an installed unit of capacity, which may or may not be utilized in the first production interval. Thus when \(\theta(t) \geq \theta^*(t,K)\),
\[
\Delta(C_{i,m,t})^W = \text{Max} \{\Delta(C'_{i,m,t})^{SD} - \Delta c_K(\Delta K), (\Delta(V_{i,m,t})^{SD} - \Delta c_K(\Delta K)\}
\]
for \(\theta(t) \geq \theta^*(t,K)\)
Equation A5-20

Once \(\Delta(C_{i,m,t})^W, \Delta(C'_{i,m,t})^{SD}, \Delta(V_{i,m,t})^{SD},\) and \(\Delta c_K(\Delta K)\) are determined in this manner, the capacity amount can be increased until
\[
\Delta(C_{i,m,t})^W + \Delta(C'_{i,m,t})^{SD} + \Delta(V_{i,m,t})^{SD} - \Delta c_K(\Delta K) = 0
\]
Equation A5-21
at which capacity level the value of the opportunity vector
\[
OV_{i,m,t} = [ (C_{i,m,t})^W + (C'_{i,m,t})^W + (V_{i,m,t})^{SD} - C_K(K) ]
\]
Equation A5-22
will be maximized. Pindyck performs this calculation and obtains the following equation which governs the value of the optimal capacity, \(K^*\), for any observed price \(\theta(t)\):
\[
[1/\delta \beta_1] [r - \beta_1 (r - \delta')] [\theta(t)]^{\beta_2} [(2 \gamma + c_2)K^* + c_1]^{(1- \beta_1)}
- [(2 \gamma + c_2)K^* + c_1] / r + [(\beta_1 - 1) (\theta(t))] / \delta \beta_1 - c_K = 0
\]
Equation A5-23
Appendix A6

Application of Majd and Pindyck (1987) Analysis of Time-to-Build to Product Initiative Options

Majd and Pindyck make several simplifying assumptions which both reduce the complexity of the development implementation option valuation problem and allow them to focus on the impact of speed of development (the inverse of "time to build") on the value of a development project. Their key assumptions are (a) that all development costs are variable, but irreversible, (b) that starting up and shutting down development are costless and can be done instantly, and (c) that once development is completed, production will begin immediately without options to shut down or abandon. Given these assumptions, there would be no value to being in a ready-to-develop state, and the firm will move directly between \([\text{OV}^{D}_{i, m, t}]^{\text{wait to invest}}\) and \([\text{OV}^{D}_{i, m, t}]^{\text{develop}}\). In addition, the firm would also develop at the maximum possible rate (i.e., at full development capacity) or will completely shut down development. Finally, the two possible states of wait-to-invest and active development will have the simplified options values:

\[
[\text{OV}^{D}_{i, m, t}]^{\text{wait to invest}} = (CD_{i, m, t})^{SD}
\]

Equation A6-1

and

\[
[\text{OV}^{D}_{i, m, t}]^{\text{develop}} = V_{i, m, t} - C_{D}(t_k) - C_{P}(t_k)
\]

Equation A6-2

where Equation 7-41 follows from Equation 6-43, and \(t_k\) is the beginning of the \(k\)th development interval during the development period.

The decision rule which gives the optimal development strategy for the firm in this case is to actively develop during the \(k\)th development interval when

\[
[\text{OV}^{D}_{i, m, t}]^{\text{develop}} > [\text{OV}^{D}_{i, m, t}]^{\text{wait to invest}}
\]

\[
V_{i, m, t} - C_{D}(t_k) - C_{P}(t_k) > (CD_{i, m, t})^{SD}
\]

Equation A6-3

Thus, in order for active development of a new product over the next interval to be optimal, the present value of the expected revenue stream from producing the new product must exceed the present values of remaining
development costs and all production costs by the value of the forfeited option to shut down development. Defining this threshold value of the revenue stream as \( V^{\Delta_{i,m,t}} \),

\[
V^{\Delta_{i,m,t}} \geq (CD^\text{i,m,t})^{\text{SD}} + C_D(t_k) + C_P(t_k) \quad \text{Equation A6-4}
\]

Majd and Pindyck obtain an analytic solution to the simplified development option of Equation 7-40:

\[
(CD^\text{i,m,t})^{\text{SD}} = a(V^\text{i,m,t})^\alpha \quad \text{Equation A6-5}
\]

where

\[
\alpha = \left[ - (r - \delta' - \sigma_v^2/2) + \left[ (r - \delta' - \sigma_v^2/2)^2 + 2r\sigma_v^2 \right]^{1/2} / \sigma_v^2 \right] \quad \text{Equation A6-6}
\]

The value of coefficient \( a \) in Equation 7-44 must be solved for jointly with the threshold value \( V^{\Delta_{i,m,t}} \) and requires numerical methods.

Adapting \( t' \in \text{Majd and Pindyck} \) numerical example to the model of product development, Figure A6-1 shows how the threshold net project value if it were available for production now (i.e., \( V''^{\Delta_{i,m,t}} - C_P(t_k) \)) would vary with the rate of value erosion \( \delta \) for two different maximum possible speeds of development: completion in 12 years vs. completion in 3 years. For \( \delta = 0 \), development will never begin because \( V_{i,m,t} \) will not depreciate in market value if the firm waits to develop and the firm can capture all of the unexpected increases in \( V_{i,m,t} \) by just holding the development option (assuming no organization costs of keeping the option alive). For low values, \( 0 < \delta \leq 0.02 \), threshold values remain high for both slow and fast development speeds. As \( \delta \) increases, however, the threshold value of the slow development (12-year) project increases rapidly, because much of the project's market value will have depreciated by the completion of development. The fast development (3-year) project has a relatively low threshold value over a broad range of \( \delta \), only beginning to rise steeply when \( \delta' = 0.13 \).

