Improving the Valuation of Research and Development: A Composite of Real Options, Decision Analysis and Benefit Valuation Frameworks

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ABSTRACT

The objective of research and development (R&D) is to create valuable complements to the existing capabilities of the firm. Unfortunately, valuing R&D is difficult because it is an uncertain and sequential process that often yields complex benefits such as simultaneous cost and performance improvements. These characteristics obscure important sources of value from common valuation methods such as net present value analysis (NPV).

This thesis examines methodologies that have been singularly applied to evaluate R&D, and combines several into a composite framework as improved approach to valuing R&D. It focuses on valuing opportunities to revise R&D projects in response to uncertainty resolution, better matching valuation frameworks to project uncertainties, and integrating methods for valuing complex benefits with financial valuation frameworks.

The composite methodology includes a financial valuation model that combines real options and decision analysis to resolve the difficulty of valuing option-like decision opportunities in R&D projects. This model is applicable across a range of project uncertainties. Multi-metric valuation methods and scenario analyses can transform complex benefits into dollar values that are compatible with the financial valuation model.

A case study based on an automotive producer's investments in advanced materials R&D demonstrates the composite methodology. It also compares several valuation models including real options, decision analysis, NPV, and a weighted benefits index.

The thesis demonstrates that R&D is significantly more valuable than common valuation methods suggest. In particular, it provides a legitimate basis for quantifying in dollars the appreciable strategic value of long-term, high-risk R&D efforts that frequently appear unattractive on an NPV basis. It also identifies conditions under which various methods for valuing projects are applicable, and highlights resolution and practicality trade-offs associated with these valuation frameworks.

Thesis Supervisor: Joel P. Clark
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Chapter 1: Introduction

Research and development (R&D) is difficult to value because it is an uncertain and complex undertaking. Generally, R&D aims to create technical capabilities to enable product features that satisfy end-user needs. However, uncertainty makes it hard to envision the exact sequence of steps (and costs) that will translate technology into product. To compound the problem, technology often yields complex sets of technical and economic benefits. The revenues that an innovator generates from a technology depend on how end-users value these benefits and a variety of competitiveness issues. Consequently, estimating the value of R&D investments is hardly ever a straightforward exercise.

The difficulty of valuing R&D is most apparent when potential uses of a technology are not obvious. First, a lack of identifiable target markets practically renders the estimation of potential revenues impossible. More importantly, uncertainty is amplified because the development agenda is not informed by end-user needs. Therefore, it is not clear if specific investigations could yield anything of value. As a result, it is hard to gauge if such a technology is promising, or when it might be commercially viable, let alone assess its value.

For example, when the laser was first developed, lawyers at Bell Laboratories were hesitant to apply for a patent because the invention appeared to have no relevance to the telephone industry. Presumably it was not valuable to the company. [Rosenberg, 1994] Today, the proposition that the laser had limited value seems absurd, given its ubiquity in applications ranging from compact disc players, medical instruments, scanning equipment, printing and telecommunications. Such is the power of hindsight.

Not surprisingly, myopic insight with respect to basic technology is common. IBM initially believed that there would be no commercial demand for computers. [Freeman, 1989] Xerox invented the personal computer and failed to capitalize on it. [Smith 1988] Western Union (the telegraph company) turned down the opportunity to license the telephone patent for a modest sum. [Rosenberg, 1994] In these cases and many others, uncertainty and the lack of obvious applications clouded the true value of key innovations.
DIFFICULTIES OF VALUING APPLIED R&D

Although uncertainty regarding uses of a technology is reduced as R&D becomes more applied, valuing these investments is still difficult. First, significant technical, implementation and market related uncertainties remain. Therefore, the potential for failure is real and the sequence and timing of events required to bring the technology to market is unclear. Second, estimating the value of project benefits remains difficult because end-users often make complex trade-offs between product features, and the revenue that the innovator will generate is likely to fall short of the value that the end-users place on the technical advancements.

Uncertainty and the Sequential Nature of R&D

R&D is regarded as a risky activity because the results and value of R&D investments are uncertain. However, R&D is also sequential in nature, and many risks are mitigated simply by making informed decisions over time as uncertainty is resolved. This does not mean that R&D is a riskless activity, but the ability to react over the life of a project does influence the risk profile and the value of R&D projects.

Active management allows promising R&D efforts to receive continued attention while less promising projects are culled from the portfolio. As a result, the actual costs and payoffs of R&D are asymmetric. Decisions to continue investing are made when the benefit of doing so is expected to outweigh the expense. Repetition of the decision process continually crops away outcomes that are unfavorable. Therefore, the expected cash-flows of an R&D project may not be at all representative of the actual value of the project. R&D derives much of its value from the sequence of incremental steps that the resolution of uncertainty stimulates.

The ability to manage projects actively has recently received significant attention because making opportunistic decisions over the life of a project yields a payoff structure that is similar to investments such as stock options. [Luehrman 1997, Trigeorgis 1996, Dixit and Pindyck 1994] An option provides the right to buy or sell an asset, such as a stock, for
a predetermined price, sometime in the future. The holder of the option is not obligated to
exercise this right, and will act only when it is opportunistic. Therefore, the decision to
exercise an option strongly resembles real life choices such as deciding to implement a
promising technology in a commercial application. Since special valuation frameworks are
required to value options properly, it is possible that applying these frameworks to real
projects will reveal useful insights regarding project value. The term real options refers to
this use of financial options models.

Other frameworks are also potentially useful for investigating the sequential nature of
R&D. Decision analysis in particular has a rich history of examining the value that
contingent decisions add to real projects. [Schmidt and Freeland 1992] While there are
some distinct technical differences between real options methods and the decision analysis
approach to valuing options, both recognize practical importance of decision opportunities.

Translating (Complex) Benefits to Estimates of Revenue

Another difficulty of valuing R&D stems from the effort required to translate the
project benefits into estimates of revenue that can be compared with the costs of conducting
the project. For any application of a technology, two major steps are required. First, the
value of the benefits of the technology to the end-user must be assessed. Then, the portion
of this value that the innovator will capture in the form of revenues must be estimated.

Estimating the value of project benefits to the end-user is particularly problematic
when technology yields complex benefits such as simultaneous changes in several technical
features of a product. In such cases, the subjective tastes of end-users determine the value
of the technology. It is often hard to assess these tastes directly. Instead, some mechanism
for considering the complex value trade-offs that end-user make is needed.

Even if technology yields easily estimated financial benefits, such as a cost reduction
or efficiency improvement, other factors influence the total value of the technology to the
end-user and thereby the maximum price that they are willing to pay. These include the
availability of alternatives and switching costs. For example, structural ceramics offer
potentially unparalleled performance characteristics in automotive and electronic applications. In automotive engine uses, the premium that producers are willing to pay for this performance is often small because other materials are usually satisfactory. [Mangin, 1993] In contrast, ceramics command significant price premiums in many electronic applications because few alternatives exist. [Neely, 1992]

Switching costs also influence how much end-users will pay for a technology. For example, a technology that requires investments in new equipment may be less attractive to end-users with established plants, compared to investors who are considering greenfield options. Hesitation to incur these costs influences the rate of technology adoption. Fisher and Pry (1971) and Tincher (1992) show that substitution horizons in excess of twenty years are common in the materials industry. During this time, suppliers either become more efficient and offer the product at a price that is increasingly attractive to more end-users, or the value of the technology increases due to incremental improvements or changing end-use market dynamics. Combinations of these drivers are also possible.

Regardless of how end-users value the benefits of a technology, estimating the revenues that an innovator will receive remains difficult. Simply multiplying the size of a market for a technology by an estimate of the value of the technology to an end-user is not usually sufficient. The scale of a target market is obviously important. It defines quantities of product that end-users might be willing to purchase. However, Teece (1986) notes that the innovator will usually capture less than the full value of the technology. Other parties in the value chain, such as suppliers, end-users and intermediaries, split the remainder.

The fraction of technology value that the innovator captures is the appropriable value of the technology. Factors that influence appropriability include the relative strength of competitors, suppliers and customers. [Collis and Montgomery 1997, Porter, 1980] The combination of these influences determines what price end-users will actually pay for a technology. In many cases, end-users benefit by getting a choice of technologies at prices that are lower than the maximum that they are willing to pay. For example, competitors may
retaliate against new technologies with price cuts or increased R&D of their own. [Cooper and Schendel 1976] Similarly, a supplier with strong control of distribution channels to a market can often appropriate some of the value of innovations. [Teece 1986]

Despite these difficulties of valuing R&D investments, significant pressure to do so exists. Although technology is a key source of competitive advantage in many industries, efficient investing is critical because resources for conducting R&D are limited. While the level of commitment might vary by firm and industry, most R&D managers end up making difficult choices because the number of potentially promising projects exceeds the organizational capacity or will to invest. [IRI 1997, Whiteley, Bean and Russo 1997] Therefore, some estimate of technology value frequently plays a crucial role in the project selection process, as organizations struggle to identify the most promising opportunities.

OBJECTIVE STATEMENT AND THESIS OUTLINE

This thesis aims to improve upon current R&D valuation practice by addressing difficulties caused by uncertainty, the sequential nature of R&D, and the complexity of valuing project benefits. It focuses on:

- valuing opportunities to revise R&D projects in response to uncertainty resolution;
- better matching valuation frameworks to project uncertainties (risks);
- integrating methods for valuing complex benefits with financial valuation frameworks.

Common methods that work well for evaluating other types of investments, including net present value (NPV) and portfolio matrices, systematically overlook or trivialize one or more of these issues. The net result is information losses that lead to distortions in estimates of R&D value. In many cases, R&D is more valuable than these frameworks suggest.

To address these issues, this thesis develops and demonstrates a methodology that addresses the difficulties of valuing R&D that other frameworks cannot consider sufficiently. The methodology is a composite of assessment frameworks with promising characteristics. First, real options and decision analysis models are applied to value R&D projects that can
be revised based on findings or changing firm needs. Further, the mix of real options and
decision analysis varies to accommodate a wide range of project risk characteristics. Finally,
multi-metric valuation models are used to help value projects with complex benefit streams
such as simultaneous cost and performance improvements.

The result is a better metric of project value that shows promise for increasing the
returns on portfolios of R&D investments by helping to identify the most promising
investments. While value is not necessarily the only useful metric for judging a project, it is
often an important consideration. [Hauser and Zettelmeyer, 1996] The value metric
developed in this work can be applied on a stand-alone basis to enable more meaningful
comparisons of projects across the R&D spectrum. It could also be combined with other
metrics as part of an overall R&D management and planning process. However, the
improved metric of value shows promise for reducing the need to rely on supplemental
metrics because it better expresses the value of projects that are currently difficult to value.

More importantly, the proposed valuation methodology uses a tangible, credible,
dollar basis for demonstrating that the value of many R&D investments is significantly
greater than common methods indicate. This is especially true for longer-range projects that
tend to have negative net present values (NPVs), but are funded because they are
"strategic." The options perspective helps to quantify this strategic value and justify it, and
the methods for valuing complex benefits show promise for better expressing the value of
capabilities based investments in financial terms. Therefore, the methodology does not just
provide a better metric of value. It yields a basis for comparing R&D investments with other
firm-wide investments and demonstrating that regardless of the uncertainty, R&D is an
extremely valuable pursuit because it has an options-like structure.

This thesis is divided into eight chapters. Chapter 2 sets the context for the work by
exploring the objective of R&D, the role of financial value in project management, and the
difficulties that common R&D valuation approaches encounter.
The next three chapters identify methods that show promise for addressing the R&D valuation difficulties that Chapter 2 identifies. First, Chapter 3 reviews financial valuation methods including net present value (NPV), decision analysis and real options. It examines the ability of each method to value contingencies that can comprise much of a R&D project's value. Next, Chapter 4 examines the types of uncertainty that influence the value of R&D and the ability of financial valuation models to address these uncertainties. It develops a framework which suggests that most R&D valuation problems can be treated using a combination of real options and decision analysis. Then, Chapter 5 details the mechanics of adapting multi-metric valuation models to place a financial value on complex R&D benefit steams. These models can be used in conjunction with the financial valuation frameworks in cases where it is difficult to quantify the dollar value of R&D benefits directly.

Chapter 6 introduces the composite R&D valuation methodology that this thesis develops. This methodology combines financial and multi-metric valuation models to create a framework that improves upon current valuation practice by better addressing R&D contingencies, the wide-range of R&D uncertainties, and complex benefits streams that R&D often yields. Chapter 6 addresses three major topics. First, it describes the steps in the methodology. Second, it provides a detailed procedure for structuring the components of the methodology and valuing projects. Finally, it introduces the specific forms of valuation models that this thesis uses to value a portfolio of materials R&D investments.

The case study in Chapter 7 uses a portfolio R&D projects which is based on a major automotive producer's investments in advanced materials technologies to demonstrate the practicality of applying the valuation framework. A comparative analysis of valuation frameworks, including the composite methodology that this thesis develops, demonstrates conditions under which each approach serves as a useful signaling device for guiding investment decisions. Chapter 8 summarizes the findings, notes limitations of the methodology and suggests opportunities for continuing research both within and beyond the R&D function.
Chapter 2: The Role of Project Value in R&D Management

Chapter 1 suggests that R&D is difficult to value because it is an uncertain, sequential undertaking that yields benefits that are not easily translated into estimates of revenue. Chapter 2 builds on these points and sets the context for this thesis by defining critical issues that a comprehensive metric of R&D value should consider if it is to be a useful component of a decision-making system. Specifically, Chapter 2 explores the complementary role of R&D, the current role of financial valuation in R&D management, and difficulties that common valuation methodologies face when applied to R&D investments. The remainder of this thesis focuses on developing and applying a methodology that addresses the issues that Chapter 2 defines. Although this work is mainly concerned with corporate and other privately funded efforts, many of the lessons learned could apply to public R&D spending decisions.

THE OBJECTIVE OF R&D: CREATING VALUABLE COMPLEMENTS

The basic goal of research and development is to create tremendous value, and the value that successful innovations produce is significant. Mansfield (1980) is well known for noting the powerful role R&D plays in generating wealth. In slight contrast, Kealey (1996) suggests that R&D expenditures are indicative of economies that were a priori better structured to encourage and utilize innovation, rather than being the direct cause of success. He does not deny the value R&D creates, but challenges the Baconian assumption that simply funding basic science guarantees spillover economic benefits. While this cause and effect relationship is important to both public and private policy decisions, the bottom line is that innovation plays a crucial role in the success of corporations and industrialized nations. In fact, Lucier, Moeller and Held (1997) find that innovation is the only factor which separates the best long-term performing firms from laggards.

Unfortunately, the process of selecting and guiding research and development projects is not so simple because R&D spans a wide range of short and long-term activities with different characteristics. Each of these tasks entails different timeframes and resource
requirements. Additionally, the benefits of different R&D activities may accrue as easily measured dollar returns, complex sets of technical advances or intangible capabilities.

However, these disparate R&D tasks are still ultimately aimed at creating value. Therefore, the true complexity of valuing R&D stems from the need to value a range of investments with differing characteristics.

Furthermore, the span of R&D activities signals another critical part of the R&D objective. The simultaneous pursuit of short and long-term activities attempts to provide a firm with technology that meets future needs under a range of potential outcomes. Short-term investments typically aim to satisfy the needs of existing businesses. Longer-term investments tend to create technology that addresses the path the firm expects to follow in the future and provide hedges against unexpected deviations from this path.

Thus, the range of R&D activities reflects a need to create complements to the existing capabilities of the firm, across a wide range of potential future outcomes. Complementarity is important for at least two reasons. From the perspective of the R&D function, creating complements fills gaps in the capabilities of the firm. From the perspective of the firm, technology that is complementary to existing capabilities is more readily converted into commercial innovations.

Therefore, the objective of R&D is to create value by developing technologies which complement the existing capabilities of the firm. As a result, it is not surprising that Baconian assumption that simply funding unbridled research explorations will always yield valuable innovations has been thoroughly discredited. Such a policy ignores the complements issue entirely. In contrast, reviews of best practice in R&D suggest that successful companies formulate a clear and integrated understanding of their overall business strategy and link appropriate supportive technology strategies to it. [Adler, McDonald, MacDonald 1992, Chester, 1994, Foster, Linden, Whitely and Kantrow 1985, Foster, 1996, Braunstein and Salsamendi, 1994] These strategies work because the role of complements is explicitly treated in the management of R&D funding.
For near term R&D, the complementary link between business and technology strategy is most obvious. For example, Goodman and Lawless (1994) suggest that R&D for direct product and process support is fundamentally concerned with creating information barriers that allow a firm to outperform its competitors. Therefore, a chemical manufacturer that follows a low cost producer strategy should invest in process developments that will be difficult and time consuming for a competitor to imitate. [Porter 1980, Hayes and Wheelwright 1984] In contrast, a product leader in the same industry should emphasize technology advances that will keep it on the frontier of functionality offered to the end-user. [Freeman 1989]

A firm that fails to align business and technology strategies has little grounding for making targeted R&D decisions. Serendipity may lead to success, but aimless drifting is a more realistic outcome. Not surprisingly, Roberts (1991) finds that a major determinant of new venture success is a cross-disciplinary management team that channels technology development to support a well-developed business strategy.

For longer-term R&D efforts, links between business and technology strategies might be less obvious, but the objective is still to create valuable complements. Unfortunately, the tendency of firms to mis-diagnose the importance of new technologies is widely documented. [Utterback 1994, Foster 1986] This results in part because the benefits of longer-term efforts are more complex or intangible, and there is greater overall uncertainty.

The capabilities of the R&D organization also become an increasingly important complement that allows a firm to identify important, long-term investments. Consider R&D that aims to identify and create new opportunities. The Edisonian approach of trying everything is not feasible. Instead, a firm must make calculated choices about what avenues to pursue. The path that is selected is largely dependent on the existing capabilities of the research organization.

As a result, the long-term success of R&D is as much a function of building the right organizational complements as it is the result of picking winning technologies from a set of
highly uncertain prospects. A firm simply cannot identify winning propositions unless the technical staff is cognizant of their existence.

Much of the recent literature on technology strategy suggests that a resources view of the firm with respect to R&D staff is critical, and that the objective of providing opportunities for the future is best achieved by building core technological bases or platforms. [Prahalad and Hamel 1990, Kogut and Kulatilaka 1994(a), Rumelt 1984, Wheelwright and Clark 1992] Establishing the requisite capabilities is a difficult, long-term process. However, the capabilities development task cannot be taken lightly since these choices directly influence the future direction of R&D within the firm.

Many other sources of opportunity creation are also related to capabilities. Harhoff (1991) extends capabilities to models of the spillover effect of R&D, which recognize that firms often appropriate technology from exogenous sources. Similarly, Schrader (1990) and von Hippel (1988) examine informal, inter-firm, information trading between R&D groups. Reciprocal trading along non-strategic dimensions is common and valuable, but this knowledge trading is deeply rooted in the understanding that it will be a two-way street. Trading networks rapidly exclude free-rider firms with limited capabilities.

Capabilities also influence the ability of a firm to police the environment for potential threats. Firms frequently encounter problems with this activity. Schon (1979) suggests change is difficult because it uproots existing technology and market capabilities, corporate structures, and the bases on which power and prestige are defined. Tushman, Newman and Romanelli (1986) find that firms are hesitant to change, until competitive and internal pressures become unbearable. Similarly, Henderson and Clark (1990) find that competing firms fail to see impacts on competitiveness stemming from even minor variations in product architecture. Goodman and Lawless (1994) refer to these problems as "base technology constraints," while Katz and Allen (1982) label them as the "not invented here" (NIH) syndrome. Regardless, these issues clearly complicate the selection of R&D projects.
Further, the strategic use of R&D can extend past creating complements for use within the firm. Traditional economic models of R&D assume that firms appropriate technology benefits through direct commercialization or licensing. Harhoff (1991) instead suggests that firms might invest in R&D with the intention of influencing the structure of an industry by giving technology away. This strategic appropriation concept focuses on directly influencing buyer and supplier links, and appropriating value through increased demand for complimentary products, or preservation of competition in buyer or supplier networks.

For example, Harhoff (1991) notes that Alcoa stood to gain from the introduction of aluminum cans, but chose not to integrate into packaging. Instead the firm developed the forming technologies and presented existing packaging producers with an option: produce aluminum cans, or face a formidable new competitor. Another related case might be Xerox's patent thicket approach to keeping photocopying technology out of the hands of its competitors.

Overall, the organizational management issues that R&D faces almost overshadow the difficulty of selecting technology investments. However, project selection is also a critical process that must be accomplished under a range of constraints including funding and capacity limitations, the rate at which competencies evolve, and even the incentive structures of the organization.

These constraints force managers to consider not only the merit of a proposed R&D endeavor, but the opportunity cost that results from likely having to forego another. Therefore, correctly valuing the complementary contribution of R&D projects is important. Unfortunately, the sequential, uncertain, complex and complementary nature of R&D can complicate the valuation process. These are key issues that the valuation methodology that this thesis develops must consider.
THE ROLE OF VALUE IN MANAGING THE R&D PORTFOLIO

Given the complexities of R&D management, it is not surprising that many frameworks for aiding R&D decision-making exist. These include financial analysis and forecasting methods, gauges of technical merit such as peer review, patents and publications, portfolio matrices, and customer driven approaches. An exhaustive overview of these techniques is beyond the scope of this work, but Hauser (1996) provides a fairly comprehensive, annotated bibliography that summarizes 147 sources on R&D metrics.

Similarly, Werner and Souder (1997) surveyed the R&D performance measurement literature from 1956 to 1995. They found that integrated metrics that combine qualitative and quantitative measures were most effective, but these metrics are also the most costly and time consuming to develop and use. These authors suggest that the appropriate choice of R&D metric depends on user needs, the type of R&D, data availability, and willingness to devote effort to the assessment. They also develop a framework that suggests preferred metrics for different types of R&D. It recommends qualitative metrics for basic R&D, and places increasing emphasis on quantitative metrics as R&D moves from applied research to product and process development.

The main objective of this thesis is to improve the financial valuation of R&D. In part, the reason that so many R&D decision aids are available is that it is often difficult to value R&D efforts using standard financial analysis methods. This occurs when the sequential, uncertain and complex nature of R&D complicates the valuation process to the point that standard methods are not capable of fully expressing the complementary contribution of a project. Therefore, R&D management finds other bases for justifying R&D investments, until projects reach a stage where financial valuation models adequately reflect complementary value.

The "Three Tiers of R&D" framework proposed by Hauser and Zettelmeyer (1996) compactly describes the current role of financial valuation in R&D management. Similar to Werner and Souder (1997), these researchers build on the common idea that R&D is a
continuum that spans basic science to applied work by defining several levels of R&D and identifying metrics that are best applied to each stage.

In their framework, Tier 3 projects are applied research projects conducted for or within business units. Examples include near-term problem fixes and cost reductions for existing products and processes. Tier 2 efforts focus on selecting technologies to match or create core technology strategies. Examples include major product functionality changes and the development of entirely new cost and performance frontiers. These projects frequently yield complex benefit streams that are difficult to quantify directly in terms of dollars, and the overall level of uncertainty is greater than it is for Tier 3 efforts. Tier 1 projects are basic research explorations.

In addition to identifying the types of metrics that are needed for each tier, Hauser and Zettelmeyer (1996) also consider how various incentives and principle-agent conflicts should be treated in an R&D management process. For example, some subsidization of business unit level R&D may be required to stimulate the development of technologies that have firm-wide uses. The subsidy should reflect the complementary value of the technology to other business units. An additional subsidy might be required to overcome differences in risk preferences of managers and the firm.