The impact of development speed on the value of a development opportunity for which \( \delta = 0.06 \) (assumed to be a typical project value) is shown in Figure A6-2. If the new product could be developed instantly, the value of
the project to produce the new product would be $15 million. As the time required to develop the new product increases, the value of the development opportunity decreases. In this example, doubling development time from 3 years to 6 years, for example, decreases the value of the new product opportunity by about 30% from $6.85 million to $4.75 million. Alternatively, one could say that doubling the speed of development increased the value of the new product opportunity by about 45%.
Threshold Net Production Project Value
(if production could begin immediately)

($ million)

Time to Develop = 12 years

Time to Develop = 3 years

\[ \delta' \]

Project Parameters:

Total Development Cost = $6 million (nominal dollars)

Risk-free Interest Rate \( r = 0.02 \)

\( \sigma_v = 0.20 \)

Figure A6-1: Change in Threshold Project Value with \( \delta \) for Two Development Speeds

(Source: Majd and Pindyck 1987, page 22)
Net Present Value of New Product Development Opportunity ($ million)

Limit of Project Value (with Zero Time to Develop)

Value of Speed

Maximum Rate of Investment: 1.0  2.0  3.0 $ million/year
(Time Needed for Development: 6  3  2 years)

Project Parameters:
Total Development Cost = $6 million (nominal dollars)
Risk-free Interest Rate $r = 0.02$
$\sigma_v = 0.20 \quad \delta = 0.06$

Figure A6-2: Change in Net Present Value of Development Opportunity with Increase in Development Speed
(Source: Majd and Pindyck 1987, page 24)
Appendix A7

Program for Options Valuation of Lockheed 1011 Tristar Development Project
with Two Additional Leveraged Models (Chapter 8)
a Variable named C behaves as defined by user

Note: Programmed on Theorist, Version 1.0 (Prescience Corporation)

These are the formulas used to value a product development option as a European call option:

\[ C = \left(V_0 e^{-\delta \tau}N_1 - Ke^{-r \tau}N_2\right) \]

\[ N_1 = 0.5 + w \left\{ \frac{-d_1 d_1}{2} \left[ y_1 (c_2 + y_1 (c_3 + y_1 [c_4 + y_1 (c_5 + y_1 c_6)])) \right] \right\} \]

\[ N_2 = 0.5 + w \left\{ \frac{-d_2 d_2}{2} \left[ y_2 (c_2 + y_2 (c_3 + y_2 [c_4 + y_2 (c_5 + y_2 c_6)])) \right] \right\} \]

\[ d_1 = \frac{1}{\sigma \sqrt{\tau}} \left( \ln \left[ \frac{V_0}{K} \right] + \left[ r - \delta + \frac{\sigma^2}{2} \right] \tau \right) \]

\[ d_2 = d_1 - \sigma \sqrt{\tau} \]

\[ w = 1 \]

\[ c_1 = 2.5066 \]

\[ c_2 = 0.31938 \]

\[ c_3 = -0.35656 \]

\[ c_4 = 1.7815 \]

\[ c_5 = -1.8213 \]

\[ c_6 = 1.3303 \]

\[ y_1 = \frac{1}{1 + 0.23165 w d_1} \]

\[ y_2 = \frac{1}{1 + 0.23165 w d_2} \]

Following are formulas for valuing the Lockheed 1011 Tristar product development project with additional leveraged product model options:

\[ Y = Y_1 Q^{-b} \]

\[ 26.384 = 26.384 \]

\[ V_A = \sum_{t=49}^{T} nP \frac{1}{(1 + k')^{t-A}} + \sum_{t=55}^{T} n'P \frac{1}{(1 + k')^{t-A}} \]

\[ 6092.3 = 6092.3 \]
\[ V_0 = V_A \frac{1}{(1+k)^A} \]
\[ K = \sum_{t=43}^{T} Y_1 \frac{(n[t-A])^{1-b} - (n[t-A-1])^{1-b}}{(1+k)^{t-A}} + \sum_{t=55}^{T} Y_{37} \frac{(n'[t-A])^{1-b} - (n'[t-A-1])^{1-b}}{(1+k)^{t-A}} \]
\[ C = (4097.5e^{-0.5\tau})N_1 - 3716.4e^{-r\tau}N_2 \]
\[ d_1 = \frac{1}{\sigma\sqrt{\tau}} \left( \ln \left( \frac{4097.5}{3716.4} \right) + \left[ r - \delta + \frac{\sigma^2}{2} \right] \tau \right) \]

**These variable values are constant for all Lockheed 1011 option cases evaluated:**

- \( Y_1 = 100 \)
- \( Y_{37} = 26.384 \)
- \( k = 0.12 \)

\[ k' = (1+k)^{12} - 1 \]
\[ 0.0094888 = 0.0094888 \]
\[ r = 0.03 \]
\[ P = 15 \]

**These variables will have different assumed values in evaluating different Lockheed 1011 option cases:**

- \( b = 0.369 \)
- \( T = A + 120 \)
- \( A = 42 \)

- \( \tau = \frac{A}{12} \)
- \( \delta = 0.06 \)
- \( n = 4 \)
- \( n' = 2 \)
- \( \sigma = 0.5 \)
- \( Q = 37 \)
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