Hauser and Zettelmeyer (1996) suggest that financial metrics are most appropriate for guiding Tier 3 efforts. They deem financial metrics sufficient for guiding Tier 3 investment decisions because these projects are by definition closely aligned to the needs of a specific business unit, product or market. The close link between the technology and the business application eases the process of estimating project revenues. Further, the near-term nature of Tier 3 efforts constrains the general level of uncertainty. As a result, financial metrics adequately express the complementary contribution of Tier 3 projects to the business unit. Again, additional mechanisms may be required to encourage consideration of spillover uses within other business units of the firm.
These researchers also note the potential usefulness of real options for valuing Tier 3 R&D. However, Chapter 3 explores the use of options models to value R&D projects, and it finds that the short-term nature of Tier 3 projects may diminish the need for these frameworks. Simpler models may suffice.

For Tier 2 projects, Hauser and Zettelmeyer (1996) suggest that effort-indicating metrics should supplement financial metrics because too much market focus leads to false selection and rejection distortions. Effort-indicating metrics include counts of patents and publications, and peer reviews of research progress. Essentially, they argue that financial metrics represent incomplete expressions of the complementary value of Tier 2 projects.

Thus, it is not an overemphasis of market focus that biases financial metrics against Tier 2 projects. Rather, by definition Tier 2 projects are simply harder to value using conventional frameworks than Tier 3 projects. Tier 2 projects aim to create broad technology platforms that can be spread over many business units or products. Consequently, Tier 2 is longer-term, more uncertain, and the range of potential market applications is less well understood. The use of effort-indicating metrics acts as a mechanism to help focus R&D on producing valuable capabilities that complement the firm's existing strengths or fill perceived strategic needs. Without such metrics, there is a tendency to overemphasize projects that generate near-term revenues.

However, an improved financial valuation model that more completely represents the complementary contribution of Tier 2 projects could reduce the need to rely on alternative metrics. The options frameworks that Chapter 3 examines are promising because they explicitly treat uncertainty and the sequential nature of R&D. Also, some of the multi-metric models and scenario analysis methods that Chapter 5 introduces show promise for converting complex benefits and capabilities improvements into terms that the financial options models can evaluate.
<table>
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Figure 2-1: The Tiers of R&D Spectrum, Example Projects, and Relevant Metrics [Based on Hauser and Zettelmeyer 1996]

Because Tier 1 projects are essentially basic science investments, it is difficult to identify linkages to markets. Therefore, these projects are simply not amenable to financial valuation. Hauser and Zettelmeyer (1996) suggest a portfolio approach to basic R&D, where the goal should be to fund high variance projects and negatively correlated objectives. However, the objectives should be funded with some cognizance of their relationship to the firm's technology and business strategy. Further, projects that relate to a specific objective should be positively correlated efforts. It is the objectives, or technology clusters, that should be negatively correlated. This results in a higher likelihood that a valuable, complementary technology will emerge under all possible future outcomes.

Figure 2-1 summarizes the Tiers of R&D framework. The figure describes R&D projects that likely fit within each Tier, matches R&D metrics to the R&D continuum, and indicates the rationale for these recommendations.
The practical point to take from this discussion of metrics for managing R&D, is that dollar value is an attractive basis for decision-making, but it is also difficult to gauge for many projects. As a result, secondary metrics are sometimes needed until a project becomes sufficiently linked to a market application that financial analysis can be applied. The goal of this thesis is to extend the reach of financial valuation methods. This will provide a basis for fairly demonstrating that R&D, especially Tier 2 projects, is much more valuable than common metrics indicate.

**IMPROVING THE FINANCIAL VALUATION OF R&D**

A major goal of this thesis is to improve upon current R&D valuation practice by addressing difficulties caused by uncertainty, the sequential nature of R&D, and the complexity of valuing project benefits. Addressing these issues will result in a metric of project value that more completely expresses the complementary contributions of R&D investments. The methodology the thesis develops focuses on:

- valuing opportunities to revise R&D projects in response to uncertainty resolution;
- better matching valuation frameworks to project uncertainties (risks);
- integrating methods for valuing complex benefits with financial valuation frameworks.

Unfortunately, common valuation practice often ignores these issues. The result is that important information about R&D value is frequently lost. Many managers intuitively understand this problem, and adjust for it on an *ad hoc* basis. For example, a project might be funded because it is "strategic" even if it appears financially unattractive.

The Tiers of R&D framework highlights the importance of the first and last of these three focal points. First, it notes that discounted cash-flow methods miss valuable R&D contingencies, and it suggests that real options methods could be used to value these asymmetries. Second, the tiers model finds that financial metrics are inadequate for some forms of R&D because they fail to recognize valuable, complementary project features. This results because some projects create broad capabilities rather than specific products or
processes. Because these projects yield complex benefits that are not easily converted into dollar consequences, it is hard to value them using financial metrics alone.

The tiers model does not specifically address the applicability of specific financial valuation models to projects with different risk characteristics. It simply recommends real options as the best of the financial metrics. This thesis improves upon this general recommendation by demonstrating conditions under which various financial valuation procedures, including real options, are most appropriate for evaluating R&D projects.

Further, this thesis aims to create a framework that addresses the difficulties of valuing R&D in a manner that is practical for implementation in actual R&D settings. Given the increasing pressures for R&D to deliver commercially viable results, the resulting analysis capabilities should be especially useful. The methodology does not aim to address broad issues such as how to develop and align technology and business strategies, but it could easily be applied to help shape these strategies and sort between potential technology investments that fit within them.

Some examples of technology strategy frameworks which could incorporate such a metric of value are outlined by Goodman and Lawless (1994), Adler, McDonald and MacDonald (1992), Roussel, Saad and Erikson (1991), and Petrov (1982). However, the degree to which the improved metric better reflects the true complementary contribution of a project to the firm could also reduce the need to rely on such structures.

The following sections begin to explore the shortcomings in R&D practice in more detail, and describe how some of the information losses can be avoided by applying alternative valuation methodologies. These arguments provide the basis that this thesis uses to develop an improved valuation methodology.
Revising Projects: The Contingent Nature of R&D

A major shortcoming of current R&D valuation practice is a tendency to ignore opportunities to revise plans, in response to new information, throughout the life of a project. In fact, the ability to react to change allows managers to exploit opportunities while limiting losses, and can dramatically increase the value of a project.

For example, net present value (NPV) is best suited for evaluating investments for which the timing and magnitude of future cash-flows are completely characterized in terms of a continuous distribution. In these cases, the common practice of using expected values yields a reasonable estimate of project value. However, NPV often undervalues projects that include future decision stages, because these opportunities introduce asymmetries into the distribution of cash-flows that are ignored in practice. Since most R&D is highly contingent, NPV tends to understate its value. NPV also has other problems with valuing contingent projects that this thesis introduces shortly.

Other value-oriented frameworks face similar problems. For example, Figure 2-2 shows a commonly applied risk-reward matrix [Arnold, 1988]. While it is easy to follow, this type of framework oversimplifies the process through which benefits are realized.

Consider two high-risk projects that rely on unproven technology and require large development investments. If the expected rewards are similar, Figure 2-2 would place these projects in the same category. However, the value of the two projects could vary more widely than this suggests, especially if commercial feasibility could be determined at an earlier stage for one project. In the event of unpromising results, there would be more opportunity to avoid losses by stopping the effort before incurring the bulk of R&D costs. Thus, risk alone is not a detriment. Project value depends on the magnitude and timing of resource commitments required to resolve uncertainties.
These observations help to explain why there is a growing interest in valuing R&D using options models or decision analysis; these frameworks recognize that valuable decisions are made during the life of an R&D project. Each framework has specific assumptions and limitations, but both show promise for improving R&D valuation practice. This work explores the practicality of applying real options and decision analysis to R&D valuation and the conditions under which these models are appropriate.

**Differing Project Characteristics and the Problem of Singular Frameworks**

A common problem with many decision frameworks stems from an assumption that a certain form of data is available for conducting an assessment. This is not always true, and converting information into a usable form is often difficult or poorly done. When a system fails to produce the form of data an assessment methodology requires, or data is force-fit into a framework, a poor basis for guiding decisions results. For example, Cooper and Kaplan (1988) note the increasing irrelevance of traditional burden rate approaches to
accounting for understanding product cost in environments where labor is only a small fraction of the total cost. The rise of activity-based costing resulted from this recognition.

R&D valuation practice also tends to suffer from an overly rigid attempt to value all projects using the same methodology. A better goal is to seek a common set of metrics, and to apply a range of methodologies that best represent the type of problems faced and that can utilize the form of project data that is available.

Therefore, rather than identifying the "best" method for valuing R&D, this thesis aims to extend the use of financial metrics further into the R&D spectrum by developing a flexible valuation framework. The objective is to integrate several methodologies, and to allow the type of project to drive the exact sequence of steps in an assessment.

Thus, while some communities might argue that real options approaches are the only proper way to value a project and others might insist that decision analysis techniques are more intuitive, this work seeks a workable compromise that captures the best of both methods, while maintaining practicality for implementation. It argues that each model is suitable for treating specific forms of project risk, and that the risk profile of individual projects determines which model is most applicable, or if a combination is required.

Similarly, methods for valuing projects with complex benefits are utilized where needed, as precursors to financial valuation. These are discussed next. However, the overall result is a valuation methodology that leads to a dollar metric of value, but the path through which the individual assessments are developed varies according to the type of project.

**Valuing Complex Benefits**

R&D is often a multi-objective undertaking, and financial payoffs are not the only benefit. As a result, financial analysis alone is not sufficient for valuing all projects. For example, many projects improve technology performance, or a combination of product cost and functionality. Also, R&D sometimes broadly enhances technical capabilities, rather than delivering a targeted result to a product line or process. Although these investments may ultimately yield financial benefits, quantifying the returns is problematic for two reasons:
• the contribution of performance increases is hard to isolate and translate directly into financial consequences;

• estimating the breadth and rate of technology implementation is difficult for pure technology and capabilities oriented projects.

For example, incorporating lightweight, advanced materials into automotive valve-trains would enable several product improvements including noise reduction and increased engine power. [Mangin 1993] Customers value these features, but estimating their value requires a detailed understanding of a complex set of trade-offs. Often, such information is not readily available or lacks resolution, especially for early-stage R&D concepts. External influences, such as regulation, can compound the problem by encouraging technical developments that are not congruent with consumer preferences.

Also, despite the difficulty of valuing technical capabilities, they remain an integral part of R&D. Unfortunately, most work related to the assessment of capabilities focuses on aggregate levels and would be difficult to apply to project valuation. For example, Cohen and Levinthal (1990) describe the role of capabilities in shaping an organization's ability to recognize and commercially apply valuable new information. Henderson and Cockburn (1994) show that competencies in technical systems lead to improved performance in drug development. Neither group estimates the value of creating new capabilities.

This research seeks to improve the valuation of technology and capabilities focused R&D, at the project level, by integrating methodologies that value multiple benefits with financial models. It attempts to reach further into the R&D spectrum by applying methods that might help value some of these capabilities at an earlier stage. As with any R&D metric, there are likely to be limits to which these goals can be achieved, but substantial improvement over current practice is sought.
Chapter 3: Valuing R&D Options

Chapter 3 explores the applicability of financial valuation methodologies to R&D projects. It begins by highlighting limitations of net-present value (NPV) as a tool for valuing R&D, and introduces two more promising approaches: decision analysis and real options. These models are attractive because they explicitly focus on including the value of opportunities to revise R&D plans in estimates of project value.

**NET PRESENT VALUE ANALYSIS AND MODELS OF RISK AND RETURN**

Net present value (NPV) is a standard financial valuation model that is commonly recommended for evaluating investment opportunities. The objective of the methodology is to compare positive and negative flows of cash over a specified timeframe for the purpose of judging the worth of an entity that produces these flows. This requires that future cash flows be adjusted to account for the time value of money, since a future dollar is worth less than a dollar today. A process known as discounting converts all flows into current dollars. A factor known as the discount rate, which acts much like an interest rate for a bank account, enables the conversion. Adding the adjusted cash flows yields an estimate of current value. Equation 3-1 summarizes the NPV process.

\[
NPV = \sum (Benefits_n - Costs_n)/(1 + r)^n \quad (\text{for all } n)
\]  

In this model, *Benefits* refers to positive cash flows, while *Costs* are negative cash flows. The term \( n \) identifies the time when the flows occur, and \( r \) is the discount rate. NPV is the sum of the discounted benefits and costs.

While the magnitude and timing of benefits and costs is sometimes highly uncertain, often the most controversial step of conducting an NPV assessment stems from the selection of the discount rate. The assessed value of an investment, its NPV, is frequently sensitive to the discount rate choice.
Consider a project that requires an up-front cost and that returns a stream of benefits for several years. In the NPV model, the impact of the up-front cost is constant since the present value of a payment today is simply the full amount of that payment (i.e., cost incurred at $n=0$). In contrast, the influence of the benefit stream will decline as the discount rate increases. Thus, the project will look less attractive for larger discount rates. Technically, there is nothing wrong with this trend. However, managers tend to select inappropriately high discount rates to value projects. [Pindyck 1994, Kester 1984] For projects with benefits that occur far in the future compared to costs, such as many R&D efforts, this leads to an unfair bias.

**Selecting a Discount Rate: Models that Relate Risk and Return**

Finance theory does provide guidance on how to select an appropriate discount rate for a project. The objective is to identify a rate that appropriately adjusts project cash flows for the time value of money and that accounts for any risk that the cash flows face.

Perhaps the most well known model for estimating the appropriate discount rate for an investment is the Capital Asset Pricing Model (CAPM). This portfolio model estimates the expected return on a single investment by comparing it with a portfolio of investments that has a known rate of return.

For the purpose of this thesis, another model that relates risk and return, known as Arbitrage Pricing Theory (APT), is more illustrative of some key concepts that are later utilized to develop options based models of R&D projects. APT aims to achieve the same goal as the CAPM, but it estimates the expected return on an investment by correlating the these returns with realizations of a relatively small set of priced goods and other economic factors. Similarly, the options models that this work develops use an empirical approach to relate project cash flows to priced assets to enable an appropriate discounting procedure.

The CAPM and APT models are highlighted below. Introductory finance texts such as Brealey and Myers (1991) and Sharpe and Alexander (1990) provide detailed overviews of these models and NPV.
The Capital Asset Pricing Model (CAPM)

The CAPM relates the risk of an investment to the level of return it should yield. It suggests that risk takes two forms: unique and market. Further, unique risk is completely diversifiable, but market risk is not. As a result, the CAPM proposes that the level of return an equilibrium market requires from an investment is a function of its market risk component. This proposition has been demonstrated to correlate with observations of securities prices.

Equation 3-2 summarizes the findings of the CAPM, and is known as the securities market line. It relates the expected equilibrium return on an investment ($r_i$) to the risk-free rate of interest ($r_f$), a metric of the relative level of market risk in the investment ($\beta$), and the return expected for holding the market portfolio of securities ($r_m$).

$$r_i = r_f + \beta(r_m - r_f)$$ (3-2)

Equation 3-2 indicates that the expected equilibrium return for an investment increases linearly with $\beta$, which is the investment beta. Technically, beta is the ratio of the covariance of the returns on the individual investment and the market portfolio to the market variance. Therefore, Equation 3-2 essentially indicates that the equilibrium expected return from an investment increases with its level of market risk.

Estimating the market risk component of traded securities is reasonably straightforward, since price data is widely available. A simple regression model of Equation 3-2 yields the desired estimate of $\beta$. Even if data is not available for a specific stock, as would be the case for an initial public offering, securities that are similar to the investment of interest provide a basis for comparatively assessing the market risk. As a result, the CAPM is widely used in the securities industry.

Extending the CAPM to real investments yields a basis for selecting a discount rate. The discount rate should reflect the level of market risk in the project. Then, a positive NPV
investment represents an opportunity to obtain a return in excess of equilibrium. As a result, the decision rule for managers simplifies to "invest in all positive NPV projects."

In practice, knowing that the market risk of an investment should define the discount rate may not simplify the process of estimating it. Projects are not traded assets, so a direct regression analysis approach to gauging the risk in not possible. Instead, a financial approach that relies on comparative project data is common. This requires debt and equity beta estimates for standard operations within a particular business. The discount rate for a specific project is then calculated based on these estimates.\textsuperscript{1} Data availability can vary depending on the type of project. Unfortunately, the process can be extremely difficult for R&D projects that are heterogeneous.

**Arbitrage Pricing Theory: Relating Expected Return to Exogenous Factors**

The fundamental idea underlying the CAPM is that the value of an investment is relative to the value of other investment alternatives. Therefore, the degree to which an investment will be more or less valuable in the future depends on how it compares with the future values of other investment opportunities.

The security market line (SML) expresses this concept (Equation 3-2). It defines a relativistic relationship between the expected return on investment, the risk-free rate and the expected return on a broad set of investments (the market portfolio). The SML indicates that the expected equilibrium return on an investment increases as the correlation between the investment and the market portfolio becomes more positive. Typically, this trend is explained by stating that the risk premium that investors demand for an investment increases with the investment's market risk component because market risk cannot be diversified.

An alternate explanation of the SML is that the equilibrium rate of return on an investment increases for increasing positive correlation with the market portfolio because the relative value of an investment diminishes when many investments yield similar results. For example, an investment that is positively correlated with the market portfolio is expected to

\textsuperscript{1} See Copeland, Koller and Murrin (1990) for a more extensive discussion of valuing projects.
yield positive returns in an environment where many investments yield positive returns. As a result, the relative value of the expected returns on the investment is reduced because these returns are expected to occur in conjunction with an overall increase in wealth. This overall increase in wealth acts to diminish true purchasing power. Therefore, as compensation for this relativity of wealth, an equilibrium market will demand an increasingly higher return for investments that correlate with a broad portfolio of investments.

Thus, market risk can be viewed in two different ways. The diversification argument states that consumers demand compensation for bearing market risk because they cannot eliminate it through diversification. The relative wealth argument states that the returns on an investment become relatively less important when these returns closely mimic the returns of a broad portfolio. What is important to recognize is that both arguments are concerned with the impact that exogenous market outcomes have on the value of an investment (i.e., how will the price of an asset compare to the prices of other assets in the future). Risks that are unique or endogenous to an individual investment are unimportant to equilibrium models because they can be averaged out by holding many investments. Alternatively, endogenous risks have no relation to the overall expected level of wealth, and therefore it is not possible to gauge a priori how these risks will affect the relative value of an investment.

Arbitrage Pricing Theory (APT) illustrates more clearly than the CAPM that the level of return estimated by equilibrium models is only influenced by the correlation of these returns with exogenous factors such as the prices of other assets. In fact, APT directly estimates this form of relationship. Equation 3-3 presents a general form of an APT model.

\[ r_i = \alpha + \beta_1 f_1 + \beta_2 f_2 + \ldots + \beta_{n-1} f_{n-1} + \beta_n f_n \]  

(3-3)

Similar to the CAPM, \( r_i \) in Equation 3-3 is the expected return on the individual investment. The coefficients \( (B_j \text{ for } j = 1 \text{ to } n) \) act much like the beta in Equation 3-2, and alpha is a constant. However, the APT model does not a priori specify the set of factors \( (f_j \)
for \( j = 1 \) to \( n \) that determine the equilibrium return on the investment. Instead, empirical analysis is required to develop relationships with high explanatory power.

Campbell, Lo and MacKinlay (1997) provide a detailed discussion of the APT and the current state of the art in developing and testing these empirical models. Typically, the marginal explanatory power rapidly diminishes after a model based on five to ten factors is estimated. Common factors include interest rate spreads, prices of traded assets, prices of goods and metrics of economic strength (e.g., GDP).

The key point to take from this discussion is that equilibrium models of risk and return are only concerned with the degree to which the expected cash flows of an investment are correlated with the prices of exogenous factors such as securities and traded goods. **Endogenous uncertainties that are not correlated with prices of exogenous factors require no risk premium.** This distinction becomes critical when applying options based models to value R&D projects with exogenous and endogenous uncertainties.

**The Critical Shortcoming of NPV as an R&D Valuation Tool**

Although selecting a discount rate can be difficult, this is not a sufficient reason for dismissing NPV as inadequate for R&D valuation. However, in practice, NPV suffers from a deficiency that does raise questions about its merit for these investments. A major criticism of net present value analysis (NPV) is that it systematically favors short-term, low-risk projects, at the expense of long-term efforts that can be revised over time in response to findings or changing needs. [Hayes and Garvin 1982] This occurs because NPV typically ignores the value of the ability to make future decisions. As a result, NPV tends to undervalue many real investments. For highly contingent activities like R&D, the error can be significant. A related problem is that NPV is not able to value contingent projects correctly, even if it does try to incorporate their influences on expected cash flows.

To illustrate this shortcoming of NPV, consider the following example. A company has the opportunity to invest in a new R&D project. It needs $100,000 to run a one-year
field test on a material it has developed. The material will certainly pass, but the test is required by law to be completed before the product can be placed into service.

The company also has a standing offer from an end-user who would like to license the technology exclusively. When the tests are finished, this end-user will pay a fee of one million times the price of the material it currently uses, and the company that developed the material will transfer the technology, at an estimated cost of $1,100,000.

The current price of the incumbent material is $1.00 per ton. However, the price of this traded commodity fluctuates over time. The company that developed the new material technology estimates that next year there is a fifty percent chance that the commodity price will be $1.8 per ton and a fifty percent chance that it will cost $0.55 per ton. Assuming that a discount rate of ten percent applies, is this project worthwhile?

Table 3-1 shows how this type of information is typically incorporated into an NPV model. It presents cash flows and the present value of these flows for each year, and totals the overall NPV in the last column. The NPV of the project is negative (-$31,818), and according to the NPV decision rule, it should be rejected.

The calculation in Table 3-1 assumes that the company completely commits to licensing the technology at the outset, but this ignores an important feature of the project. The company can make this decision after the test is completed. If the technology will license for $550,000, it makes little sense to spend an additional $1,100,000 to transfer it.

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
<th>Cash Flow</th>
<th>Present Value (Discount rate = 10%)</th>
<th>Net Present Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Initiate Testing Program</td>
<td>($100,000)</td>
<td>($100,000)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Transfer Technology</td>
<td>($1,100,000)</td>
<td>($1,000,000)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Collect License Fee</td>
<td>0.5 * $550,000 + 0.5 * $1,800,000</td>
<td>0.5 * $500,000 + 0.5 * $1,636,364</td>
<td>($31,818)</td>
</tr>
</tbody>
</table>
A more realistic alternative would be to start the project, observe the uncertain price when the tests are finished, and accept the license agreement only if the most promising outcome results (i.e., $1,800,000 license). Because the technology transfer stage is the most costly part of the project, this strategy puts only a minimal amount of money at risk to determine if continuing is worthwhile. This type of progression, choosing to continue and increase expenditures as uncertainty diminishes, is more descriptive of many real projects.

Table 3-2 shows a revised financial analysis that accounts for the future decision opportunity, assuming that a ten percent discount rate still applies. It points out two major differences. First, when the expected benefit of licensing is only $550,000, the project stops. This avoids an inefficient expenditure in Year 1. Second, if the project stops, the company does not collect a license fee. Thus, the likelihood of completing the project and licensing the technology for $1,800,000 is fifty percent. There is a similar chance that the project will end before the transfer and licensing stages. Applying this logic, the NPV of the project is positive (+$218,182), and it should be pursued.

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
<th>Cash Flow</th>
<th>Present Value (Discount rate = 10%)</th>
<th>Net Present Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Initiate Testing Program</td>
<td>($100,000)</td>
<td>($100,000)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Transfer Technology</td>
<td>0.5 * 0</td>
<td>0.5 * 0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ 0.5 * ($1,100,000)</td>
<td>+ 0.5 * ($1,000,000)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Collect License Fee</td>
<td>0.5 * $0</td>
<td>0.5 * $0</td>
<td>$0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ 0.5 * $1,800,000</td>
<td>+ 0.5 * $1,636,634</td>
<td>$218,182</td>
</tr>
</tbody>
</table>

The $250,000 difference between the NPV in Tables 3-2 and 3-3 results because continuing the project is an option, not a requirement. This value stems from the company's ability to avoid the unappealing choice of spending additional money in Year 1 to gain a comparatively smaller benefit. Clearly, such decision opportunities are valuable. Therefore, frameworks that ignore options will undervalue projects that have many of them. A practical shortcoming of NPV is that oversimplified procedures such as that shown in Table 3-1 are often used unless a mechanism to force the consideration of options is adopted.
Why Simple Modifications to NPV May Not Be Satisfactory

Exploring the value of the example project suggests that NPV may not be the best method for valuing R&D. The later part of this section on financial models discusses promising alternatives. However, two other points regarding the calculations in Tables 3-2 and 3-3 are worth raising. These include the validity of the assumption that the discount rate should be the same in both NPV calculations and the potential complications that might result from incorporating multiple future decisions into an NPV estimate.

First, while the assumption of a ten percent discount rate might be valid for the NPV calculation in Table 3-1, the addition of a future opportunity to revise the project changes its risk profile. If the uncertainty that is resolved prior to this decision correlates with priced exogenous factors and the ten percent discount rate is appropriate for the no-option project in Table 3-1, then it is not valid to use this rate for the valuation in Table 3-2.

In fact, no single, constant discount rate applies if project uncertainty correlates with exogenous, priced factors. Therefore, NPV will not be suitable because it is not possible to properly discount cash flows for risk. This is the case for the example in Table 3-2 and for many other projects. Thus, while the value of opportunistic actions tend to increase with uncertainty, discounting expected cash flows at a standard rate is a distortion.

For example, if an option is introduced to a project that was previously valued using a proper risk-adjusted discount rate, then continuing to value the project using that same discount rate and an approach similar to that shown in Table 3-2 will introduce two errors. First, using discrete outcomes ignores valuable extremes that continuous models can capture. Second, the constant discount rate will understate the risk adjustment to the extent that the uncertainty is positively correlated with priced factors (typical). Therefore, these two errors tend to be partially off-setting. However, it is not possible to determine by inspection if the project is over or undervalued. A potential advantage of the real options approach that this chapter reviews is that it solves these problems.

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2 The options theory and real options sections in this chapter clarify points made in this paragraph.
Also, while the example in Table 3-2 estimated the value of a single option to continue a project, most projects include a broad range of options. For example, promising results might merit an increase in expenditures for the next phase of a project, while discouraging findings might lead to a decrease. Stopping an effort is another alternative. Implementation decisions are also options that have important implications for R&D value.

In general, project value increases with the number of options available, but not always in an easily predicted manner. For example, the options to continue a project, and increase or decrease funding are variations of a continuation option that exist simultaneously. Valuing these options separately and adding them together is not correct, because redundancies would be over-counted. Unfortunately, this fact results in a complicated valuation process; Trigeorgis (1996) provides examples of options interrelations and project value, solved by dynamic programming techniques.

To compound the problem, most projects have multiple decision phases. This increases the complexity of valuation because prior decisions influence future options. An extreme case is abandoning a project, which renders all future options worthless. This particular example helps to explain why organizations are often hesitant to end projects that are losing money. The value of preserving future options may off-set short-term losses.

Given these complications, it is easy to understand why options are commonly ignored in project valuation efforts. Yet, managers do recognize that NPV may not fairly represent project value. Kester (1984) points out that citing "strategic value," and overstating cash flows are common approaches to defending a project that is unattractive on an NPV basis, but may have option-like features. In contrast, many managers insist that projects show a positive NPV, even for inappropriately high discount rates. While this is possibly myopic, Dixit and Pindyck (1994) argue that waiting is often valuable. This behavior indicates an understanding that starting a project has an opportunity cost in the form of forgone opportunities to delay. Combined, these distortive and conflicting adjustments lead to confusion and hinder a process that can be useful.
DECISION ANALYSIS

Decision tree analysis is a potentially useful methodology for evaluating projects with options because it provides an easy to follow, structured view of projects. In this role, it can act as a framing device for focusing valuation efforts on identifying valuable project options, and thereby avoid the pitfalls of approaches like that shown in Table 3-1. Unlike a master-plan, which commits to a pre-defined set of activities (e.g. Table 3-1), decision analysis recognizes that only uncertainty resolution reveals what is most appropriate in subsequent stages. As a result, it emphasizes the creation of valuable options in projects.³

The example developed in Table 3-2 demonstrates the basics of decision analysis. When it is applied to value contingent projects, the method is essentially an NPV that focuses on eliciting expected outcomes that result from making opportunistic choices. In the example project case, the recommended initial action was to start the project. The best responses to the future outcomes included continuing if the technology license was worth $1,800,000, and stopping work if the license was only worth $550,000.

Figure 3-1 shows a decision tree for the example project. Squares represent decision points, circles are uncertainties, and triangles are end-points. It also presents discounted cash flows, probabilities, and recommended decisions for each stage. Non-optimal paths are cut-off with double lines. The project value estimate is the same as presented in Table 3-2.

However, decision analysis is a flexible methodology that can accommodate much more complicated valuation problems. It is easy to add more decision points and to increase the number of discrete outcomes that are considered. For example, Figure 3-2 illustrates a R&D decision tree that requires two decisions. The first decision is the same project initiation question shown in Figure 3-1. The second decision is an intermediate step between project initiation and implementation. It allows the results of one stage of R&D to inform the choice to continue or not.

³ Clemen (1991) and de Neufville (1990) provide detailed introductions to the mechanics of decision analysis, including tree structuring, Bayesian revision and decision criteria.
Figure 3-1: A Decision Tree View of the Example R&D Project

Figure 3-2: A More Complex R&D Project Decision Tree
The major uncertainty that Figure 3-2 portrays is the likelihood that R&D will be successful. The model that Figure 3-2 represents breaks this probability into three components. The first probability (Ps1) is the likelihood the project will remain promising after the first stage of research, which has an associated cost of R&D1. The next two probabilities are the likelihood of total success, conditional upon the results of the first stage. Thus, Ps2 (probability of success given a promising first stage outcome) is expected to be greater than Ps3 (probability of success given an unpromising first stage outcome). Choosing to continue after the first stage (at a cost of R&D2) leads to an implementation decision if the second stage of R&D is successful.

Figure 3-2 makes two key points. One, it is easy to add decisions (options) to the model. Two, the added complexity increases data requirements. The critical question to consider is whether or not the level of resolution required for the model can be satisfied. Many R&D organizations are comfortable estimating a single probability of success. [Hauser and Zettelmeyer 1996] Splitting these into several stages of dependent probabilities may be a stretch of their capabilities, since even the simple probability is only an educated guess.

Additionally, there can be benefits to expanding the number of discrete probabilistic outcomes in a decision tree. Appendix A presents a practical way of accomplishing this goal when a statistical distribution of possible outcomes can be assumed.

However, the need to quantify probabilities and outcomes, which can be difficult for R&D, is a commonly criticized shortcoming of decision analysis methods. For example, the NPV analysis developed in Table 3-2 and Figure 3-1 assumed equal probabilities of obtaining high or low license fees. The result of the revised NPV assessment suggests that initiating the project is a good idea (NPV was positive).

Estimating probabilities is often controversial. Methods like Merkhofer's (1987) cumulative distribution measurement technique offer formalized procedures, but critics counter that subjective probabilities are hard to gauge with much precision. [Freeman 1989, Rosenberg 1994] Thus, the recommendation to start the project is open to criticism.  

45
Figure 3-3: Sensitivity Analysis Finds Threshold Probabilities

One way to alleviate this problem is to use sensitivity analysis to assess the conditions under which a choice seems appropriate. Figure 3-3 presents such a sensitivity analysis of the example project. Instead of using a discrete probability, it varies the probability of receiving a high license fee from zero to one and examines the changes in value. This reveals a threshold probability of 0.15, above which it makes sense to start the project (NPV>0) and below which it is better not to invest. This approach eliminates the need to estimate probabilities exactly. In this case, starting the project seems reasonable unless there is a strong belief that it has roughly less than a one in five chance of succeeding.

Overall, the application of decision analysis to R&D valuation is not a new concept, but there is room to improve its implementation. More than thirty years ago, Baker and Pound (1964) and Cetron, Roepcke and Martino (1967) noted a proliferation of decision models in the literature, but a lack of real-world acceptance. They cite technical reasons as

---

4 In this particular case, the probability of obtaining a high license fee was based on price data for a key driver of project value, and is less circumspect. Generally, arguments against probability estimation refer to subjective estimates of endogenous uncertainties such as the likelihood of success. For the purpose of developing an illustrative example of sensitivity analysis, this issue is overlooked.
the problem: a poor understanding of how to treat uncertainty, a need for better data, and too much emphasis on optimization. A decade later, Baker (1974) and Baker and Freeland (1975) suggest that the failure to account for organizational factors and R&D complexities were important limitations. In 1992, Schmidt and Freeland noted the increased use of organizational factors, but recommended that basic decision analysis models could still provide value if implemented without ignoring these issues.

The goal for this work is to use decision analysis as one method for estimating the options value of R&D projects, to support an overall portfolio management process. Rather than making the models extremely complex, the focus is on using the simplest form possible to describe the major options. In many cases, this should provide sufficient information to decide if, on a value basis, a project is worth initiating or continuing. R&D managers can then weigh the results with other organizational constraints to shape the portfolio.

However, a potential shortcoming of decision analysis is that it does not solve the discount rate problem that plagues NPV when projects have future decision opportunities. Both the revised NPV assessment and the decision analysis model require discount rate assumptions that are incorrect. The remainder of this thesis continues to consider the importance of this deficiency as it develops the overall R&D valuation framework.
REAL OPTIONS

Real options is another method for valuing projects with future decision opportunities. It is based on models that are used to value financial instruments, and tries to value projects correctly from a finance perspective of obtaining a satisfactory level of return for a given level of risk. In contrast, decision analysis may only approximate project value. However, real options models may face other limitations. For example, some models make assumptions about the underlying asset that may not hold for real projects. This work explores the differences between decision analysis and real options, and aims to identify conditions under which each is useful for improving R&D valuation practice.

This section introduces the topic of real options. It reviews basic options pricing models, discusses the extension of these frameworks to real projects, and applies simple call option models to value the example R&D project introduced earlier in this chapter.

The Black-Scholes Option Pricing Model

The most well known financial options model is the Black-Scholes (1973) pricing formula for a specific type of stock option known as a call. For a relatively small up-front cost, this option provides the owner the right to purchase the underlying stock for a pre-determined (strike) price, on a specific date in the future. Because the option is a right, but not an obligation, the holder will exercise it only if conditions are favorable. As a result, the call option has an interesting payoff structure. Once purchased, there is no additional potential for loss and the potential for upside gain is unlimited.

For example, consider a call option with a strike price of $10.00 on a share of stock currently trading for $8.00. If the stock moves above the strike price, for instance to $12.00, the option holder could exercise the right to purchase a share of the stock for $10.00 and sell the share for $12.00, netting the difference of $2.00. In contrast, if the stock remains below the strike price, it would not be in the option holder's interest to buy the share for $10.00 when it currently trades for less. In this case, the option would go unexercised and the holder would see no additional gain or loss, even though the stock lost value.
Figure 3-4: Payoff for a Call Option with Strike Price (K) for Stock Price (S)

Figure 3-4 depicts a general payoff diagram for a call option. Note that the figure disregards the cost of acquiring the option. For any stock price (S) greater than the option strike price (K) it is favorable to exercise the option. The net gain is then the difference between the stock price and strike price (S-K).

While describing payoffs is relatively simple, the key problem is gauging how much options are worth. Figure 3-4 only indicates what the option would yield if exercised when the stock was at a specified price. At first inspection, it appears that NPV could value the option using the potential future payoffs (cash flows) and an associated set of probabilities derived from a statistical analysis of the underlying stock. However, the riskiness of the option changes every time the stock price changes, and the stock price changes unpredictably.\(^5\) As a result, it is not possible to determine the appropriate, risk-adjusted, discount rate that NPV requires. Thus, options require a different valuation model.

\(^5\) Stock prices are commonly assumed to follow a random walk; all known information is already incorporated into the price, and future price changes occur only as new, unforeseen events occur. For a more detailed discussion of the random walk and its variations (e.g., strong versus weak), see Malkiel (1990).
The problem of valuing options was first solved by Black and Scholes (1973) for a specific type of option known as a European call, which cannot be exercised until the expiration date. The Black-Scholes model essentially relates the call option to a portfolio of the underlying stock and borrowed money that yields the same payoffs. Because the payoffs are the same, the value of the option must equal the value of the portfolio. Since the stock and loan can be valued precisely, the price of the option can be inferred.

Equation 3-4 is the Black-Scholes formula for valuing European calls on stocks that do not pay dividends. Five factors influence the value of the option (C): the stock price (S), the strike price (K), time to expiration (t), the risk-free rate of interest (r) and the standard deviation of expected returns on the stock (σ). Cox and Rubinstein (1985) and Hull (1993) develop the model in detail, and explore extensions such as the influence of dividends.

\[
C = S \times N(x) - Ke^{-rt} \times N(x - \sigma \sqrt{t})
\]  

(3-4)

where, \( N(x) \) = cumulative, standard normal distribution

\[
x = \ln(S/(Ke^{-rt}))/\left(\sigma \sqrt{t}\right) + \sigma \sqrt{t}/2
\]

Figure 3-5 shows the Black-Scholes value of a call option versus current stock price and volatility (\( v = \text{volatility in Figure 3-5} \)). Several trends are important. First, the option has a non-zero value that exceeds the immediate exercise value (S-K for S>K and 0 for S≤K), as long as there is uncertainty in what the price of the underlying asset will be when the option expires (\( v>0 \)). This is true even if the stock price is currently less than the option strike price. The option has a positive value under these conditions because it still may be worth exercising at expiration, and the downside is limited to zero gains. Second, the option

---

6 An American call can be exercised at any time up to and including the expiration date. While they are more representative of real project options, American options can be more difficult to value. This issue is taken up after some important features of options are illustrated using the Black-Scholes model.

7 The risk-free rate of interest is often approximated as the yield on short-term U.S. Treasury bills. Texts such as Brealey and Myers (1991) provide a more detailed discussion of risk and return.

8 With the exception that if the underlying asset becomes worthless, so does the option.
increases in value if uncertainty (volatility) in the value of the underlying asset increases, (i.e., \( v=2 > v=1 \) in Figure 3.9). Again, the asymmetric nature of options drives this result. A higher volatility increases the chances of large payoffs while the downside remains limited to zero gains. Thus, the Black-Scholes model is powerful because it simultaneously accounts for the continuous range over which the underlying might vary and applies the correct level of risk-adjustment to the resulting probabilistic cash flows.

Some other important observations that result from the Black-Scholes model are that the call option increases in value with the current stock price and decreases in value with increases in strike price. Increasing the time to expiration for European calls does not have a definite influence on value, but American calls, which can be exercised at any time up to expiration, always increase in value with extended time to expiration. Table 3-3 provides Hulls' (1993) summary of factors which influence options value, including put options, which provide the right to sell the underlying asset in the future.

![Figure 3-5: The Value of a Call Option with Time Left to Expiration Exceeds the Immediate Exercise Value and Increases with Volatility (v).](image-url)
Table 3-3: Stock Option Value Drivers and Influences

<table>
<thead>
<tr>
<th>Factor/Option Type</th>
<th>European Call</th>
<th>European Put</th>
<th>American Call</th>
<th>American Put</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underlying Price</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Strike Price</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Time to Expiration</td>
<td>?</td>
<td>?</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Volatility of Underlying</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Risk-free Rate of Interest</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Dividends</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Source: Hull (1993)

The Binomial and Other Complex Options Models

The Black-Scholes model is useful for pointing out important features of options, but is limited in scope. Merton (1973) adds important extensions to the model, including the influence of dividends, but developing closed-form models becomes increasingly difficult with the addition of new terms. Regardless, some special cases exist. These include stochastic dividend yields (Geske, 1978), compound options (Geske, 1979), options on the minimum or maximum of two assets (Stulz, 1982), options on assets which earn non-equilibrium rates of return (McDonald and Siegel, 1984), options on several underlyings (Stapleton and Subrahmanyan, 1984) and stochastic volatilities (Hull and White, 1987).

For financial securities, these models are extremely pertinent, but their applicability to R&D projects is less obvious for reasons including practicality and information availability. This work focuses on drawing insights from application of the most fundamental models, which still may be difficult to implement.

One model that does appear promising for real options cases is a general, binomial approach developed by Cox, Ross and Rubinstein (1979). This methodology can value many complicated features, including the early exercise terms of American options.

The binomial approach is an iterative process that divides the time to expiration of the option into discrete steps and works backwards from the last period to the present. At each discrete point, the range of possible underlying prices is considered and the optimal
action for the option holder to take is determined. This leads to a final assessment of option value, and complete set of strategies to follow as the price of the underlying asset changes.

The binomial model appears similar to decision analysis and dynamic programming. The key to the process is that Cox, Ross and Rubinstein integrate important assumptions about the behavior of the underlying asset that allow them to properly value the option. Specifically, the underlying asset is assumed to yield an equilibrium rate of return. Then, the binomial model estimates how the price of the asset would evolve in a risk-neutral world. In such a world, an equilibrium priced asset would yield the risk-free rate of return. Once a distribution of price outcomes is obtained, the model discounts the option cash flows at the risk-free rate, which is the proper discount rate in a risk-neutral world. In other words, instead of finding a set of risk-adjusted discount rates to apply to the expected cash flows, the binomial approach adjusts the cash flows so the risk-free rate applies. This is known as the risk-neutral approach to valuation.

The risk-neutral approach is of fundamental importance to the analysis of complex derivatives because it solves the discounting problem associated with contingent assets. This is also what is accomplished in the Black-Scholes model. In fact, when the binomial model is extended to many short time-periods, it becomes the Black-Scholes model.

Figure 3-6 illustrates a one-period binomial example. Cox and Rubinstein (1985) provide a more detailed overview of the model. The example values a call option on a stock (S) with a strike price K. The current value of the underlying asset (S) is known and two future outcomes are possible: 1) a high outcome Su, where u is one plus the percentage change in S if it moves up in price, 2) and a low outcome Sd, where d is one plus the percentage change in S if it moves down in price. If the high outcome results, the option pays Cu, which is the maximum of Su-K or zero. If the low outcome results, it pays Cd which is the maximum of Sd-K or zero.
Figure 3-6: Binomial Tree Representations of Changes in Underlying Asset (S) and Associated Changes in Call Option Value.

The current value of the call option is obtained by working recursively back through the binomial tree, multiplying each outcome by a risk-neutral probability and discounting at the risk-free rate. Equation 3-5 is the solution to the one-period tree in Figure 3-6:

\[ C = \frac{pCu + p'Dd}{r} \quad (3-5) \]

where,  
- \( Cu = \text{Max}[Su-K, 0] \) = value of the call if stock moves up  
- \( Cd = \text{Max}[Sd-K, 0] \) = value of the call if stock moves down  
- \( p = \frac{r-d}{u-d} \) = risk-neutral probability of S increasing to Su  
- \( p' = \frac{1-p}{u-d} \) =  
- \( r = 1+\text{risk-free interest rate} \)
The factors $u$ and $d$ represent the one-period stock price changes and are estimated based on the price dynamics of the underlying asset. The Black-Scholes, binomial and other derivatives models assume that the underlying follows a mean-drift process. This process has two components, an average drift rate that represents long-term expected returns on the asset, and a stochastic term that describes the uncertainty in future prices (Equation 3-6).³

\[ dS/S = \mu dt + \sigma dZ \]  

(3-6)

where, $\mu = \text{expected return on } S$, $\sigma = \text{standard deviation of expected returns on } S$, and $dZ = \varepsilon \sqrt{dt}$ is a Weiner process (a random walk).

This process leads to a lognormal distribution of relative price changes, represented in Equation 3-7, where $Z$ becomes the standard-normal distribution for short times.

\[ LN(S_{t+\Delta t}/S_t) = \mu \Delta t + \sigma \sqrt{\Delta t} \, Z \]  

(3-7)

For short time periods, the upward change in $S$ can be estimated as shown in Equation 3-8.

\[ LN(S_{t+\Delta t}/S_t) = \sigma \sqrt{\Delta t} = LN(u) \]  

(3-8)

Then, since relative price changes in the lognormal distribution are equally likely, Equation 3-9 describes both $u$ and $d$ for the binomial model.

\[ u = 1/d = e^{\sigma \sqrt{\Delta t/n}} \]  

(3-9)

where, $n$ is the number of intervals used to simulate the one-period price change.

³ See Dixit and Pindyck (1994) for a detailed review of drift processes.
The concept of risk-neutrality becomes more apparent by examining the expected return on the stock EV(S):

\[ EV(S) = pSu + p'Sd = (r-d)/(u-d)Su + (u-r)/(u-d)Sd \]

\[ [EV(S)](u-d) = rSu - rSd \]

\[ EV(S) = rS \]

Thus, the binomial model acts as if the return on the underlying asset is expected to be the risk-free rate of return. Since this represents the return expected in a risk-neutral world, the risk-free rate can be applied to discount cash flows that are functions of the underlying asset (e.g., the call option).

**Extending the Binomial Model to Multiple Periods**

In general, the binomial model is useful because it can be applied to value a variety of options. Extending the model to include many periods and terms is relatively simple.

Consider the extension of the binomial model to two periods. Three possible outcomes of the stock price are possible: Suu, Sud and Sdd. The corresponding values of the call option are Cuu, Cud and Cdd, which are defined as the maximum of zero and the difference between the stock price and strike price. After these values are established, the recursive procedure used repeatedly until the current value of the call is obtained. Thus,

\[ Cu = [pCuu + p'Cud]/r \]
\[ Cd = [pCud + p'Cdd]/r \]
\[ C = [pCu + p'Cd]/r \]

\[ C = [p^2Cuu + 2pp'Cud + p^2Cdd]/r^2 \]  \hspace{1cm} (3-10) \]

where, \( Cuu = \text{Max} \ [0, \text{Suu-K}] \)
\( Cud = \text{Max} \ [0, \text{Sud-K}] \)
\( Cdd = \text{Max} \ [0, \text{Sdd-K}] \)
Equation 3-9 represents the value of a European call option with two time periods until expiration. Cox and Ross (1985) extend the model to many periods, and show that at the limit it becomes the Black-Scholes model.

The Influence of Dividends and American Exercise Terms

Cox and Ross (1985) also show how to include the influence of dividend payments. Two approaches are possible for European options. If a constant dividend yield is assumed, then the starting value of the underlying asset is modified by multiplying the current value by a compounded factor of one minus the dividend yield (Equation 3-11). If a constant yield cannot be assumed, the present value of dividends must be subtracted directly (Equation 3-12). These approaches also work for the Black-Scholes model (see Equation 3-4).

\[ S \rightarrow S(1-\delta)' \]  \hspace{1cm} (3-11)

where, \( \delta = \) constant dividend yield and \( t = \) time before expiration of option

\[ S \rightarrow (S-D) \]  \hspace{1cm} (3-12)

where, \( D = \) present value of expected dividends

Further, the binomial model can be adapted to value American options, which can be exercised at any time. The major complication is that the optimal action at each time period must be evaluated. For example, in the two-period case, the values of \( Cu \) and \( Cd \) become:

\[ Cu = \text{Max} \left[ 0, \text{S}_u-K, \left( p \text{Cu}_u + p' \text{Cu}_d \right)/r \right] \]
\[ Cd = \text{Max} \left[ 0, \text{S}_d-K, \left( p \text{Cu}_d + p' \text{Cd}_d \right)/r \right] \]

Therefore, the value of the option is not expressed in a form as simple as Equation 3-10. Dividend payments can also be worked into the analysis of each interval.
An Extendable Call Option

An interesting case that can be evaluated using the binomial model is an extendable call option. The extendable call requires its owner to pay a fee periodically to keep the option alive. If the fee is not paid, the option expires immediately and can never be exercised. If the fee is paid, the option remains alive for another period. If the option is still alive at the end of the last period, it is either exercised or allowed to expire. An American version of this option also allows the possibility of exercising the option during intermediate periods. Equation 3-13 provides the value of such an option, for two periods.

\[ C = \frac{[p \cdot Cu + (1-p) \cdot Cd]}{1+r} \]  \hspace{1cm} (3-13)

where, \( Cu = \text{Max} [0, S-K, (p \cdot Cuu + (1-p) \cdot Cud)/(1+r)-X] \)
\( Cd = \text{Max} [0, S-K, (p \cdot Cud + (1-p) \cdot Cdd)/(1+r)-X] \)
\( Cuu = \text{Max} [0, Suu-K] \)
\( Cud = \text{Max} [0, Sud-K] \)
\( Cdd = \text{Max} [0, Sdd-K] \)

The only difference between the value of the extendable call and a simple American call is that the term \( X \) is subtracted from the values of the option if it is held for one period. The model can easily be extended to any number of periods, and \( X \) could be a vector rather than a constant. Further, limits on early exercise can be added.

Thinking in terms of R&D, the extendable call could represent a project with multiple decision stages during the R&D phase. \( X \) would represent the payments required to continue the project at each period, while \( K \) would be the final implementation cost. The model could also span both R&D and implementation, but then \( K \) would represent the last payment required to complete implementation.
Dynamic Programming for Multiple Options and Decisions

The extendable call example demonstrates a method for considering multiple decisions during the life of a R&D project, but focuses only on continuation options. Kulatilaka (1993) and Trigeorgis (1996) present more general dynamic programming methods that can simultaneously consider multiple decision stages and unlimited sets of project options (i.e., accelerate, suspend, delay, continue, abandon, etc.). This approach is useful because it is extremely flexible in terms of the issues that can be accommodated. However, complex numerical methods are required to conduct the simulations, and the methodology is much less intuitive as a result.

The Emergence of Real Options

A number of critics, including Hayes and Garvin (1982) and Kulatilaka and Marcus (1992), have pointed out NPVs tendency to favor short-term, low-risk investments. Responses to these criticisms include calls to consider the strategic or options value of investments [Kester 1984, Sharp 1991]. Others, such as Holder and Riggs (1985), suggest that over-simplistic application of NPV is the real problem. However, Myers (1984) summarizes the consensus by comparing the applicability of NPV to real projects and securities. He argues that NPV is perfectly adequate for valuing projects with safe cash flows, just as it is for valuing low-risk bonds and stocks. On the other hand, NPV is no more suitable for valuing businesses with significant growth opportunities, including those generated by R&D, than it is for valuing traded options.

This agreed inadequacy of NPV has stimulated numerous efforts to apply options models to improving valuation of strategic investments. Copeland, Koller and Murrin (1990) and Brealey and Myers (1991) provide introductions to real options. These discussions focus on valuing real investments using the Black-Scholes and binomial models. Dixit and Pindyck (1994), Trigeorgis (1995, 1996), Kulatilaka and Marcus (1988) provide more advanced overviews. These works compare NPV to general options models, dynamic programming and decision trees. They also examine how differences in project value vary with key model inputs.
Most of these authors promote financial options models in lieu of decision trees, because the real options overcome the discount rate problem. However, Weston and Copeland (1986) point out that financial options models make assumptions about the underlying asset that may not be true for real projects. As a result, it may be difficult to ascertain which method provides the most realistic estimate of project value.

Pindyck (1991) also notes that the options approach assumes that the variations in project value can be proxied by a real traded asset. This is likely to be the case when option value drivers correlate with a commodity, share or portfolio price, but may break-down for projects with loose ties to such assets. For example, Kensinger (1987) suggests that while real options models improve the valuation of efforts to extract and process natural resources, considering options that occur downstream in the distribution, marketing and servicing of products is more problematic. In these functions, specific skills including expert judgment and competitiveness become increasingly important, but are hard to quantify. Similar issues may apply to the R&D function.

Therefore, implementability and organizational acceptance of a framework may also be important factors in selecting a valuation model. For example, Leuhrman (1997) suggests that decision analysis and real options models lie on a continuum of informal to formal financial valuation tools. In his framework, project context becomes a major driver of valuation method choice.

**Specific Real Options Models and Case Studies**

A number of formal real options models have been developed, typically in a form similar to the Black-Scholes model. While these models are useful for illustrating the value of specific option-like features, they may be less appropriate for valuing projects that contain multiple options. A few examples are described below.

The value of waiting to invest is investigated by McDonald and Siegel (1986) and Dixit (1992). These works explore optimal investment timing when uncertainty resolution occurs before a commitment to project funding is required. For example, the value of a
project might depend on a market uncertainty that will be partially resolved by observing how rapidly consumers accept a similar or complementary product. High demand would suggest going forward, while low demand might encourage waiting. Choosing to invest is like exercising a call option; it yields a set of future cash flows in return for an up-front cost. These models also consider opportunity costs of waiting, such as forgone sales, and resolve these conflicts with the benefits of having a better basis for making the investment decision.

McDonald and Siegel (1985) also evaluate the option to shut down a money-losing operation and Sachdeva and Vandenberg (1993) consider the similar option to abandon a project. The major difference between the two options is that shutting down is not necessarily a final action, while abandoning is permanent. Essentially, shutting down includes a future option to re-open. Both models demonstrate that the ability to limit losses by halting production is an important part of valuing opportunities to build a new plant.

Trigeorgis (1996) reviews many other real options models that are available in the literature, including growth options, staged investments, deferring, scaling and switching. Rather than focusing on a single option, Trigeorgis (1993) examines the interaction of options to defer, abandon, contract, expand and switch use. He values these options individually and in combinations to show that value is not additive for interdependent options. Trigeorgis (1991) also proposes a general framework for valuing multiple options.

A variety of real options case studies have also been developed. Many focus on natural resource based investments, because an obvious underlying asset exists and market pricing data useful for estimating the volatility of the underlying is available. Brennan and Schwartz (1985) examine timing options and the effect of long-term supply contracts in the copper mining industry. Siegel (1987) applies options frameworks to value offshore oil properties. Also, Kemula (1993) examines timing, growth and abandonment options in the oil and gas industries. He values the timing option using a modified call option model for a dividend paying stock. In this case, dividends represent forgone project returns that result
from waiting to invest. Kemma uses more complex compound call and put option models value growth and abandonment problems.

Kulatilaka (1993) also relies on oil and gas price data to value flexibility provided by a dual-fuel industrial steam boiler. This work is of particular interest because he uses a generalized dynamic programming framework, rather than a derived option value model like Black-Scholes. As a result, the method is applicable to a wider and more complex array of real options. For example, Kulatilaka also uses the framework to value flexible manufacturing systems [Kulatilaka 1988], global manufacturing networks [Kogut and Kulatilaka 1994 a] and platform investments [Kogut and Kulatilaka 1994 b].

In fact, aggregate-level uses of real options seem to be a major focus of recent work. Sanchez (1995, 1993, 1991) uses options models to describe strategic flexibility available to firms and how it influences product development strategy. For example, he illustrates the value of modular and platform designs that spin-out a large number of new products from a common design base. Michaels (1995) uses options valuation methods to improve the valuation of high-technology companies for which much value lies hidden in R&D investments. Amram (1997) demonstrates how to value biotech start-ups using the Black-Scholes model. Similarly, Nichols (1994) describes how Merck uses the models to value investments in start-up companies and acquisitions. Finally, Bowman and Hurry (1993) proposes the integration of options into general strategy models.

**Real Options and R&D Project Valuation**

A few published works have explicitly explored the use of real options for R&D project valuation. Treating R&D as a call option is a common approach, in which benefits represent the underlying, implementation costs act as a strike price, and the implementation date is the expiration date of the option. Figure 3-7 depicts this analogy.

and Hamilton (1988) compare R&D projects to a simple call option, and suggest that real options models are most appropriate for focused, applied R&D. This is probably true to the extent which project uncertainty is largely due to exogenous factors such as the price of inputs, rather than endogenous influences such as the uncertainty regarding the likelihood that R&D yields a workable result (i.e., probability of technical success). Additionally, the time horizon will influence the usefulness of the options approach. Short time horizons will generally lead to a narrower range of outcomes, which reduces the value of options. Other works focus on the sequential nature of R&D and attempt to develop optimal investment timing models [Grossman and Shapiro 1986, Roberts and Weitzman 1981].

Overall, these efforts indicate that options approaches can expose hidden value in R&D. This occurs because R&D is often highly contingent. While most efforts focus on either financial options or decision analysis, this research aims to compare, and possibly integrate, both methods. A major goal is to develop a practical basis for comparing projects, and model simplicity is emphasized.

Figure 3-7: An Analogy Between R&D and a Call Option
Valuing the Example Project Using a Real Options Approach

This section demonstrates the real options approach using the hypothetical research project presented in Table 3-1. NPV suggests the project has a negative value (−$31,818). However, a decision tree (revised NPV) analysis indicated that the project is quite valuable (+$218,182) since it has a continuation option.

The Black-Scholes model can be applied to value the project using the analogy that choosing to invest in the testing phase of the project provides the option to license the technology a year later. If the option is exercised, a licensing fee is collected in exchange for the cost of technology transfer. The licensing benefits are analogous to a stock price, and the cost of technology transfer represents the strike price of the option.

Since the license fees are directly tied to the price of commodity material that is assumed to trade in equilibrium, the current price of the material can be used to estimate the current value of the licensing contract. Thus, the current value of the contract is $1,000,000 (1,000,000 * current price of $1.00). Similarly, the range over which the license fee might vary defines the volatility of the option. The price volatility of the commodity material substitutes directly in this case, and can be estimated using Equation 3-9 and the price data from Table 3-1.

Combined in the Black-Scholes model, these factors lead to an estimate of project value. Table 3-4 presents the results of applying the project data from Table 3-1 and the Black-Scholes model (Equation 3-4) to value the example project.

To be financially attractive, the real options value of the project must exceed the initial R&D expense, since this is the cost of acquiring the option to continue. Table 3-4 indicates that the project value is $118,332, which is the value from the Black-Scholes model (+$218,332) less the initial project cost of $100,000. Like decision analysis, this real options approach indicates that the project has positive value and is worth pursuing, contrary to the NPV recommendation.
Table 3-4: Valuing the Example Project in a Real Options Model

<table>
<thead>
<tr>
<th>Financial Option Factor</th>
<th>Real Options Equivalent</th>
<th>Example Project Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock Price</td>
<td>Current Value of License Contract</td>
<td>$1.00*1e^6 = $1,000,000</td>
</tr>
<tr>
<td>Strike Price</td>
<td>Cost of Project Completion</td>
<td>$1,100,000</td>
</tr>
<tr>
<td>Time to Expiration</td>
<td>Time to License Decision</td>
<td>1 year</td>
</tr>
<tr>
<td>Volatility of Stock Returns</td>
<td>Volatility of Commodity Material Price</td>
<td>LN(1.8/1)/1^0.5 = 0.6</td>
</tr>
<tr>
<td>Risk-Free Rate of Interest</td>
<td>Risk-Free Rate of Interest</td>
<td>5%</td>
</tr>
<tr>
<td>Value of Financial Option</td>
<td>Value of Project Option</td>
<td>$218,332</td>
</tr>
<tr>
<td>Net Gain</td>
<td>Project Value</td>
<td>$218,332-$100,000</td>
</tr>
<tr>
<td>(Option Value-Option Cost)</td>
<td>(Option Value-Initial R&amp;D Costs)</td>
<td>$118,332</td>
</tr>
</tbody>
</table>

However, the real options estimate of project value (+$118,332) differs from the decision analysis result (+$218,182). This difference results primarily from the incorrect application of an arbitrary, constant discount rate in the decision tree. In fact, the error that results from using discrete probabilistic estimates of commodity price in the decision tree tends to undervalue the cash flows compared to the Black-Scholes model. Thus, assuming a constant discount rate applies to projects with options can introduce significant valuation errors when project value is strongly correlated with an exogenously priced asset.

Figure 3-8 makes the magnitude of the discounting error more apparent. It presents the elasticity of the option versus outcomes of the underlying asset. The beta of an option is the product of the option elasticity and the beta of the underlying asset. Therefore, Figure 3-8 indicates that the beta of the option is two to four times that of the underlying, across the range of outcomes considered in the decision analysis valuation ($0.55 to $1.8).

Consequently, the appropriate discount rate for a project with an option on this asset is much higher than it would be for a project without the option, and it varies across outcomes of the underlying. This confirms that applying the constant discount rate that was used to evaluate the project without an option to evaluate the project with an option understates the risk adjustment. It is also inappropriate because the proper discount rate varies across outcomes.

---

10 Option Elasticity = N(x)*S/C, where N(x), S and C are defined in Equation 3-4. [Cox and Ross 1985]
Figure 3-8: The Option Elasticity Shows that the Option Beta Exceeds the Beta of the Underlying Asset (S) and Varies Across Outcomes of S

The binomial model can also be applied to value the project. For a one-period call option (see Equation 3-5), the values of u and d are 1.8 ($1.8/$1.0) and 0.55 ($0.55/$1.00), respectively (see Equation 3-8). Since S is $1,000,000, Su and Sd are equal to $1,800,000 and $550,000. The strike price is $1,100,000, so Cu and Cd are $700,000 and $0 (i.e., Max[0, S-K]). Then, given r equal to 1.05, p and p' are 0.4 and 0.6 (Equation 3-8). The value of the one-period call option is therefore:

\[ C = [p \cdot Cu + p' \cdot Cd]/r = [0.4 \cdot 700,000 + 0.6 \cdot 0]/1.05 = 266,667 \]

Subtracting the cost of R&D yield the estimate of project value:

\[ \text{Project value} = 266,667 - 100,000 = 166,667 \]
This differs from the Black-Scholes value, but the difference is due to errors that result from using one interval to represent the time period, not discounting problems. Table 3-5 shows the results of applying the binomial model using up to four intervals to represent the time period. It shows that as the number of intervals used to simulate the evolution of the commodity price are increased, the option value predicted by the binomial model converges with the Black-Scholes model.

<table>
<thead>
<tr>
<th>Table 3-5: Comparing the Binomial and Black-Scholes Models</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>u</td>
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<tr>
<td>d</td>
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<td>p</td>
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<tr>
<td>p'</td>
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<tr>
<td>C</td>
</tr>
<tr>
<td>C-R&amp;D Cost</td>
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</tbody>
</table>

A GENERAL APPROACH TO VALUING REAL OPTIONS

A legitimate criticism of the example R&D project this chapter has examined is that the project has a revenue stream that is a simple multiple of a commodity material price. While this enables an easy comparison of several valuation methodologies, it is hardly representative of reality. Most R&D projects do not have such a simple relation between priced assets and cash flows. This problem is a common criticism of real options demonstrations. [Kensinger 1987]

Unfortunately, the lack of obvious underlying assets has resulted in some good intentioned, but flawed uses of options models to value projects. Common approaches force-fit projects into the Black-Scholes model. For example, Sanchez (1991) estimates project revenues, discounts these at a rate on order of the weighted average cost of capital (WACC), and uses the result as the current value of the underlying asset. He then applies

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the Black-Scholes model and examines project value using volatility as a sensitivity variable. Belnap (1995) and Michaels (1995) use similar processes, and this analogy is frequently cited in the literature (e.g., Newton and Pearson 1994, Mitchell and Hamilton 1988).

While this approach allows cognitively useful analogies to be developed, it runs counter to the rationale of developing options models in the first place. First, the application of a risk-adjusted discount rate to the revenue stream is inappropriate because these revenues will be influenced by the opportunistic actions that project options enable. Therefore, the level of risk in the revenues is non-constant. Second, the project revenues are not a traded asset or economic good. Therefore, the risk-neutral procedure that the Black-Scholes model implicitly uses is not applicable. There is simply no basis for assuming that the current value of revenues and a subjectively estimated standard deviation describe equilibrium expectations of how these revenues will evolve over time.

Similarly, Schwartz (1994) criticizes Dixit and Pindyck (1994) for suggesting that real options can be represented in dynamic programs using a discount rate that simply reflects the decision maker's valuation of risk. Again, this ignores a fundamental issue that option valuation methods were specifically developed to address. Dynamic programs are essentially decision trees, and the same valuation problems that this chapter demonstrates using decision trees will result from the application of an arbitrary rate in dynamic programs.

Fortunately, Kulatilaka (1993) and Trigeorgis (1995) describe a general real options methodology that solves these issues. The solution strategy requires four major steps:

- identify a set of priced assets such that all project cash flows can be modeled as functions of one or more of these assets or of other cash flows;
- transform these priced cash flow drivers into risk-neutral distributions;
- apply the transformed drivers to estimate cash flows;
- discount the resulting cash flows using the risk-free rate since they represent expectations in a risk neutral world.
For example, Kulatilaka (1993) uses this method to value a switching option that a duel-fuel boiler burner provides. For an additional up-front cost, a duel-fuel burner allows low cost switching between fuels. As a result, fuel price differences can be exploited. In contrast, single-fuel burners provide complete exposure to fuel price fluctuations.

First, Kulatilaka expresses the cost of running the burner as a function of oil and gas prices. Second, the actual price dynamics of these inputs are modeled using historical data and Equation 3-6, and then a risk-neutral approach is applied to estimate expectations in a risk-neutral world. Third, the risk-neutral price expectations and cost functions are used in a dynamic program to estimate the expected costs of running the duel-fuel burner and single-fuel burners over a ten year period. Finally, because risk-neutral transformations of input prices are used, the costs of running the burners can be discounted at the risk free rate. The value of the flexibility option provided by the duel-fuel boiler is obtained by comparing the discounted cost of operating the flexible boiler with the discounted costs of running single-fuel burners.

The real options example that this chapter developed effectively applies this type of process, but the cash flows are simply direct multiples of the underlying asset price and a simple call option analogy is used. The binomial model example is the most transparent demonstration. First, the priced asset that drives the R&D project revenues is the commodity price. Second, the risk-neutral approach that the binomial process utilizes transforms the expected prices of the commodity into a set of risk-neutral expectations (e.g., Su and Sd with associated probabilities Pu = p, and Pd= p'). Third, the project cash flows are modeled by examining the option to license the technology. Finally, once the optimum licensing decisions are determined using the risk-neutral drivers, the project cash flows are discounted at the risk-free rate.

In other cases, the relationship between project cash flows and exogenous factors might be more complex. Further, different types of options might be considered. For example, the case study that this thesis develops relates exogenous priced factors to the
production of vehicles using a simple linear regression model. Variations in production volume are then simulated using the risk-neutral distribution of the driving factor (a stock price). These variations in output are then applied to value R&D projects that accrue revenues as a function of production output. Appendix B presents the regression model and detailed calculations of the risk-neutral drivers.

Overall, the power of this general approach is that it is readily adaptable to a broad range of real options cases. A major contribution of this thesis is a demonstration of how to relate R&D cash flows to exogenous factors such as priced assets and how to apply risk-neutral procedures to these transform these cash flow drivers.

Additionally, this general approach also helps to illustrate a condition under which decision analysis and real options converge. If project cash flows are uncorrelated with priced assets, then the risk premium in a risk averse world is zero. Thus, no adjustment to the distribution of driver outcomes is required for the risk-neutral valuation procedure. Under this condition, the general real options approach reduces to a simple decision tree that discounts cash flows at the risk-free rate. This is an important point because R&D uncertainty often has little to do with priced exogenous factors. In these cases, real options and decision analysis may not yield dramatically different estimates of project value. Chapter 4 explores this issue further.

Finally, Kulatilaka's (1993) is also attractive from an operational point of view, since it provides natural break-points for splitting work between organizational functions with different capabilities. For example, finance groups could develop general relations between drivers of project cash flows and priced assets, and could transform these drivers into risk-neutral distributions. This would leave R&D (and other project teams) free to concentrate on estimating the resources required to complete a project, and the potential benefits (i.e., cost and revenue functions). This information could then be combined to estimate the value of the project, inclusive of options.
A Note on the Equilibrium Drift Assumption

The risk-neutral valuation procedure is useful for valuing derivatives because it solves the discounting problem. This is accomplished by replacing the drift rate in Equation 3-6 with the risk-free rate, which is the certainty-equivalent drift rate for a risk-neutral world. However, this assumes that the underlying asset is traded in equilibrium (i.e., current price reflects adequate risk premium). This can present a problem for real options cases, because the underlying asset often is not traded in equilibrium.

Kulatilaka (1993) discusses this problem and demonstrates adjustments to the certainty-equivalent drift rate that allow risk-neutral valuation procedures to be applied. In the case of assets that fall short of an equilibrium return, the certainty-equivalent rate is simply the risk-free rate reduced by the shortfall. In the case of goods prices that are not stored in equilibrium, the appropriate risk premium must first be estimated using an equilibrium model such as the CAPM. The shortfall is then estimated as the difference between the required return given risk and the actual drift from price dynamics.

Therefore, the following is a more general approach to estimating a risk-neutral rate of return. First, the CAPM states that the expected return on an asset ($R_a$) is equal to the risk-free rate ($R_f$) plus a risk premium ($R_p$).

$$R_a = R_f + R_p \tag{3-14}$$

For equilibrium traded assets such as stocks, the total return on the asset results from both capital gains ($G$) and dividends ($D$). So, Equation 3-14 becomes,

$$G + D = R_f + R_p \tag{3-15}$$

In a risk-neutral world, $R_p$ is zero, so the expected risk-neutral growth rate ($G_{RN}$) of a traded
asset is given by Equation 3-16.

\[ G_{RN} = Rf - D \]  

(3-16)

Then, for factors that might not yield an equilibrium level of return, an additional term (the shortfall) is subtracted from Rf in Equation 3-16.

\[ G_{RN} = Rf - D - \text{Shortfall} \]  

(3-16)

In Kulatilaka's models, \( G_{RN} \) substitutes directly for the drift rate in Equation 3-6. In the binomial model, the shortfall is best treated using the dividend adjustment procedure presented in Equation 3-11.
Chapter 4: Selecting a Financial Valuation Model for R&D

Chapter 3 detailed the mechanics of applying financial analysis to value R&D projects. It made two critical points: 1) R&D projects often have valuable future decision opportunities (options) that are overlooked by common valuation procedures, 2) methods that explicitly examine these options can yield very different estimates of project value.

First, Chapter 3 demonstrates that when projects include future decision opportunities, NPV, as commonly applied, can understate project value. The main reason that this problem occurs is that without explicit framing devices, NPV tends to assume that commitment to a project is irreversible. Therefore, it estimates project value using expectations of cash-flows that do not consider the influence of future actions. Unfortunately, decision opportunities can be significant sources of project value. Chapter 3 introduces two financial valuation methods that recognize the value of these opportunities. These include decision analysis driven NPV and real options.

Second, Chapter 3 shows that valuing projects with embedded options using decision tree based NPV and real options can yield different estimates of project value. This stems from a critical difference in the two methodologies. Real options models correctly discount project cash-flows for risk. In contrast, NPV in a decision tree requires the use of an arbitrary discount rate. When project cash-flows are correlated with exogenous, priced factors such as a commodity or a stock, this difference can be significant. However, if project cash-flows are not correlated with exogenous priced factors, then the real options approach is equivalent to conducting NPV in a decision tree using the risk free rate as a discount rate.

These points are illustrated using an example project with a single decision opportunity that was contingent upon the observed price of a commodity material. NPV that ignored the decision opportunity suggested that the project was not attractive. A decision analysis based NPV indicated that the option to continue had sufficient value to justify starting the project. A real options assessment showed that while the project was
attractive, the decision analysis approach overvalued this particular option. Thus, real options was the most appropriate valuation methodology for this project.

However, the example in Chapter 3 oversimplifies the reality of R&D. In particular, it is unlikely that most R&D projects will only have uncertainties that are related to the price of an exogenous, traded asset. In fact, most projects will have significant, endogenous uncertainties that have no relation to exogenous market outcomes. Examples of endogenous uncertainties include the likelihood that a R&D effort will yield a feasible result, and the range over which the technical achievements of a feasible technology might vary.

Chapter 4 focuses on exploring the reality of the R&D uncertainty environment, and develops a framework that recommends specific valuation models based on the level of exogenous and endogenous uncertainty in a project. It concludes that a hybrid combination of a decision tree and a real options model forms a general model that can value any project with identifiable cash-flows. However, this general model may not always yield more insight than simpler frameworks.

This conclusion is reached by exploring two key issues related to project valuation. The first is the degree to which a framework can reasonably represent the important structural elements of a project. The second is the degree to which representative models are efficient. Efficiency means that a model is the simplest form of framework that is required to value a project properly (i.e., sufficient and necessary).

Chapter 4 closes with further reflections on the conditions that render project options important. It discusses metrics of exogenous and endogenous uncertainty, and explores the relation between project revenues, costs and the value of options. It also examines organizational and contextual influences that drive the selection of financial valuation frameworks.
Figure 4-1: Representativeness of Financial Models for Projects with Options (Models that Capture Important Project Value Drivers)

**REPRESENTATIVENESS OF FINANCIAL VALUATION MODELS**

Figure 4-1 highlights the ability of three financial models to represent important value drivers of projects with future decision opportunities. It builds on the first key point of Chapter 3 (valuation frameworks that ignore options can undervalue projects) by indicating that project options are only important when there is uncertainty. Models that ignore contingencies, such as simple implementations of NPV, become less relevant as uncertainty increases because the decisions introduce asymmetries into the project cash-flows.

Consider the value of a project with an implementation decision that occurs one year from the present when there is no uncertainty about the future price of an asset that drives the project revenues.\(^{11}\) The NPV of the project is the discounted expected value of the revenues less the discounted costs of initiating the project and implementing the results:

\[^{11}\text{Note: The following discussion relies on notation introduced in Chapter 3.}\]
\[ NPV = \frac{(EV(S) - K)}{R} - R&D\ Cost \quad (4-1) \]

where, the expected value of revenues, \( EV(S) \), is known with certainty, and \( R = 1 + \) the risk-adjusted discount rate

A two-outcome decision tree that avoids implementation when a low outcome \( (S_L) \) is obtained leads to the following expression of value:

\[ DA_{NPV} = \frac{P(S_h - K)}{R} - R&D\ Cost \quad (4-2) \]

where \( P \) is the probability of obtaining the high outcome, \( S_h \)

The decision tree avoids a loss equal to \( (1-P)(S_L - K)/R \). However, in the certainty case, \( EV(S) \) is obtained with a probability of one, and the value of investing reduces to the simple NPV model (Equation 4-1). Both frameworks recommend investing if the estimated value exceeds zero.

Finally, the binomial model would represent the value of the project as follows:

\[ C = \frac{[pCu - p'Cd]}{r} \quad (4-3) \]

where \( Cu = \text{Max}[0, Su - K] \)
\( Cd = \text{Max}[0, Sd - K] \)

For the certainty case, \( Su = Sd = rS \). Then, since \( p + p' = 1 \), the project is valued as follows:

\[ C = \text{Max}[0, S - K/r] - R&D\ Cost \quad (4-4) \]
S-K/r is equal to (EV(S)-K)/R, since EV(S) = rS and R= r for certain revenue streams. Therefore, the three models value the project equally.

Similarly, for relatively low levels of uncertainty, a simple NPV model that focuses on expected values without considering potential future actions will yield a value estimate that is close to the options methods. For example, consider the decision tree model represented by Equation 4-2. The value of the avoided loss (1-P)(S_t-K)/R is small until P<<1 (and S_t<<K).

Thus, Figure 4-1 makes two important points. First, it is never incorrect to apply options methods to value projects. These models aim to accomplish the same goal as NPV, while valuing contingent decisions. As a result, the resolution of options models is at least equivalent to simpler models. Second, the benefit of an options approach is mainly realized in uncertain environments. As a practical matter, this issue is important only if conducting an options assessment is deemed more difficult than using other value metrics.

Figure 4-1 therefore questions general recommendations that options methods are useful for valuing R&D projects. It suggests that there are specific conditions under which different valuation methods apply. However, Figure 4-1 does not specify the conditions under which real options or decision analysis will be the most appropriate approach to valuing projects in uncertain environments. This issue is addressed through the following discussion of model efficiency.

EFFICIENCY OF FINANCIAL VALUATION MODELS

Figure 4-2 indicates which valuation models are most appropriate under specific uncertainty environments. It considers exogenous, market-related uncertainties (i.e. priced factors) and endogenous, project-specific uncertainties. Four uncertainty environments are represented: 1) low exogenous and endogenous uncertainty, 2) high exogenous and low endogenous uncertainty, 3) low exogenous and high endogenous uncertainty, 4) high exogenous and endogenous uncertainty.

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12 What constitutes low uncertainty is discussed shortly, and is dependent on several factors.
Figure 4-2 identifies models that are the efficient choice for a given uncertainty environment. Efficiency has two components. First, the model must be sufficient to value the project properly. Second, of the sufficient models, the efficient model has the simplest form. Figure 4-2 indicates that NPV is the efficient choice for low uncertainty environments, real options is efficient for environments with high exogenous uncertainty alone, decision analysis is best when only endogenous uncertainty is high, and a combination of real options and decision analysis is needed for simultaneously high levels of exogenous and endogenous uncertainty.

First, consider quadrant one in Figure 4-2. When there are no major uncertainties, the value of an option approaches zero, and NPV, decision analysis and real options will converge. This point was illustrated during the discussion of Figure 4-1. Therefore, Figure 4-2 recommends NPV for the low uncertainty case because it is the simplest of the three models.
Next, quadrant two in Figure 4-2 recommends real options for valuing projects that have high levels of exogenous uncertainty. The rationale is simple. Options become increasingly important as uncertainty increases, and only real options models are capable of valuing project options that are dependent on the price paths of traded assets. Decision trees can represent the structure of the option, but cannot solve the discounting problem. Chapter 3 discusses this issue in detail. In particular, Figure 3-8 illustrates that the beta of the option, and therefore the appropriate discount rate, exceeds the beta of the underlying asset and is non-constant. Thus, a constant discount rate in a decision tree is inappropriate, and no basis for selecting a set of proper, risk-adjusted rates exists. The risk-neutral valuation procedure that real options models utilize solves this problem.

In contrast, the third quadrant of Figure 4-2 recommends decision analysis as the efficient model. In this case, an options framework is needed because the general uncertainty environment is high, but real options models effectively collapse into decision analysis methods. Simply put, endogenous project uncertainties are not correlated with external market events. Therefore, the beta of cash-flows that are functions of endogenous uncertainties is zero, and the proper discount rate for evaluating these cash-flows is the risk-free rate. As a result, discounting cash-flows in a decision tree using the risk-free rate is necessary and sufficient.

Finally, quadrant four represents the case when a project faces both appreciable exogenous and endogenous uncertainties. In this case, it follows from the discussion of quadrants two and three that a combination of real options and decision analysis is needed. A project valuation is conducted by translating any exogenous uncertainties into risk-neutral distributions, combining these translated distributions with the endogenous uncertainties in a decision tree, and discounting the resulting project cash flows at the risk-free rate.

It also follows that a combined real options and decision analysis model is a general valuation framework that is sufficient for valuing any project in any quadrant of Figure 4-2. Therefore, always using a combined model is a fail-safe approach for valuing projects.
tradeoff that the case study in this thesis examines is the relative increase in data requirements. If these are manageable, the combined model is a promising general methodology. If not, the following discussion of conditions that render options important becomes more relevant.

**THE ROLE OF UNCERTAINTY IN THE VALUE OF OPTIONS**

So far, Chapter 4 has not defined what constitutes a high level of uncertainty. While it is difficult to eliminate all subjectivity, the following sections provide additional insight regarding the conditions under which options models will yield signals that differ significantly from simpler metrics of value.

**Time Dependence of Uncertainty**

Uncertainty in options models refers to the range of outcomes over which the underlying is likely to vary. The basic metric of uncertainty is a standard deviation. For exogenous, priced factors, the standard deviation is commonly time-dependent. This stems from the mean-drift process that many such assets follow (see Equation 3-6). For endogenous uncertainties, such as the likelihood that a technology will work, it is more difficult to generalize how the uncertainty evolves over time. Common methods for measuring subjective probabilities do not introduce any time dependence (see Merkhofer 1987), but these probabilities are usually measured with a specific decision problem in mind that establishes the relevant timeframe. However, it seems reasonable to assume that these subjective estimates will show a larger spread for events that are expected to occur at a later rather than an earlier date.

Regardless, given that most R&D projects with identifiable cash-streams (i.e., Tier 2 and 3 projects) will have both endogenous and exogenous uncertainties, it is appropriate to state that at least some project uncertainty will increase as the project timeframe increases. Thus, the importance of applying models that evaluate contingencies will also increase with the timeframe over which decisions can be made.
The Relation of Revenues and Costs

Figure 4-3 illustrates another important issue that determines if an options approach will yield significantly different signals than simpler metrics of value. It shows three different probabilistic distributions of the underlying asset (S), and indicates their relation to the strike price of the option (K).

Figure 4-3 points out that the mean of a distribution is also an important determinant of option value. For example, the outcomes in Case 1 are all less than the strike price (the option is out of the money). In this case, the value of the option approaches zero, because it is not likely that the option will ever be exercised. A simple NPV assessment using the expected value of the distribution and the strike price would signal the same conclusion (NPV is negative, option is worthless). Similarly, Case 3 lies entirely above the strike price (the option is in the money). In this case, the option will almost always be exercised, and its value approaches \( S - K/r \). NPV would also signal that this option is valuable, but it would incorrectly value the option if the underlying is correlated with priced exogenous factors.

Only when the distribution of outcomes is positioned near the strike price (Case 2) does a dramatically different signal result. In this case, NPV still suggests that the option has little value (expected value is equal to strike price). Methods that explicitly value options are required to capture the important asymmetry. The option will be exercised for outcomes that are greater than the strike price, but not for lesser outcomes. Thus, the option based model captures all of the profitable opportunities, but none of the losses that get rolled into the simple NPV.

Case 2 also represents a situation where the value of the option is most sensitive to the level of uncertainty. While NPV would continue to suggest the option was worthless, increasing the spread of the distribution (the uncertainty) in Case 2 rapidly increases the value of the option, since the asymmetries of cash-flows become more pronounced. In contrast, the range of outcomes (the uncertainty) is less important in Case 1 and 3, as long as the bulk of the expected outcomes remain entirely below or above the strike price.
Figure 4-3: Relating Option Value to Underlying Uncertainty and Strike Price

Figure 4-4: Options Models are Most Likely to Signal Different Investment Policies than NPV for Near the Money Cases (S Close to K)
Figure 4-4 is similar to Figure 4-3. As a practical tool, it indicates that the degree to which options models will yield a different signal than simple metrics is strongly related to the relative level of underlying value and strike price. The width of the band where mixed signals occur will increase with uncertainty. However, the exact form of option model that is most appropriate remains dependent on the type of uncertainty (see Figure 4-2).

**IMPLICATIONS FOR R&D PROJECTS**

Chapter 4 makes two key points that should be kept in mind when deciding whether or not to use an options approach to value R&D projects. First, properly applied, options models always yield an appropriate estimate of project value. In particular, a combination of real options and decision analysis forms a general valuation framework that can treat both exogenous, market related uncertainties and endogenous, project-specific uncertainties. Second, the benefits of options methods accrue at several levels. On an absolute basis, these models yield the most correct value estimate. On a relative basis, the signal that options valuation methods provide will differ from simpler value metrics mainly when project uncertainty is high (i.e., long timeframe and wide spread of potential outcomes) and the underlying driver of option value is close to the exercise cost (i.e., option is near the money).

For the Tiers of R&D framework (Hauser and Zettelmeyer 1996), these findings indicate that while Tier 3 projects are the most amenable to financial valuation, the short-term focus and low uncertainty of these efforts reduces the likelihood that options based valuations will reveal dramatically different investment policies compared with standard financial valuation methods. In contrast, the Tier 2 efforts should benefit from an options perspective, since these projects are longer-term and have more uncertainties.

The frameworks presented in Figure 4-1 through Figure 4-4 can help to assess when a specific project should be valued using an options approach. For example, for the R&D implementation options that the case study in this thesis examines, Figure 4-4 implies that a preliminary inspection of expected project revenues and implementation costs will indicate if options models will signal different investment policies than simple NPV methods.
CONTEXTUAL DRIVERS OF VALUATION FRAMEWORK SELECTION

Much of this thesis explores improvements to difficulties of applying conventional valuation methods to R&D. It argues that real options and decision analysis methods are better methods for valuing projects with contingencies. In particular, decision analysis is most applicable to project-specific, endogenous uncertainties, while real options is best for valuing the influence of exogenous, market-related uncertainties.

However, organizational context also influences the choice of valuation frameworks. Consider the experiences of Merck and Kodak. These two companies acknowledge that the options-like nature of R&D is important and that NPV ignores these valuable features. Both use options analysis in their R&D management processes, but Merck relies on real options models while Kodak prefers decision analysis [Nichols 1994, Faulkner 1996].

Key differences in the business and functional environment probably influenced these choices. The homogeneity of R&D processes, the relationship of project to tangible dollar benefits, and the background of the individuals that choose to implement options analysis appear critical. Table 4-1 compares Merck and Kodak along these dimensions.

Consider the business environment that Merck faces in drug research. Pharmaceutical R&D is highly regulated, so there is homogeneity in how projects progress. As a result, Merck can develop statistical estimates of project costs, variations, and survival rates for the various stages of pre-clinical and clinical trials required to obtain government approval for a new drug. Additionally, epidemiological data provides a basis for forecasting potential demand, and any successful project is essentially a new drug to which sales dollars accrue. Successful projects essentially become stand-alone products. This environment makes it relatively easy to implement the Black-Scholes option pricing formula because the available sources of data closely match the requirements of the model.

In contrast, Kodak produces photographic equipment, film and complementary products such as the color printer evaluated in Faulkner's (1996) paper. Although dollar benefits of developments might be readily estimated, Kodak's R&D efforts probably cover a
wider scope than Merck's. Thus, project timeframe and costs are probably less predictable, and it is hard to describe an average project. As a result, developing a Black-Scholes model of R&D projects in this environment is more difficult. Kodak believes that the flexibility of decision analysis off-sets losses in precision that result from using decision trees to approximate the value of real options.

Functional environment can also play a role in framework selection. A finance group drives Merck's options effort, and many people working are familiar with the details of financial models. In contrast, R&D is responsible for Kodak's effort. In this case, decision analysis is probably a better communication tool, since fewer individuals are familiar with financial options models. As Faulkner suggests, the "options thinking" perspective of decision analysis may be more important than the attempt to value technology precisely.

Compared along these dimensions, the automotive materials technology case being developed for this thesis has more in common with Kodak than Merck. The environment is heterogeneous and the case study is being developed in an R&D setting. Further, the complexity of the product, in terms of components and systems, is greater than that faced by either Kodak or Merck.

These observations indicate that precision is not always the major objective of valuing R&D. Frameworks that provide improved signals may be sufficient. Certainly, organizations are willing to trade-off only so much practicality for improved resolution. These issues are also explored during the case study in Chapter 7.

<table>
<thead>
<tr>
<th>Table 4-1: Options Analysis Cases in R&amp;D</th>
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<tr>
<td></td>
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<tr>
<td><strong>R&amp;D Process</strong></td>
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<tr>
<td></td>
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<tr>
<td><strong>Product</strong></td>
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<tr>
<td><strong>Project Financial Benefits Estimation</strong></td>
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<tr>
<td><strong>Functional Champion</strong></td>
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<tr>
<td><strong>Framework Choice</strong></td>
</tr>
</tbody>
</table>
Chapter 5: Methods for Valuing Complex R&D Benefits

Chapter 5 examines methods that rank alternatives based on several criteria or contexts. The objective is to identify methods that can place a dollar value on complex R&D benefits, and that could be used in conjunction with financial valuation models. Multi-attribute utility theory shows promise for meeting this objective, but may be too complicated for practical implementation. For this reason, some methods that approximate the value of complex benefits are also considered. Finally, scenario planning is reviewed because it focuses on integrating important contextual issues into the valuation process.

Some General Multi-Metric Decision Methodologies

A variety of methods for ranking alternatives based on several attributes exist. Unfortunately, for the purpose of valuing R&D, the field narrows since many do not yield a dollar estimate of value. Therefore, using the results in financial models is not possible.

Some standard approaches are introduced below. A detailed discussion of each is beyond the scope of this work, but useful references are noted. In particular, Field (1985) and de Neufville (1990) provide detailed criticisms of the sorting and optimization models. Many of their arguments also apply to frameworks such as quality function deployment and the analytic hierarchy process.

Simple Sorting Techniques

These methods sort a set of alternatives by one or more criteria. Exclusionary methods eliminate any choice that fails to meet a threshold (e.g., must cost less than x dollars). Conjunctive models disregard all but one attribute (e.g., fastest microprocessor). Lexicographic methods sort alternatives by all attributes of concern, according to a separate ranking of the attributes. Alphabetizing is a lexicographic sort. Another example is selecting the lowest cost tennis racquet from the set that weigh the least. Not only do these frameworks fail to quantify the value of an alternative, simple sorting techniques also tend to be poor decision aides because they ignore tradeoffs that end-users make between attributes.
**Optimization Models**

Linear, non-linear and goal programming are examples of optimization techniques that identify conditions which maximize or minimize a specific aspect of a system. These models require a mathematical model of a system that includes constraints and relationships between variables. For example, a linear program might minimize the cost of mixing an alloy, given prices and constraints on the quantities of the constituents. Although there have been attempts to tailor these models to R&D portfolio analysis, Liberatore and Titus (1983) find that adoption by industry is virtually non-existent. Complexity and data availability hinder their use. Field (1985) also notes that the results of such assessments are contextual; the addition of new alternatives requires a complete reassessment.

**Weighted Scoring Methods**

Weighted indexes identify a set of attributes on which to judge a set of alternatives, assign a scaled score to each alternative for each attribute, and multiply this score by a weighting. The result is a metric of preference. Table 5-1 presents an example of a weighted scoring that compares two products (A and B) by cost and product life. The table uses a scale of 1 to 3, with 3 being the best outcome (i.e. lowest cost or longest life). The importance weights also range from 1 to 3, with 3 being most important. In this example, the low cost, short life Product A outranks the high cost, long life Product B.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Importance Weight</th>
<th>Product A Characteristics</th>
<th>Product B Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Product Life</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Weighted Score</td>
<td></td>
<td>3<em>3+1</em>1= 10</td>
<td>3<em>1+1</em>3 = 6</td>
</tr>
</tbody>
</table>

David (1986) points out that weighted scoring models have many attractive features, including ease of use and adaptability. However, Schoemaker and Russo (1993) note that agreeing on the weights and attribute ranks is difficult, and that the model often oversimplifies the problem. It certainly only provides a relative ranking. In the example, it is not possible to say in a meaningful way how much better Product A is than Product B.
Quality Function Deployment

The "house of quality" is a product development methodology that is similar to weighted scoring models. It is a key design tool of the widely successful quality function deployment (QFD) management process. [Hauser and Clausing 1988] The house of quality uses a matrix to compare design attributes to product features and compares these with competing products and customer perceptions. The goal is to provide guidance on setting targets for product features, even if complex interactions between features occur.

Recent work suggests that QFD improves cross-functional communication between engineering, marketing and manufacturing. [Griffin and Hauser 1992] While extending QFD concepts to R&D might be fruitful, the methodology still does not result in a dollar metric of value. As a result, it is not attractive as a precursor to R&D project valuation. However, the focus on end-users is important, and it is possible that information gathered through the "voice of the customer" portion of QFD could assist R&D valuation efforts.

Analytic Hierarchy Process

The analytic hierarchy process (AHP) is a multi-metric decision model with several promising features. Specifically, it compares alternatives on qualitative and quantitative dimensions, the assessment procedures are relatively easy to conduct, and it identifies a preferred choice. [Saaty 1980] AHP is also useful for group decision-making. [Dyer 1992]

AHP breaks an objective into levels (hierarchies) to structure the problem in an intellectually intuitive manner. Figure 5-1 shows Liberatore's (1987) R&D hierarchy. It starts with corporate technology goals (Level 1), and splits these into business goals including maintain, expand and diversify (Level 2). Then, process, product and exploratory R&D efforts (Level 3) are related to the Level 2 categories. This hierarchy permits a ranking of projects based on their impact on the overall technology goals of the firm.
Unfortunately, AHP suffers from problems that limit its usefulness. In particular, Dyer (1990) shows that adding new choices to an assessment may lead to "rank reversal." Essentially, a preferred alternative may appear unfavorable upon the introduction of a near, or duplicate copy in a subsequent assessment. This is akin to saying that one prefers a Mercedes to a Saturn when the two are directly compared, and then switching to the Saturn if it is compared simultaneously to the Mercedes and a BMW. Dyer (1990) details the mechanical flaws that cause this problem. Although, Saaty (1990) rebuts this criticism, AHP is still not attractive for R&D valuation because it results only in a relative ranking.

**MULTI-ATTRIBUTE UTILITY ANALYSIS**

Multi-Attribute Utility Analysis (MAUA) is a promising method for valuing R&D with complex benefits because it can lead to a dollar based estimate of value. MAUA provides a quantitative basis for valuing alternatives. It develops a scale, referred to as utility, that weighs each relevant attribute according to its importance to a set of
stakeholders (e.g. consumers, regulators, engineers). Overall, a single metric of value results, where higher levels of utility are preferred to lower levels.

Applied to technology assessment, MAUA recognizes that individuals value sets of product attributes, and that they make trade-offs between these attributes when deciding on an alternative. MAUA provides a basis for estimating how potential end-users value technical and economic product features. As a result, it can indicate which product is likely to be preferred by a given a set of stakeholders. More importantly, it can gauge how much specific improvements would improve the competitive position of a less favorable choice.

The basic output of utility analysis is an expression of stakeholder preferences. Figure 5-2 graphically represents preferences for price and performance as utility curves, which indicate combinations of these attributes that specific stakeholders value equally. Consider the line labeled "moderate utility" in Figure 5-2. If this utility curve accurately reflects a stakeholder's preferences, he should be indifferent between any products that offer a combination of price and performance that lies along it. In general, higher levels of performance and lower levels of price are preferable. Therefore, products with higher utility lie to the left and above the "moderate utility" curve, while those with lower utility are to the right and below.

Although the generalizations that lower price and higher performance are preferable obviously lead to similar insights, utility additionally provides a basis for estimating how much more valuable one alternative is than another. As a result, it provides a basis for identifying a preferred alternative in cases where clear dominance is not obvious.

For example, Figure 5-3 shows how utility identifies a preferred product (A, B, C, or D), for three possible sets of stakeholder preferences: price-sensitive, pays for performance, and compromises. The steepest utility curve represents a price sensitive end-user because large performance gains are required to offset small price increases. Conversely, end-users who pay for performance tolerate large price increases in return for small performance gains.
Figure 5-2: Utility Gauges the Value of Sets of Product Attributes for Specific User Groups and Identifies Combinations They Value Equally.

Figure 5-3: Utility Identifies Preferred Choices for Different Preference Sets
Figure 5-4: MAUA Estimates the Value of Improving the Price and Performance of Product B By Comparing it to the Value Leader, Product D.

The preferred product for each case lies to the left of the utility curve while all others lie on it or to the right. Thus, A is the price sensitive choice, C is the performance choice and D is the best compromise. Product B is never preferred.

Although this static view of competitiveness provides a useful benchmark, utility can also gauge how product improvements would affect desirability. Suppose that R&D could improve Product B. The preference curves in Figure 5-3 provide a basis for estimating the level of performance increase or price decrease needed for Product B to be competitive. Thus, MAUA can be a powerful tool for guiding product development.

MAUA Applied to R&D Valuation

Figure 5-4 illustrates how utility can help to value R&D projects. It highlights an R&D effort to improve the price and performance of Product B. Utility curves represent preferences for price and performance. The value (utility) of a product increases for combinations of price and performance that approach the upper left corner of the figure,
since end-users should prefer low price and high performance. For this set of preferences, Product D has the highest utility.

Suppose an R&D project could improve the and performance and cost (and thereby the price) of B to levels represented by B' in Figure 5-4. If R&D is successful, Product B' will be more valuable than the current leader, Product D, even though B' has lower performance. Utility can estimate the difference in value difference be tween these products. This is the additional amount an end-user should be willing to pay for B' such that it has the same utility (or value) as product D.

This willingness to pay (WTP) approximates the value of the R&D project benefits to the end-user. It represents the value that the innovator hopes to appropriate. However, as Chapter 1 discusses, it is likely that this increase in value will be shared with other market participants. For example, the end-users are likely to appropriate some of the value. Otherwise, they have little incentive to switch from Product D (i.e., if innovator tries to appropriate the entire WTP, the end-users are indifferent between D and B'). Regardless, the WTP metric is quite valuable because it provides a boundary estimate of R&D value.

To estimate the willingness to pay, the price which equates the utility of Products B' and D is estimated. This is represented by B" in Figure 5-4. The difference between the price of B" and B' is the additional willingness to pay that results from the superior price and performance position offered by B' as compared to D.

Algebraically, the utilities of price and performance combinations represented by D, B', and B" are given as follows:

\[ U(D) = f(\text{Price}_D, \text{Performance}_D) \]
\[ U(B') = f(\text{Price}_{B'}, \text{Performance}_{B'}) \]
\[ U(B'') = f(\text{Price}_{B''}, \text{Performance}_{B''}) \]
Then, the willingness to pay (WTP) is the difference between the costs of B" and B':

\[ WTP = Price_{B''} - Price_{B'}. \]  \hspace{1cm} (5-1)

Financial valuation models can use this estimate of WTP, combined with estimates of what fraction is appropriable, to value the R&D project.

The relevant functions are typically developed by conducting a series of interviews with appropriate end-users. In a number of materials substitution cases, product engineers have served as proxies. Field and de Neufville (1988), Mangin, de Neufville, Field and Clark (1995), Roth (1992), Roth, Field and Clark (1994), and Clark and Neely (1995) present examples from automotive, aerospace and industrial products.

**The Mechanics of Utility**

MAUA values alternatives based on a set of attributes. Equation 5-2 represents an alternative \((X_j)\) with \(n\) attributes \((x_{ij})\):

\[ X_j = \{x_{1j}, x_{2j}, x_{3j}, ..., x_{nj}\} \]  \hspace{1cm} (5-2)

For example, \(X_j\) could be a car, and three attributes of concern \((x_{ij}\) for \(i=1\) to \(3\)) might include price, warranty period, and quality.

MAUA translates a vector of attributes \((X_j)\) into a single utility metric by separately defining functions that describe the value of individual attributes (i.e., single attribute utility functions), assessing an importance weight of each attribute, and combining the results in either a multiplicative (Equation 5-3) or additive (Equation 5-4) model that defines total utility. In Equations 5-3 and 5-4, \(U(X_j)\) represents the overall multi-attribute utility (MAU), \(u(x_{ij})\) represents the single attribute utility functions, \(K\) is the MAU scaling factor, and the \(k_i\) are scaling factors for the individual utility functions.
\[ 1 + KU(X_i) = \Pi[1 + K_k u_i(x_i)] \quad \text{for } i = 1 \text{ to } n \]  
where, \( 1 + K = \Pi[1 + K_k] \) \hspace{1cm} (5-3)

\[ U(X_j) = \sum k_i u_i(x_i) \quad \text{for } i = 1 \text{ to } n \] \hspace{1cm} (5-4)

Clemen (1991) and de Neufville (1990) provide overviews of these models and the axioms that form their foundation. Keeny and Raiffa (1976) explore MAUA in detail.

Conducting a MAUA based analysis requires a five step assessment procedure that is essentially a structured interview with a stakeholder. Field (1985) and Mangin (1993) demonstrate the procedure which includes the following steps:

- Introduce terminology and ideas to decision-maker
- Identify attributes of interest
- Assess single attribute utility functions
- Assess importance weights (scaling factors)
- Check for consistency and reiterate if necessary

One key factor that distinguishes MAUA from other multi-criteria decision-making methods is that it incorporates end-user risk preferences into the valuation. Other models such as the weighted scoring index simply assume that all tradeoffs are linear. MAUA recognizes that end-uses can show diminishing marginal returns for gains in attributes, or simply be hesitant to try a new alternative (i.e. averse to risk).

This risk preference issue creates some concerns when the methodology is suggested as a replacement for financial analysis, because the risk preferences of an individual in an organization may not best represent the needs of the firm. However, this work aims to use utility only as a basis for valuing complex R&D benefits, by expressing end-user preferences. Project valuation is conducted using a set of promising financial models.
Figure 5-5: Process for Valuing Complex R&D Benefit Streams

THE PRACTICAL APPLICATION OF MULTI-METRIC MODELS TO VALUE R&D

Figure 5-5 summarizes the objective of applying multi-metric benefit valuation methods to help value R&D projects. The multi-metric tools gauge changes in the value of a product to end-users based on changes in product features that stem from technical advances. Combined with cost estimates, the assessment of value changes from the end-user perspective leads to an estimate of potential marginal revenue that the developer of the technology hopes to appropriate. This estimate of marginal R&D revenue lead to an estimate of total potential project revenues. The total value of potential revenues then forms the basis for estimating the options value of the R&D project by serving as the underlying asset in an implementation option.

This section explores the practicality of applying multi-metric methods to value complex R&D benefits. It begins by highlighting cases in which MAUA been applied to materials technology assessments. Next, practical limitations to MAUA are discussed. Finally, it introduces potential approaches for approximating the value of multiple benefits.
Previous Uses of MAUA in Materials Technology Assessments

MAUA has been applied to assess the competitiveness of several advanced materials technologies with similarities to those that comprise the portfolio of technologies this thesis examines. Examples include Field (1985), Nallicheri (1990), Roth (1992), and Mangin (1993). Each of these works focuses on specific engineering systems such as automotive bumpers or engines, and uses utility to assess the conditions under which a new material is preferable to an incumbent.

Mangin's (1993) example is representative of these assessments. He examines the commercial potential for advanced ceramic, automotive valve-train components. MAUA forms a basis for estimating the willingness of engine manufacturers to pay for performance enhancements. Interviews with engine designers at several automotive manufacturers, using the procedure outlined earlier in this chapter, yielded the requisite data. Attributes considered include engine noise, friction, power and cost. Individual utility functions for each attribute \( x_i \) were estimated assuming they fit the form in shown Equation 5-5:

\[
U(x_i) = \left( \frac{x_i - x_i^*}{x_i^* - x_i^*} \right)^c
\]

(5-5)

where,

\[ x_i^* = \text{the best possible level of } x_i, \quad U(x_i^*) = 1 \]

\[ x_i^* = \text{the worst possible level of } x_i, \quad U(x_i^*) = 0 \]

\[ c = \text{a descriptor of an end-users risk profile, where,} \]

\[ c < 1 \text{ implies risk aversion} \]

\[ c = 1 \text{ implies risk neutrality} \]

\[ c > 1 \text{ implies risk positive} \]

Multi-attribute utility was estimated using the multiplicative form shown in Equation 5-3.

Generally, Mangin (1993) finds that engine designers are risk averse with respect to materials substitution \( c < 1 \). This behavior can result from a hesitance to try unproven technology, diminishing marginal returns for performance increases, or a combination of these factors. Unfortunately, separating the individual effects is difficult.
However, the MAUA results identify two distinct segments of engine producers: high and low end vehicle manufacturers. While both groups show some willingness to pay for performance improvements, the high end segment places more value on the performance gains that ceramics offer. Although this finding is not surprising, Mangin also uses MAUA to estimate how much the end-users are willing to pay.

Table 5-2 summarizes the MAUA results as cost premiums engine producers are willing to pay for performance enhancement (from Mangin, Neely and Clark 1993). The maximum and minimum premiums are calculated using a standard deviation obtained from the MAUA data. European manufacturers 1,2,4 and 5 are the high end group. Each is willing to pay almost $100 per engine to obtain the performance benefits offered by ceramic components. The low end segment (USA 1,2,3 and Europe 2) is only willing to pay about one-third the premium of the high end segment.

<table>
<thead>
<tr>
<th>Engine &amp; Manufacturer</th>
<th>Maximum Premium ($)</th>
<th>Estimated Premium ($)</th>
<th>Minimum Premium ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Six-Cylinder Engine</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA 1</td>
<td>47</td>
<td>34</td>
<td>25</td>
</tr>
<tr>
<td>USA 2</td>
<td>47</td>
<td>34</td>
<td>25</td>
</tr>
<tr>
<td>USA 3</td>
<td>47</td>
<td>34</td>
<td>25</td>
</tr>
<tr>
<td>Europe 1</td>
<td>95</td>
<td>95</td>
<td>80</td>
</tr>
<tr>
<td><strong>Four Cylinder Engine</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europe 2</td>
<td>125</td>
<td>116</td>
<td>107</td>
</tr>
<tr>
<td>Europe 3</td>
<td>13</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>Europe 4</td>
<td>129</td>
<td>119</td>
<td>109</td>
</tr>
<tr>
<td>Europe 5</td>
<td>118</td>
<td>109</td>
<td>100</td>
</tr>
<tr>
<td>Europe 6</td>
<td>15</td>
<td>15</td>
<td>14</td>
</tr>
</tbody>
</table>

By comparing the MAUA results with estimates of ceramic manufacturing process costs, Mangin (1993) identifies approximate conditions under which the ceramic valve-train components are commercially feasible. Key influences include production volume, yield, and
raw material cost. Thus, his research demonstrates how MAUA informs process development about what must occur for a technology to be economically attractive to specific sets of end-users.

A similar approach could be taken with many R&D projects. However, the willingness to pay estimates would serve as estimates of potential marginal revenue that could be appropriated through technology implementation.

**Limitations to MAUA**

Although MAUA is promising because it delivers a dollar estimate of willingness to pay and it enables comparisons of a wide variety of projects, the methodology has some limitations. Foremost, it focuses on incremental technology improvements. To develop a willingness to pay metric, MAUA requires that an incumbent technology and customers, or relevant proxies. Thus, utility may not be especially useful for long term, basic R&D. However, it is likely to be applicable to a significant portion of corporate portfolios, since much of industrial R&D is applied work.

Another possible limitation to utility for portfolio valuation stems from its potential for complexity. Much of the work that has applied utility to assess advanced materials substitutions has focused on specific products and limited sets of alternatives. To evaluate project portfolios, which might contain dozens of projects and affect hundreds of products or sub-systems, the level of effort required to develop meaningful utility assessments must be carefully attenuated.

Further, Perlack, Beim, Bowman and Hobbs (1997) provide a recent and detailed review of multi-criteria decision-making methodologies, including MAUA and AHP. Their work suggests that MAUA's complicated assessment procedures often overshadow its advantages, and that for many ranking purposes a weighted index approach (multi-attribute value analysis) provides essentially the same results. This is an important point, since maintaining practicality is a goal for the R&D valuation methodology this thesis develops.
Grouping projects and identifying major strategic technical objectives on which to focus valuation are two likely approaches to addressing the assessment complexity issue. This constrains the number of factors in an evaluation, and consequently the complexity of managing the multiple criteria assessment.

Developing methods for approximating utility also might improve the methodology's ease of use. Clark and Neely (1995) demonstrated one such approach to approximating utility and applied it to value industrial burner technologies.

Using a simple linear-additive value function to approximate utility is another possible way of managing the practicality of valuing multiple R&D benefits. This involves directly estimating dollar based estimates of value for specific changes in a product attribute. For example, weight savings could be valued on a dollar per pound basis. This approach is best suited to situations where empirical data, marketing research or other logical bases for developing the estimates exist.

Some potential approaches for approximating the value of complex R&D benefits are discussed next. As with the real options and decision analysis models, many organizations might be willing to sacrifice the precision of more formal multi-metric models for a substantial gain in practicality. Again, the level of effort that is put into an assessment should be commensurate with the importance of the decision.

**Approximating the Utility and Value of Complex R&D Benefits**

The major drawback to the MAUA process is that it is time consuming. As a result, using MAUA to assess the value of benefits for every R&D project in a portfolio may be economically untenable. Even if projects can be grouped into broad categories to limit the number of assessments, the methodology is highly context and application dependent. As Table 5-2 indicates, the findings can vary widely for different market segments.

One approach to addressing this problem is to approximate utility using a simplified survey of end-users. Clark and Neely (1995) developed such an approach to assess the conditions under which continuous-fiber ceramic composites (CFCC's) would be attractive
as industrial burners in several U.S. markets. The major benefit of CFCC's in this application is that they dramatically reduce the emission of combustion products, including nitrous oxide compounds. However, these materials tend to be expensive and are susceptible to damage compared to the incumbent burners which are typically made from steel.

To estimate the cost target that CFCC's need to meet to be competitive with steel burners, Clark and Neely (1995) performed a simple survey of potential end-users in several geographical areas. The respondents ranked a number of product attributes using a scale of one to three, with one being most important and three being least important. Table 5-3 shows the results of the survey. These rankings, and information regarding the technical performance of various burners shown in Table 5-4, were used to approximate utility functions for the individual attributes and scaling factors for MAUA.

Table 5-3: Survey Results from Interviews of Industrial Burner End-Users: 1 = Most Important, 3 = Least Important
[Clark and Neely 1995]

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Average Importance (Southern CA)</th>
<th>Average Importance (Eastern OH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase Cost</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>1.4</td>
<td>1</td>
</tr>
<tr>
<td>Product Life</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>NO\textsubscript{x} Emissions</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>CO Emissions</td>
<td>1.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 5-4: Select Performance Characteristics of Industrial Burners
[Clark and Neely 1995]

<table>
<thead>
<tr>
<th>Attribute</th>
<th>CFCC</th>
<th>Incumbent</th>
<th>Best (x')</th>
<th>Worst (x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase Cost ($/MBtu)</td>
<td>4</td>
<td>2</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>Energy Efficiency (%)</td>
<td>0.82</td>
<td>0.8</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Product Life (years)</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>0.01</td>
</tr>
<tr>
<td>NO\textsubscript{x} Emissions (ppm)</td>
<td>9</td>
<td>30</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>CO Emissions (ppm)</td>
<td>5</td>
<td>30</td>
<td>0</td>
<td>600</td>
</tr>
</tbody>
</table>
Equations 5-3 and 5-5 and the following assumptions were then used to approximate a MAUA assessment:

- The more important an attribute was to an end-user, the more it was emphasized in the MAUA model. The specific assumption was that the individual utility scaling factors (see Equation 5-3) could be estimated as \( k_i = (10-2\cdot \text{Rank}_i)/10 \). Using the scale of one to three, this yields individual scaling factors between 0.8 and 0.4. Larger \( k_i \)'s mean the attribute carries more weight in the estimate of total utility.

- As an attribute becomes more important to an end-user, they become more risk averse regarding tradeoffs associated with this attribute. The exponent \( c \) in Equation 5-5 was estimated as \( c_i = (1-k_i)^*1.25 \), which yields values between 0.25 and 0.75. Larger estimates of \( c_i \) imply less risk aversion, as long as \( c < 1 \). As \( c \to 1 \), the end-user becomes risk neutral.

Generally, these assumptions concur with the opinions of the end-users who were interviewed. The ranges over which the \( c_i \)'s and \( k_i \)'s were scaled were also based on observed market behavior, but are approximations at best.

This simple approach was useful for examining the market potential for CFCC's in industrial burner applications. As Table 5-3 indicates, end-users in Southern California places more value on emissions related characteristics than consumers in Eastern Ohio. In contrast, the Ohio group stresses the importance of energy efficiency and product life. The driver for these trends is a difference in regulation. The Southern California group operates within an EPA designated ozone non-attainment area, and faces strict controls over emissions. The Ohio group faces much less regulatory pressure, and is less concerned with emissions, especially if reductions are costly.
When the results of the survey were worked into the MAUA model, it was found that CFCC's required dramatic product life improvements or cost reductions to be attractive in markets similar to the Ohio segment. Barring such improvements, niche sales in the most regulated markets were all that appeared plausible.

For example, Figure 5-6 shows that CFCC burner life would need to increase from a current expected target of ten years to nearly twenty for it to have appreciable sales (converted into emissions and energy savings in the figure) in even the highly regulated California market. However, a doubling in life without additional cost reductions is not sufficient to generate sales in more economically sensitive markets. These conclusions contrasted with U.S. Department of Energy estimates of market potential, but are more reflective of actual market activity to date. [U.S. DOE 1993]
Overall, this approach to approximating utility was useful for the CFCC case, and it is likely that similar results could be obtained for a number of R&D efforts. The key advantages are that it reduces the level of effort required to gather information from potential end-users, and the methodology can easily be automated in a spreadsheet or other software. Further, it is possible that information from other initiatives such as quality function deployment (QFD) could be used to drive this type of assessment. This would also reduce the information collection burden.

The tradeoff of using the approximation approach is presumably the lack of precision. Conducting formal MAUA interviews grounds an analysis with a source of data that can be validated. The approximation route instead makes strong assumptions about the expected behavior of end-users. Therefore, market segments that are not well understood up-front could be very difficult to address using such an approach.

As with the rest of the R&D valuation methodology developed in this thesis, it is likely that the best practical approach is to conduct multi-metric assessments at the level which is most suitable to a particular project. Small investments may not require complex assessments. In contrast, multimillion dollar, long-term propositions might benefit from more formal analyses.

*Other Potential Approaches to Valuing Complex Benefits*

Although utility theory is a compelling approach to valuing complex R&D benefits, even the approximation method outlined above may exceed the level of effort that is acceptable in many R&D environments. This section considers some additional alternatives that might be employed to approximate the value of specific technical advancements. These include boundary limits and cost avoidance activities. In many cases, the data needed for these types of estimates can be rapidly collected using resources readily available within an organization.

Boundary limits simply attempt to gauge the most an end-user might pay for a specific level of performance in a product. This limit can then be used to infer a dollar value
per unit level of performance (i.e., a linear value) that can be applied to estimate the value of different levels of performance gains. Compared to utility, this approach misses the marginal tradeoffs and interactions between attributes that might occur, but as an approximation, the method requires much less effort. In many cases, this type of approach might be sufficient for making a reasonable decision regarding an R&D project.

For example, some of the research projects that this thesis examines focus on light-weighting vehicles through substitution of alternative materials. In many cases, the weight savings would be used to achieve greater vehicle fuel economy. Therefore, one way to bracket the value of such weight savings is to estimate the resulting fuel cost savings that a consumer would obtain.

Table 5-5 presents an example estimate of fuel savings value. It assumes an initial vehicle weight of 3000 pounds and fuel economy of 27 miles per gallon (MPG). Then it explores the impact of a 100 pound (3.33%) weight reduction. Using a automotive design rule know as the 10-5 rule, which estimates a ten percent reduction in vehicle weight leads to a five percent increase in fuel economy, this results in a new fuel economy of 27.5 MPG. Assuming an average driver travels 12,000 miles per year, a gas price of $1.25 per gallon and a ten percent discount rate, the NPV of fuel savings over a ten year vehicle life is $62, or $0.62 per pound saved.

<table>
<thead>
<tr>
<th>Annual Gas Cost @ 27 MPG</th>
<th>$556</th>
<th>$556</th>
<th>$556</th>
<th>$556</th>
<th>$556</th>
<th>$556</th>
<th>$556</th>
<th>$556</th>
<th>$556</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Gas Cost @ 27.5 MPG</td>
<td>$545</td>
<td>$545</td>
<td>$545</td>
<td>$545</td>
<td>$545</td>
<td>$545</td>
<td>$545</td>
<td>$545</td>
<td>$545</td>
</tr>
<tr>
<td>Annual Savings</td>
<td>$10</td>
<td>$10</td>
<td>$10</td>
<td>$10</td>
<td>$10</td>
<td>$10</td>
<td>$10</td>
<td>$10</td>
<td>$10</td>
</tr>
<tr>
<td>PV Savings (r=10%)</td>
<td>$9</td>
<td>$8</td>
<td>$8</td>
<td>$7</td>
<td>$6</td>
<td>$6</td>
<td>$5</td>
<td>$5</td>
<td>$4</td>
</tr>
<tr>
<td>NPV</td>
<td>$62</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPV/100#</td>
<td>$0.62/lb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Obviously this approach offers only a rough estimate of value. It ignores a large number of factors including secondary weight savings that further increase fuel economy, differences in driving habits and market segments that influence the value of such savings, and geographical differences in the price of gas (e.g., gas is three or four times more expensive in Europe). Additionally, this approach does not even consider other potential uses of the weight savings that result from the implementation of a lighter material. For example, a vehicle could be designed to channel all weight savings into performance or luxury enhancements such as acceleration or global positioning satellite technology (GPS). Finally, the valuation is an upper bound, and does not indicate what fraction of value the developer of the technology will appropriate.

However, these issues could be addressed in turn by matching the boundary limit calculation to the specific set of end-users, features and market conditions that most closely reflect operating reality. Valuing some features like GPS technology is more difficult than fuel savings, since a direct dollar benefit is not easily observed, but most companies have marketing resources that might be able to help provide the needed insights. The key is to find some reasonable starting basis for estimating the value of the feature. The analysis can then be refined as needed.

Another approach to valuing complex benefits that is similar to the boundary limit method arises in cases where implementation of a technology allows a cost to be avoided or implementation is mandated. This can occur at either the producer or end-user level, and provides a benchmark for assessing the value of the technology. Often such opportunities result from regulatory policies. For example, another way to estimate the value of vehicle light-weighting technology is to consider the influence of CAFE policy. For each MPG by which a fleet of vehicles exceeds CAFE, a penalty on order of $300 million is imposed by the U.S. Government. This $300 million per CAFE mile therefore represents a cost that advanced technology would allow a company to avoid, if CAFE were raised above its current levels.
For a technology that potentially takes 300 pounds per vehicle out of a pool of one million vehicles, and in the course of doing so, avoids this penalty, the value of weight savings might be approximated as $1.00 per pound ($300,000,000 CAFE Penalty/1 million vehicles/300 pounds). Again, this estimate is highly subjective, but it does provide a beginning basis for evaluating potentially promising weight savings technologies.

Another example of avoidance cost stems from the CFCC case described earlier in this chapter. The California market faced strict regulatory requirements regarding emissions, including expenditure guidelines for compliance. In the most severe cases, businesses were expected to spend up to $24,000 per ton of required NOx reductions. In these instances, CFCC burners were cost competitive with the only other technology that met the emissions standards. Since implementation was mandated, the spending requirements seem to provide a basis for estimating technology value. [Schweizer 1993]

However, the CFCC case demonstrates a potential problem with relying on avoidance or compliance costs as estimates of product value. DOE projections of CFCC burner technology value were based on the compliance costs, but the reality of the market was that many businesses simply failed to comply. The assumption was that the likelihood of being caught for being out of compliance was small for all but the largest industrial operations in the Southern California basin. As a result, the risk of being fined appeared acceptable given the cost of complying up-front. Other businesses simply choose to leave the county or state. Thus, avoidance and compliance costs can be tenuous bets. This fact should be considered when deciding to use them as a basis for valuing technology.

**SCENARIO ANALYSIS**

Although it is not really a multi-criteria decision-making tool, scenario analysis is an important methodology to consider because technology value often depends on the context in which it is implemented. Schoemaker (1995) describes scenario analysis as a disciplined approach to identifying possible futures. He notes two key differences compared to other planing methodologies. First, scenarios examine the joint impact of uncertainties, while
other methods tend to focus on single contingencies. Second, scenarios try to capture the new states that develop after major shocks to a system, rather than examining incremental changes. The result is a rich description of widely different potential futures that can be quantitatively examined to determine contingency plans.

Similarly, Clemons (1995) points out the tendency of organizations to be overconfident in their forecasts and anchor in the present reality. He proposes scenario analysis as a useful method for guiding major technical projects such as reengineering, again because it forces consideration of a wider range of operational and environmental uncertainties than typical planning efforts might include. These include financial, technical, project, functionality and political risks.

Essentially, scenario analysis documents potential major shifts in the competitive, operating or external environment that might dramatically influence the value or relevance of a planned activity. The objective is to identify the conditions under which such shifts might occur and inquire how plans can be modified to best account for these possibilities.

Scenario analysis is proposed in this work as a final check on uncertainties that might not be included in the basic valuation models. In particular, it can define conditions under which the value of specific project benefits might dramatically change. After being identified, these issues can be used to refine the initial project value analysis.

An example that is relevant to the R&D portfolio that this thesis examines is the regulatory environment in which automobiles are produced. In the United States of America, the Federal Government regulates the fuel economy of automobiles using a Corporate Average Fuel Economy (CAFE) metric. Established by the Energy Policy and Conservation Act of 1975, CAFE requires automotive producers to meet a specific fleet fuel economy target, or face monetary penalties. Future CAFE policies can dramatically affect the value of R&D that aims to improve vehicle fuel economy, or eliminate gasoline engines entirely. This issue is considered along with major technical, implementation and market uncertainties in estimating the value of weight savings related projects.
Chapter 6: A Composite R&D Valuation Methodology

The major goal of this thesis is to improve upon current R&D valuation practice by addressing difficulties caused by uncertainty, the sequential nature of R&D, and the complexity of valuing project benefits. It focuses on:

- valuing opportunities to revise R&D projects in response to uncertainty resolution;
- better matching valuation frameworks to project uncertainties (risks);
- integrating methods for valuing complex benefits with financial valuation frameworks.

Chapters 3 through 5 explore the potential of various financial valuation and multi-metric assessment methodologies for improving current R&D valuation practice. Several of these frameworks demonstrate promise for addressing the difficulties. In particular,

- real options and decision analysis models are useful for valuing R&D projects that can be revised in response to uncertainty resolution;
- a mix of real options and decision analysis can accommodate a wide range of project uncertainties;
- multi-metric valuation models can translate complex benefits such as simultaneous cost and performance improvements into dollar values that the options models require.

This chapter outlines the steps in a composite methodology that integrates real options, decision analysis and multi-metric valuation models into a common arrangement for valuing R&D projects. The methodology leads to a dollar metric of project value that enables meaningful comparisons between projects that span a range of objectives, uncertainties and timeframes. After Chapter 6 introduces the composite valuation methodology, it details the procedure for valuing a project. Chapter 6 closes by introducing the financial valuation model that is used for the demonstration case study in Chapter 7.
**Figure 6-1: The Composite R&D Valuation Methodology**

*THE COMPOSITE R&D VALUATION METHODOLOGY*

Figure 6-1 presents a flow-diagram of the composite R&D valuation methodology that this thesis develops. Five major steps comprise the process. These include setting the scope for the assessment, collecting project data, transforming the project data into forms required by the financial valuation framework, valuing the individual uses of the R&D results, and totaling the value of the project.
The first two steps in Figure 6-1, "Setting the Scope" and "Project Data Collection," are precursors to conducting the valuation. The next two steps, "Transforms of Project Data" and "Valuing Technology Use," are the core of the methodology, and integrate into the composite valuation methodology the options and multi-metric valuation concepts that Chapters 3 through 5 discuss. The last step, "Total Project Value," is a summation process that combines the value of different technology uses into a single estimate of project value.

Overall, the process shown in Figure 6-1 will lead to an improved metric of value for R&D projects that have significant uncertainties and embedded options. It also provides a mechanism for valuing complex technology benefits in a way that is compatible with financial valuation models. The case study in Chapter 7 demonstrates the methodology by valuing a set of R&D projects. The remainder of this chapter details the general procedure for valuing a project and develops a specific real options and decision analysis model for the case study.

THE PROCEDURE FOR APPLYING THE METHODOLOGY

Each of the major steps in the methodology represented in Figure 6-1 requires a set of actions. This section provides a step-by-step discussion of how to value a project.

Step 1: Scope of Assessment

R&D can be hard to value because it often has many potential uses. The first step in the valuation methodology identifies the uses that will be considered for estimating the value of the project. It focuses on identifying potential applications, end-user segments and scenarios that influence the value of the project. The number of uses that must be valued is equal to the number of unique combinations of these three factors (Equation 6-1). For each use, the source and level of project revenues is likely to differ, as are the timing of costs and decisions (project options).

\[ \# \text{ Uses} = \sum_{i=1}^{n} (\# \text{ End-Use Segments}_i \times \# \text{ Scenarios}_i) \]  \hspace{1cm} (6-1)

where \( n \) = \# of applications
The rationale for classifying an application of a technology in a specific end-user segment as a separate use for different scenarios is that major contextual shifts can dramatically influence the value of the technology. For example, Chapter 5 briefly discussed how CAFE regulation can influence the value of technologies that enable weight savings in passenger vehicles.

Criteria for defining applications, end-user segments, and scenarios are provided below. In all cases, some informal judgment is required to determine if the expected level of resolution is commensurate with the analysis requirements.

**Applications of technology** represent distinct uses of an R&D technology for which the target product and resulting features differ substantially from other uses of the same R&D technology. Since the product and features differ, the basis for estimating project revenues will also vary by application.

For example, applications of advanced ceramics include oxygen sensors, hip-joint replacements, and engine components. In each case, the product and features of value to the end-user differ significantly. It is more of a judgment call to decide if automotive valves and heavy-duty diesel engine valves represent different applications. The products are similar and many of the features and requirements are similar.

Again, the level of detail should be weighed against the resulting analysis requirements and the objective of the valuation. It is always possible to desegregate groups during a later phase of analysis.

**End-use segments** are a basis for sub-dividing technology applications into market segments that represent groups of end-users who place different values on the same set of technology features. Since these groups of end-users value the technology differently, the level of project revenues that will result from implementing the technology in each segment will vary.
For example, the automotive and heavy-duty diesel engine market segments place different values on the features offered by advanced ceramic valves. Both segments value the potential performance gains these components offer. However, automotive tends to be more cost sensitive, while the diesel market places more importance on long-term durability. As a result, the basic technology application might be the same, but the end-user value for a specific set of features varies. Segmenting these end-user groups improves the estimation of potential project revenue, compared to focusing on average tastes.

Scenarios describe major external events that dramatically change the value of a technology application, and the impact of these events can vary by end-user segment. As a result, scenarios also influence the potential level of project revenue that would result from implementation. However, since scenarios effectively sub-divide end-user segments by a probabilistic event, a likelihood that a scenario will occur must also be specified. The likelihood of a scenario occurring can also be treated as a sensitivity variable.

For example, end-users of advanced ceramic valves might value the technology differently if a dramatic increase in vehicle fuel economy or decrease in pollution output was mandated. Such a mandate would likely increase the overall willingness of these end-users to pay for the performance gains offered by ceramics. To value a R&D program on ceramics for engine applications, the magnitude of this influence on each end-user segment and the probability of the mandate occurring would need to be estimated. This is in addition to assessing the base case where no mandate occurs.

Table 6-1 provides an example of how applications, user-segments and scenarios result in a set of uses. It details two applications of the a technology. For Application 1, one user segment and one implementation scenario are considered. For Application 2, two segments and two scenarios are explored.

Column three in Table 6-1 indicates that five different uses result. Applying Equation 6-1 confirms this result (# Uses = 1*1 + 2*2 = 5). Column four shows that each use is also associated with a probability of a specific scenario occurring. Thus, Application
2, End-user segment \( a \), Scenario 1 is represented as \( 2a1 \) in column three, and the associated probability \( P2a1 \) is listed in column four. Table 6-1 also notes that the sum of the scenario probabilities must equal one in each end-user segment (e.g., \( P2a1 + P2a2 = 1 \)), and the likelihood of each scenario is independent of the user segments (e.g., \( P2a1 = P2b1 \)).

Step 1 simply requires uses to be defined and scenario probabilities to be estimated. Clemen (1991) and Merkhofer (1987) provide formal methods for assessing the subjective probability. Another approach is to assume a starting value and treat the scenario probabilities as sensitivity variables.

The total value of the project is the weighted sum of the value of these uses less the risk-adjusted R&D costs. The remainder of the R&D valuation process focuses on valuing each of the uses.

**Table 6-1: The Scope of the Assessment Defines the Uses**

<table>
<thead>
<tr>
<th>Application</th>
<th>Segmentation into End-User Groups</th>
<th>Scenarios Sub-Divide Segments into Uses</th>
<th>Probability of Use Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1a</td>
<td>1a1</td>
<td>( P1a1 = 1 )</td>
</tr>
<tr>
<td>2</td>
<td>2a</td>
<td>2a1</td>
<td>( P2a1 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2a2</td>
<td>( P2a2 )</td>
</tr>
<tr>
<td>2</td>
<td>2b</td>
<td>2b1</td>
<td>( P2b1 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2b2</td>
<td>( P2b2 )</td>
</tr>
</tbody>
</table>

*Note: \( P2a1 + P2a2 = 1, P2b1 + P2b2 = 1, P2a1 = P2b1, P2a2 = P2b2 \)*

**Step 2: Project Data Collection**

The second step in the methodology focuses on collecting the data that is needed to value the project. This includes estimating the timing and magnitude of the costs and benefits of the project, identifying decisions opportunities (i.e., project options), and
quantifying uncertainties. This data is required for each use identified during Step 1. For simplicity, the remainder of this discussion focuses on one use only.

**Costs**

Project costs include any expenditure over the analysis timeframe that is related to researching, developing or implementing a technology. In addition to specifying the magnitude of these costs, the timing of the expenditure is also required.

For example, the project data for the case study that this thesis develops includes annual R&D cost, an aggregate implementation cost, and an expected date for implementation. R&D costs are incurred until the implementation date, and then the option to implement is evaluated. Implementation cost is incurred on the implementation date, only if it is opportunistic to go forward with commercialization.

However, this particular form of valuation problem is not the limit of the decision tree based models. Many other forms could be developed to tailor an analysis. The critical issue for project costs is to identify the magnitude and timing of the important streams.

**Benefits**

Next, the expected level of project benefits is quantified. These benefits might accrue in a form that is readily converted into a dollar consequence, or as a set of economic and performance results that require further analysis to value on a dollar basis (i.e., transform using utility or other multi-metric model).

For example, R&D projects aimed at solving a quality problem or improving the efficiency of an existing process are often readily translated into dollar equivalents. Consider an R&D project that aims to increase the productivity of a manufacturing process, without changing any of the characteristics of the product being produced. Higher throughput translates directly to a lower cost for a given quantity of production. The cost savings that would result from the successful implementation of the R&D project therefore represent the potential benefit. A cost model could estimate the savings that would result for a range of throughput rates. This type of modeling has become increasingly popular, and many
companies have access to such models. [Clark, Roth and Field 1997] Accounting cost data is another potential information source for estimating the benefit, especially if the organization uses a management accounting process such as Activity Based Costing. [Cooper, Kaplan, et.al. 1992, Turney 1991]

In contrast, R&D that improves the functionality of a product influences its value, but it is often difficult to gauge the value change directly. The data collection step requires the identification of the technical benefits and the quantification of resulting product feature improvements that these technical results enable. Subsequently, multi-metric valuation methodologies are applied during Step 3 to estimate the value of the feature improvements in each end-user segment.

Continuing with the example of ceramic engine components, an R&D program might aim to reduce product cost and improve reliability. The technical results might be scrap reduction due to near net shape processing and an increased Weibull modulus (metric of failure likelihood) due to better process control. Assuming that the relevant end-user is an engine designer, the actual features they care about might be price, product life, and weight. To estimate the value of the R&D benefits, the expected change in end-user features must be quantified and valued using a multi-metric assessment procedure such as those that Chapter 5 highlights. Transforming the feature improvements to dollar values is accomplished during the Step 3 of the methodology.

Note that as the set of technical advances becomes more complex, it is also likely that multiple product feature configurations will be possible. As with other steps in the methodology, the key to maintaining a manageable level of analysis is to focus initially on the most promising uses. Selecting the form of technology implementation to examine therefore requires some subjective judgment, and is an activity that can benefit from a range of opinions that cut across organizational functions such as R&D, marketing and manufacturing.
Decision Opportunities

After the expected streams of project costs and benefits are quantified, project options that are to be included in the valuation are identified. These are decision opportunities that can be used to react to the resolution of uncertain events and that consequently influence the expected project cash-flows (uncertainties are quantified next).

Chapter 3 described a variety of real options that might be considered. These include opportunities to wait, continue, slow-down, speed-up, temporarily stop, or abandon a project. Trigeorgis (1996) also provides a summary of different types of real options with pointers to the literature, and demonstrates that trying to value multiple options is difficult because the values are not additive.

The decision tree based methodology this thesis develops can treat multiple options, but it is recommended that valuations be focused on what are expected to be major project options. Including every possible decision related to the R&D project rapidly renders simple decision trees impractical, and adds little to a thoughtful analysis that only considers options with significant potential for influencing the value of the project.

For example, this thesis focuses on the option to implement successful technology developments. This is potentially an important option because many R&D creations require significant investments to commercialize. The option to implement recognizes that unfavorable implementations can be avoided.

Uncertainties

Finally, major uncertainties that will influence the value of the project and its options must be specified and quantified. Chapters 3 and 4 discusses two general forms of uncertainty: endogenous, project specific risks and exogenous, market related risks. Generally, most R&D projects are exposed to both forms.

While an unlimited number of uncertainties can be incorporated in a decision tree, for practicality it is best to focus on those which appear most significant to the problem. Further, the assessments in this thesis assume probabilistic independence. If dependent
probabilities can be avoided, it dramatically simplifies the analysis. One way to achieve this goal is to limit the uncertainties, and select sets for which the independence assumption seems reasonable. If the results of an initial assessment are unsatisfactory, additional detail can be added, if there is sufficient resolution in the data to merit the complexities.

*Quantifying Endogenous Uncertainties*

Endogenous uncertainties have no relation to external, market events. Therefore, the same procedure can be used to quantify these uncertainties for both hybrids of real options and decision analysis, and pure decision trees. Chapters 3 and 4 discuss this issue.

To represent an uncertainty in a decision tree, two related sets of information are required: discrete outcomes and associated probabilities. For example, the project that Chapter 3 examines (see Table 3-1), has two probabilistic outcomes for the license fee. The high value has a probability of 0.5 associated with an outcome of $1,800,000. The low value has a probability of 0.5 associated with an outcome of $550,000.

There are several practical ways of obtaining the estimates of discrete, probabilistic outcomes. These include subjectively estimating the probability of each outcome, or assuming a form of distribution, estimating the mean and standard deviation, and developing discrete estimates using the distribution. Subjective assessments are discussed in Chapter 3, and by Merkhofer (1987) and Clemen (1991). Appendix A describes several methods for estimating discrete outcomes from continuous distributions.

The latter approach, developing discrete estimates from continuous distributions, has several advantages. First, it allows any number of probabilistic outcomes to be estimated. Second, it reduces the data collection requirements for cases where many potential outcomes are evaluated. Finally, it is also more intuitive for someone to estimate an expected outcome and an upper limit as opposed to a set of outcomes and probabilities.

The model that this thesis applies to value a portfolio of projects uses both approaches to quantify endogenous uncertainties (see Appendix C). First, a probability of
technical success is gauged using a subjective estimate. Two outcomes are considered: success or failure. The probability of failure is one minus the probability of success. In the event of failure, these particular models assume the technology is worthless. In the event of a success, the technology is fully capable of being implemented. Second, in the model for his case study, benefits uncertainty refers to the potential variation in the technical advancement associated with a successful R&D project. An expected level and a maximum level of benefits are estimated for the case study. Then, assuming that the benefits of a successful technology are lognormally distributed, a standard deviation is calculated and used to estimate a set of discrete, probabilistic outcomes (see Equation C-1, C-2, C-3 and C-4).

*Quantifying Exogenous Uncertainties*

For pure decision analysis approaches, the same procedures for quantifying endogenous uncertainties are applicable to exogenous uncertainties. However, this approach will always lead to errors in valuation since decision tress that model project options cannot correctly adjust market related outcomes for risk (see Chapters 3 and 4).

Real options based models require a two-step process for quantifying exogenous uncertainties. First, a factor that influences project revenues must be identified. Second, this cash-flow driver must be related to one or more exogenous, priced factors. The priced factors are subsequently transformed into risk-neutral distributions during Step 3, and used to estimate the influence of the cash-flow driver on project value. Because risk-neutral distributions are used to represent the factors that create exogenous project risks, the risk-free rate can be applied to the resulting cash-flows. This is similar to Kulatilaka's (1993) methodology that Chapter 3 discusses.

For example, the case study in this thesis identifies vehicle production volume as a driver of project revenues. Production is then related to the price of a traded stock by conducting a regression analysis. Appendix B develops the regression model, which is used to incorporate exogenous uncertainties into the project valuation.
Step 3: Transforms of Project Data

The next step in the methodology transforms some of the project data into forms that are required for conducting the valuation. First, for projects with complex benefits, multi-metric models are applied to transform these benefits into dollar based values. Next, if the real options approach is used to value the projects, the priced factors that are related to exogenous uncertainties are transformed into risk-neutral distributions. Finally, the project costs and benefits are transformed into expected cash-flows. These expected cash-flows are subsequently converted into conditional outcomes during the valuation process (Step 4).

Transforming Complex Benefits into Dollar Values

Projects with complex benefits receive additional attention during the third step of the valuation process. The objective is to articulate how much value specific end-users place on an application of a technology, given a particular external scenario.

Methodologies that rank alternatives based on multiple criteria are candidates for enabling the actual translation of multiple benefits into dollar values. Approaches that are attractive because they enable such a conversion include multi-attribute utility analysis and other weighted scales. Chapter 5 details the mechanics of applying these tools to R&D projects with complex benefits.

The result of an assessment is a dollar metric of the value of potential R&D benefits. This value is used to drive estimates of project cash-flows and ultimately project value.

Transforming Exogenous Uncertainties into Risk-Neutral Quantities

The risk-neutral transformation of priced, exogenous drivers of project cash-flows can be accomplished using the binomial method that Chapter 3 introduced. The result is a set of prices and associated probabilities that represent expectations in a risk-neutral world. These probabilistic outcomes are then related back to the project using the exogenous uncertainty relation defined during Step 2. Appendix B provides a detailed description of the requisite calculations. The example it develops is used for the case study in Chapter 7.
Transforming Costs and Benefits into Expected Cash-Flows

Using the dollar-based estimates of benefits from Step 2 or 3, traditional financial valuation methods are next applied to obtain a present value of the project revenues and costs. During the decision tree based valuation (Step 4), uncertainties are introduced to the cash-flows, and the influence of options is evaluated.

Because the hybrid of real options and decision analysis conducts risk-adjustments through risk-neutral transforms of exogenous uncertainties, the discounting for this model is conducted using the risk-free rate. For pure decision analysis approaches, an arbitrary discount rate is required.

The timing and magnitude of costs is established during Step 2. Therefore, these cash-flows can be discounted directly using standard NPV techniques (see Equation 3-1).

Estimating aggregate project revenues requires additional work, but is a reasonably mechanical process. It generally requires estimates of the following factors:

- the dollar value of benefits from Step 2 or 3
- the timeframe over which benefits will accrue
- the unit of influence (e.g., production units influenced per unit of time)

First, the dollar benefit from Step 2 or 3 must be expressed as the marginal revenue that would result from implementing the technology. Typically a dollar per unit of production or a dollar per year estimate will result.

Consider two examples: 1) a project that reduces a process cost by ten percent, 2) a project that increases the performance of an existing product, with no change in product cost. For the process improvement, if the initial product cost was $1.00, then the new cost would be $0.90. The marginal revenue per unit of production is therefore $0.10. In the product improvement case, a methodology such as utility could reveal the premium

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end-users would pay for the performance increase. This willingness to pay value represents a marginal product value increase and is an approximation of appropriable marginal revenue.

Equation 6-2 represents the marginal revenue of R&D implementation as the difference between the value of the product to an end-user and the cost of producing the product, after and before the introduction of the technology. The model applies to projects that generate benefits that are directly measured as dollar consequences and projects that yield complex benefits. For example, the process improvement project did not affect the value of the product to the user, so Equation 6-2 simplified to the difference between cost before and after implementation. In contrast, the product performance enhancement influenced the value of the product to the end-user, without affecting cost. In this case, Equation 6-2 simplified to the difference in value to the end-user (willingness to pay).

\[
R&D \text{ Marginal Revenue} = (User \text{ Value}_{\text{New}} - Cost_{\text{New}}) - (User \text{ Value}_{\text{Old}} - Cost_{\text{Old}}) \quad (6-2)\]

Equation 6-2 applies equally well in cases where product performance and cost simultaneously change. The value to the end user of specific levels of performance and price is assessed using a multi-metric framework such as utility. The resulting changes in end-user value are then compared to changes in production cost to determine if the technology implementation would yield positive marginal revenues.

One issue that Equation 6-2 does not address is what fraction of the benefits is appropriable. Chapter 1 and 5 discuss the factors that drive appropriability, which include the strength of competitors and end-users, intellectual property protection rights, and the availability of alternatives. All of these factors tend to diffuse some of the value away from the innovator. Some adjustment to the value obtained in Equation 6-2 is merited, but this adjustment is contextual, subjective and must be decided on a case by case basis. The case study in Chapter 7 demonstrates one approach to adjusting the willingness to pay to account for the appropriability of a technology.
Once an appropriable marginal influence of the technology is estimated, it must be aggregated into an estimate of the total expected revenues that would result from the successful implementation of the technology. The total revenue in any time period is the marginal dollar revenue multiplied by the production output. The present value of this stream of revenues is the estimate of the current value of total potential project revenues.

Equation 6-3 summarizes the present value of project revenues calculation. The variables \( t_1 \) (period where revenues start) and \( t_2 \) (period where revenues end) define the time from the date of project initiation (\( n \) periods) over which revenues accrue, and \( r \) is the discount rate.

\[
PV(\text{Revenues}) = \sum_{m=t_1}^{t_2} \Sigma(\text{Marginal Revenue}_n)\left(\text{# units}_n\right)/(1+r)^n
\]  

(6-3)

The level of detail put into this estimate again should depend on the relative importance of the R&D investment. For small projects, simple assumptions may suffice. Multimillion dollar R&D programs probably deserve more attention. However, the subsequent steps in the methodology also allow significant opportunities to incorporate uncertainties about the level of benefits into the project valuation.

**Step 4: Valuing a Single Use**

Although Step 4 represents a core of the methodology, once the requisite project data is collected and transformed, valuing the project in the decision trees is fairly mechanical. Three major activities happen during Step 4. First, the expected cash-flows are converted to conditional, probabilistic outcomes. Next, the decisions (options) are evaluated for each conditional outcome. Finally, the resulting cash-flows are rolled back through the tree and summed to estimate the value of the single technology use.

Essentially, Step 4 is just a traditional, decision tree based evaluation process. Steps 2 and 3, getting the data and converting it into a useful format, are the difficult parts of the valuation. Appendix C provides an example of how the process is conducted using the
model for the case study. Clemen (1991) and de Neufville (1990) also provide detailed introductions to decision analysis.

**Step 5: Valuing the Project**

To value the entire project, Steps 2 through 4 are then repeated until every use identified during Step 1 is valued. The total value of the project is then calculated as the weighted sum of value for each use. This is accomplished by multiplying the value of each use by the appropriate scenario probability from Step 1 and adding the results.

**THE FINANCIAL VALUATION MODEL FOR THE CASE STUDY**

This final section of Chapter 6 introduces the form of the valuation framework that is applied to the case study in Chapter 7. This particular model includes the value of the option to implement a successful R&D project in its estimate of project value. As a result, it assumes a specific R&D project life-cycle. This life-cycle is described first, and then the decision tree is presented.

The tree can be combined with real options methods (i.e., risk-neutral transforms of exogenous uncertainties) or used alone to value R&D projects. Of course, pure decision analysis methods will introduce errors if project outcomes are correlated with external market events. Appendix C describes a spreadsheet that is based on the implementation option tree, and the specific calculations required to estimate the parameters in the tree. The spreadsheet values projects using a hybrid real options and decision analysis approach (OPT), pure decision analysis (DA), and an NPV that ignores options.

**The R&D Project Life-Cycle for a Simple implementation Option Analogy**

Simple models of R&D implementation options essentially assume a three-phase R&D project life-cycle:

- The R&D investment decision
- Uncertainty resolution through R&D
- The implementation decision (i.e., commercialization)
First, the R&D investment decision encompasses a range of activities that normally occur during the actual research and development phase of technology development. These include multiple opportunities to initiate, continue, revise or abandon a project. In the simple forms of implementation option models, these R&D activities are condensed into a single choice: pursue R&D or not. If R&D is initiated, the models assume the project continues until the technology is potentially implementable.

This assumption oversimplifies reality. However, from a practical perspective, the commercialization phase of a project often overshadows the costs of pursuing R&D in the first place. [Roussel, Saad, Erikson 1991] In these cases, the loss of resolution that results from condensing the R&D decisions into a single choice is likely negligible. The major difference in value between options models and NPV in these cases stems from the opportunity to avoid costly implementation expenses when the benefits of commercialization are small.

Second, if a project pursued, the act of conducting research resolves uncertainty regarding the potential value of the technology. The model this thesis applies to the case study in Chapter 7 relies on a binary probability of success metric, but more detailed approaches such as that shown in Figure 3-2 can also be developed. Regardless, the objective of gauging project uncertainty is to build into the valuation an estimate of the likelihood that the technology will be successfully commercialized.

Finally, after the R&D phase is finished, the implementation phase becomes the major contingent feature of the project. The cost of implementation is weighed against the benefits that will accrue from the commercial launch of the technology. In cases where the benefits outweigh the cost, implementation occurs. Otherwise, the technology is shelved.

Again, the implementation phase in the models is a simplification of reality. Just like the R&D investment phase, a larger number of intermediate decision points could be introduced. Further, opportunities to continue R&D to refine the technology instead of shelving it are possible.
Overall, this project structure assumption is advantageous for several reasons. First, it follows a simple call option analogy. The total costs of conducting R&D are the acquisition price of the option. The implementation cost serves as a strike price, and the uncertain project revenues act as an underlying asset. The time to expiration is defined by the time before the implementation decision (i.e., number of years R&D is conducted), and the combination of endogenous and exogenous uncertainties create the volatility. While this analogy is not exactly correct (i.e., priced factors become the underlying assets that drive exogenous uncertainties), it is useful for communicating the concept. Second, the data requirements for this form of model are not overwhelming. The case study in Chapter 7 illustrates the requirements. Finally, it focuses on a critical R&D option that will be valuable for many projects.

_A Decision Tree Representation of an R&D Project with an Implementation Option_

Figure 6-2 shows the decision tree that this thesis uses during the case study developed in Chapter 7. This tree values an R&D project that includes an implementation option. It is representative of the type of framework the composite methodology recommends, but is not the only form that can be developed. For example, Chapter 3 discusses a variety of extensions, complexities, and other options that could be added. Again, the key tradeoff to consider is the increase in data requirements versus the expected resolution improvement. For many projects, this model overcomes shortcomings of other valuation methods, without requiring excessive data collection efforts.

The tree in Figure 6-2 starts with the initial R&D investment decision. If the project is pursued, several uncertainties are resolved, and then the implementation decision is faced. Otherwise, the value of not pursuing the work is presumed to be zero.

The tree includes three uncertainties: technical, benefit and market. Technical and benefit uncertainties are treated as endogenous influences, and market uncertainty is treated as an exogenous influence.
Figure 6-2: A Simple R&D Implementation Option Model

The tree in Figure 6-2 first considers technical uncertainty, which refers to the likelihood that a workable technological result is obtained. It considers two possible outcomes: success or failure. For each outcome, the decision tree requires an associated probability and a traceable impact on one the drivers of project option value. In Figure 6-2, the probabilities of success and failure are denoted as Ps and (1-Ps), respectively. For a successful outcome, a subsequent decision to implement the technology will result in a flow of revenues. Projects that are not successful are assumed to be worthless.

Next, Figure 6-2 examines uncertainty related to project benefits. These are variations in the level of expected project benefits, contingent upon having achieved a technical success. Again, for each possible outcome, the model requires an associated probability and a traceable influence on a factor that drives project option value. Figure 6-2 shows three probabilistic benefit outcomes: high, medium and low. The associated
probabilities are \( P_{hb}, P_{mb} \) and \( P_{lb} \). These outcomes influence the revenue stream that will result if the project is implemented.

The market uncertainty that Figure 6-2 considers is an exogenous uncertainty, which reflects the influence of external, market related outcomes on project revenues. For example, the general state of the economy might lead to volatility in the sales of a product that R&D improves. The revenues that result from implementing the R&D project are exposed to these risks. Similar to the benefits uncertainty, Figure 6-2 shows three possible outcomes for market uncertainty: high, medium and low demand. The associated probabilities are \( P_{hd}, P_{md}, P_{ld} \).

Exogenous uncertainties are treated differently in hybrids of real options and decision analysis (OPT) than in pure decision trees (DA). OPT models use risk-neutral valuation techniques to model the uncertainties and enable the application of the risk-free rate to the project cash-flows. In contrast, DA models model the uncertainties directly, and are forced to apply an arbitrary discount rate to the cash-flows. This issue is discussed in detail throughout this thesis (see Chapter 3, Chapter 4, Appendix B, Appendix C). However, the key objective of both methods is to incorporate these uncertainties and their influences on project cash-flows into the valuation.

Once all of the conditional outcomes are developed (i.e., pathways through the tree), the tree evaluates the option to implement the project, given the expected conditional revenues. If the revenue stream is greater than the implementation cost, the project is implemented. Otherwise, no further action is taken. The resulting cash-flows are then rolled back though the tree to estimate project value.

Equation 6-4 summarizes the project value calculation. Note that \( \text{Max}[x,y] \) chooses the maximum result of two possibilities, \( x \) and \( y \). In this case, the value of the option to implement is either zero or the difference between the revenues and the implementation costs.
Project Value = -PV(R&D Costs) + \( P_s \cdot [\]

\[ P_{hb} \cdot (P_{hd} \cdot \text{Max}[0, \ PV(\text{Rev}_{\text{hbbd}} \cdot IC)] + P_{md} \cdot \text{Max}[0, \ PV(\text{Rev}_{\text{hmbd}} \cdot IC)] + P_{ld} \cdot \text{Max}[0, \ PV(\text{Rev}_{\text{hldb}} \cdot IC)]) + \]

\[ P_{mb} \cdot (P_{hd} \cdot \text{Max}[0, \ PV(\text{Rev}_{\text{mbbd}} \cdot IC)] + P_{md} \cdot \text{Max}[0, \ PV(\text{Rev}_{\text{mmbd}} \cdot IC)] + P_{ld} \cdot \text{Max}[0, \ PV(\text{Rev}_{\text{mbbd}} \cdot IC)]) + \]

\[ P_{lb} \cdot (P_{hd} \cdot \text{Max}[0, \ PV(\text{Rev}_{\text{ ldbd}} \cdot IC)] + P_{md} \cdot \text{Max}[0, \ PV(\text{Rev}_{\text{ltmbd}} \cdot IC)] + P_{ld} \cdot \text{Max}[0, \ PV(\text{Rev}_{\text{ldb}} \cdot IC)]) \] (6-4)

where, \( PV = \) Present value using the risk-free rate (OPT) or arbitrary rate (DA)

\( \text{REV}_{xxxx} = \) Project revenues, conditional on the level of benefits and demand

\( \text{IC} = \) Implementation cost

\( Ps = \) Probability of success

\( Phb, Pmb, Plb = \) Probabilities of high, medium and low benefits

\( Phd, Pmd, Pld = \) Probabilities of high, medium and low demand
Chapter 7: Valuing a Portfolio of Projects

Chapter 7 applies the composite R&D valuation methodology that this thesis develops to a portfolio of R&D projects. The goals of the case study are to demonstrate the mechanics of the methodology, and to compare the results of several approaches to project valuation. The composite methodology values the projects using a risk-neutral decision tree that is a hybrid of decision analysis and real options models. Where applicable, it discusses how multi-metric valuation could be utilized to assess the value of project benefits before the entire project is valued in one of the frameworks. The case study also presents the results of valuing the projects using a pure decision tree with an arbitrary discount rate, a naive NPV analysis and a risk-reward matrix that is currently used at the company which provided the project data. Through a comparison of the valuation results, efforts to increase precision are weighed against corresponding incremental gains in insight.

The example portfolio that Chapter 7 examines is based on a major automotive producer's investments in R&D related to materials technologies. Project data was collected through informal discussions with R&D management and staff, and from a series of internal documents that the company uses to manage the portfolio. Since this information is proprietary, the case study disguises the data. However, the general trends and findings that the chapter presents are representative of an analysis of the undisguised projects.

Chapter 7 begins by describing the projects in the portfolio and how these are currently managed at the company which provided the information. Next, a single project is valued following the step by step process that Chapter 6 develops. Then, the results of repeatedly applying the methodology to the entire portfolio of projects are presented. The initial comparison of the projects relies on estimates of project benefits provided by the company. Then, the role that scenarios and multi-metric valuation models might play in developing a more complete picture of value for projects that yield complex benefits is discussed.
The case study closes with a discussion of how the analysis could incorporate some broader firm perspectives of the portfolio. This includes examining the value of the portfolio under specific scenarios, the range over which the value of the entire portfolio might vary, and the influence of key projects. These are analyses which go beyond a simple ranking of technologies on value alone. Thus, this final discussion points out a role for the metric of value that the composite framework yields within an overall portfolio management process.

The case study confirms many of the assertions of Chapters 3 through 5. First, when projects are near the money and face significant uncertainties, options based frameworks improve upon simple applications of NPV. The difference in value is appreciable, and demonstrates the promising potential of these models for conveying the true strategic value of risky R&D investments. Second, since the portfolio of projects is exposed to some exogenous uncertainties, the hybrid of real options and decision analysis yields a different and more appropriate estimate of value than pure decision analysis. Next, because many of the projects in this particular portfolio are deep in the money, the signal provided by simple metrics is comparable to the signal provided by the options models. Finally, multi-metric benefit valuation models are promising methods for extending the reach of financial valuation models. They enable a more complete recognition of the complementary contribution of projects that yield benefits that are not easily translated into dollar terms, or that might vary across potential future operating environments.

**THE PORTFOLIO OF PROJECTS**

Table 7-1 and Table 7-2 summarize eighteen projects that comprised a major automotive producer's recent investments in materials related technologies at the beginning of 1997. The list of projects in each table is sorted into groups that correspond to the tiers of R&D described in Hauser and Zettelmeyer (1996). Chapter 2 details this framework. In general, Tier 3 projects are near-term efforts with benefits that can usually be valued for specific implementations. Tier 2 efforts are longer in duration, show promise for broad applicability, and often yield complex benefits. Tier 1 projects are basic R&D explorations, for which applicability and benefits might not be apparent at all.
Table 7-1 characterizes each project by describing a focus area within the automotive industry, a project class that indicates what the effort will influence, the source of any easily traceable dollar benefit, and other major benefits that are difficult to quantify in dollar terms. For example, Project A is an effort to improve a vehicle system (area), by developing a design tool (class) that is expected to result in reduced warranty and testing costs (traceable dollar benefits). It will also produce a simulation model that might be useful in other R&D applications (other benefits).

<table>
<thead>
<tr>
<th>Code</th>
<th>Project Area</th>
<th>Class</th>
<th>Traceable $ Benefit</th>
<th>Other Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Vehicle systems</td>
<td>Design</td>
<td>Warranty &amp; testing savings</td>
<td>Model</td>
</tr>
<tr>
<td>B</td>
<td>Engine</td>
<td>Design</td>
<td>Prototype elimination ($5 MM/yr)</td>
<td>Weight savings</td>
</tr>
<tr>
<td>C</td>
<td>Powertrain</td>
<td>Design</td>
<td>Component reduction &amp; sharing</td>
<td>Model</td>
</tr>
<tr>
<td>D</td>
<td>Vehicle systems</td>
<td>Design</td>
<td>Warranty &amp; testing savings</td>
<td>Model</td>
</tr>
<tr>
<td>E</td>
<td>Engine</td>
<td>Process</td>
<td>Process step elimination</td>
<td>Model</td>
</tr>
<tr>
<td>F</td>
<td>Manufacturing</td>
<td>Process</td>
<td>Yield &amp; productivity increase</td>
<td>Model</td>
</tr>
<tr>
<td>G</td>
<td>Recycling</td>
<td>Process</td>
<td>Cost avoidance</td>
<td>Environment</td>
</tr>
<tr>
<td>H</td>
<td>Manufacturing</td>
<td>Process</td>
<td>Productivity increase</td>
<td>NA</td>
</tr>
<tr>
<td>I</td>
<td>Sensors</td>
<td>Product</td>
<td>Warranty savings</td>
<td>Monitoring</td>
</tr>
<tr>
<td>J</td>
<td>Engine</td>
<td>Product</td>
<td>NA</td>
<td>Weight savings</td>
</tr>
</tbody>
</table>

**Tier 3: Current Vehicle Focus**

**Tier 2: Future Vehicle Possibilities**

<table>
<thead>
<tr>
<th>Code</th>
<th>Project Area</th>
<th>Class</th>
<th>Traceable $ Benefit</th>
<th>Other Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Body C</td>
<td>Process</td>
<td>Reduced production cost</td>
<td>Weight savings</td>
</tr>
<tr>
<td>L</td>
<td>Body C Assembly</td>
<td>Process</td>
<td>Reduced production cost</td>
<td>Weight savings</td>
</tr>
<tr>
<td>M</td>
<td>Engine</td>
<td>Process</td>
<td>Lower cost material</td>
<td>Weight savings</td>
</tr>
<tr>
<td>N</td>
<td>Body A</td>
<td>Process</td>
<td>Lower cost material</td>
<td>Weight savings</td>
</tr>
<tr>
<td>O</td>
<td>Body A limited</td>
<td>Process</td>
<td>Lower cost material</td>
<td>Weight savings</td>
</tr>
<tr>
<td>P</td>
<td>Trucks</td>
<td>Process</td>
<td>Reduced production cost</td>
<td>Weight savings</td>
</tr>
</tbody>
</table>

**Tier 1: General Research**

<table>
<thead>
<tr>
<th>Code</th>
<th>Project Area</th>
<th>Class</th>
<th>Traceable $ Benefit</th>
<th>Other Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>Environment</td>
<td>Design Tool</td>
<td>NA</td>
<td>Design tool</td>
</tr>
<tr>
<td>R</td>
<td>External Programs</td>
<td>Other</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
Table 7-2 presents financial data related to the projects that the company currently tracks or helped to assemble for this case study. It includes the annual cost of running the R&D project, an expected cost of implementing the project, and an estimate of the expected and upper limit of dollar benefits that would accrue on an annual basis after implementation. The date when the R&D technology is expected to be ready for implementation and an estimate of the likelihood that the technology will work (probability of success) are also provided.

<table>
<thead>
<tr>
<th>Code</th>
<th>Annual R&amp;D Cost</th>
<th>Implementation Cost</th>
<th>Annual Benefits</th>
<th>Upper Limit of Annual Benefits</th>
<th>Concept Ready</th>
<th>Probability of Success</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tier 3: Current Vehicle Focus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>1.0</td>
<td>0.25</td>
<td>40</td>
<td>48.0</td>
<td>1998</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>0.8</td>
<td>0.25</td>
<td>35</td>
<td>42.0</td>
<td>1998</td>
<td>0.8</td>
</tr>
<tr>
<td>C</td>
<td>0.4</td>
<td>1.00</td>
<td>20</td>
<td>24.0</td>
<td>1998</td>
<td>0.9</td>
</tr>
<tr>
<td>D</td>
<td>0.2</td>
<td>0.25</td>
<td>3</td>
<td>3.6</td>
<td>1997</td>
<td>0.9</td>
</tr>
<tr>
<td>E</td>
<td>0.6</td>
<td>2.00</td>
<td>25</td>
<td>30.0</td>
<td>1999</td>
<td>0.8</td>
</tr>
<tr>
<td>F</td>
<td>0.2</td>
<td>0.25</td>
<td>15</td>
<td>18.0</td>
<td>1997</td>
<td>0.8</td>
</tr>
<tr>
<td>G</td>
<td>0.2</td>
<td>0.25</td>
<td>14</td>
<td>16.8</td>
<td>1998</td>
<td>0.7</td>
</tr>
<tr>
<td>H</td>
<td>0.4</td>
<td>0.25</td>
<td>10</td>
<td>12.0</td>
<td>1998</td>
<td>0.8</td>
</tr>
<tr>
<td>I</td>
<td>0.2</td>
<td>1.00</td>
<td>8</td>
<td>9.6</td>
<td>1998</td>
<td>0.5</td>
</tr>
<tr>
<td>J</td>
<td>0.8</td>
<td>1.00</td>
<td>1</td>
<td>1.2</td>
<td>1997</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Tier 2: Future Vehicle Possibilities</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>1.0</td>
<td>50.00</td>
<td>100</td>
<td>120.0</td>
<td>2000</td>
<td>0.3</td>
</tr>
<tr>
<td>L</td>
<td>0.2</td>
<td>50.00</td>
<td>50</td>
<td>60.0</td>
<td>1997</td>
<td>0.5</td>
</tr>
<tr>
<td>M</td>
<td>0.1</td>
<td>0.25</td>
<td>25</td>
<td>30.0</td>
<td>2002</td>
<td>0.6</td>
</tr>
<tr>
<td>N</td>
<td>0.6</td>
<td>50.00</td>
<td>250</td>
<td>300.0</td>
<td>1997</td>
<td>0.4</td>
</tr>
<tr>
<td>O</td>
<td>0.6</td>
<td>10.00</td>
<td>10</td>
<td>12.0</td>
<td>1997</td>
<td>0.6</td>
</tr>
<tr>
<td>P</td>
<td>0.4</td>
<td>50.00</td>
<td>50</td>
<td>60.0</td>
<td>2000</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Tier 1: General Research</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>0.2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>1999</td>
<td>NA</td>
</tr>
<tr>
<td>R</td>
<td>0.2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>2004</td>
<td>NA</td>
</tr>
</tbody>
</table>
Several details in Tables 7-1 and 7-2 are not immediately obvious, and require further elaboration. In particular, the basis that is used to separate the projects into tiers is important to discuss. In this case study, the distinction between these tiers largely defines sets of projects that require different levels of effort to value.

The single strongest influence that defines the difference between a Tier 3 and a Tier 2 project for this portfolio is the relation of the project to vehicle production. The Tier 3 projects aim to improve or solve a problem related to existing vehicle architecture, which includes current products, manufacturing processes and support functions. The Tier 2 efforts focus on creating significant new capabilities that would be most broadly utilized in future vehicle architectures. Thus, the tables include the sub-headings, "Current Vehicle Focus" and "Future Vehicle Possibilities" for Tier 3 and Tier 2 projects, respectively.

A closely related point is that the form of benefits offered the projects differs significantly between Tier 3 and Tier 2. Although Table 7-2 provides an estimate of the dollar value of benefits for each of the Tier 3 and Tier 2 projects, the basis for developing these estimates is appreciably different within these two tiers.

For the Tier 3 projects, the estimate of annual benefits in Table 7-2 is primarily based on the traceable dollar benefit listed in Table 7-1. Generally, these projects aim to achieve a goal such as improving manufacturing productivity, reducing warranty costs or eliminating steps in design or production processes. Information that allows a reasonable estimate of the value of these improvements is typically available.

In contrast, the Tier 2 projects aim to enable significant technical advances in vehicle designs by developing economical processes for utilizing new materials. In particular, the development of dramatic weight savings capabilities is a major goal of these projects.\textsuperscript{13} The ultimate value of these investments depends on the resulting mix of process economics and technical benefits, how the technical benefits are exploited in products, and possibly the

\textsuperscript{13} Much of this investment is in response to external pressures to improve vehicle fuel-economy. This issue is discussed in detail later in the case study.
context in which they are commercialized. For example, the state of the regulatory environment impacts incentives for producing vehicles that weigh less than current models.

Although Table 7-2 provides estimates of the value of Tier 2 project benefits, these estimates are translations of complex benefits into a dollar metric, contingent upon specific contextual settings. Since the value of these benefits might vary under different contextual outcomes, multi-metric valuation models and scenario analyses are likely needed to value the Tier 2 projects in a more complete fashion. This case study begins with the dollar benefit estimates in Tables 7-1 and 7-2, and then explores scenarios and multi-metric valuation as a refinement to the base case analysis.

The most obvious point to make about the Tier 1 projects listed in Tables 7-1 and 7-2 is that much less information is provided. The two projects that are classified as Tier 1 are as close as this highly applied portfolio gets to basic research. As with many basic R&D investments, it is difficult to quantify the benefits of these efforts. This does not mean that the projects have no value; their value is simply highly intangible.

In general, the composite methodology demonstrated in this thesis is not especially useful for Tier 1 projects. Hauser and Zettelmeyer (1996) provide guidance on how to manage Tier 1 efforts (see Chapter 2). Since the information that is required to value the Tier 1 efforts in the materials portfolio is unavailable, the remainder of this case study drops these projects from consideration. In practice, the company that provided the project data also excludes these projects from its valuation process. Overall, these projects represent less than five percent of the total portfolio budget, so excluding them is not likely to influence appreciably any assessment of portfolio worth.

A final point of interest is the disparity in implementation costs shown in Table 7-2. Most of the projects have similar R&D costs, and aim to yield benefits that far exceed the R&D investment. While the cost of implementing many of the projects is about the same as a year of R&D expenses, a few require tens of millions of dollars to introduce.
This range of implementation costs reflects an important difference between two forms of R&D projects that comprise the portfolio. First, many of the projects that have low implementation costs are computer modeling efforts. These projects focus on streamlining product designs or optimizing existing manufacturing processes through control parameter adjustments. While the payoffs can be tremendous, implementation is relatively simple once the modeling results are validated and perhaps a minor material change is qualified. In contrast, the projects with more significant implementation costs aim to incorporate new technology into products and the production environment. Implementing these technologies requires appreciable commitments to capital investment, testing, roll-out, and learning.

These differences in implementation costs can have implications for the value of the options to implement the projects (see Chapter 4, Figure 4-3 and Figure 4-4). Projects with low implementation costs compared to the expected range of benefits aim to create "deep in the money options." The degree to which an NPV assessment that ignores options will differ from a decision tree based NPV is minimal for these cases, because the value of forgoing implementation when facing unpromising outcomes is relatively inconsequential. A real options approach will result in a different estimate of project value because it uses a different basis for adjusting project cash-flows for risk. However, the actual opportunistic value of not incurring implementation costs when project benefits do not justify implementation remains small. In these cases, the real options approach simply represents a method for estimating the NPV of the project that forces proper discounting of cash-flows.

In contrast, the option to implement will be an important component of value for projects with relatively significant implementation costs. Proper valuation of projects that fit this description requires consideration of the option (Figure 4-3 and 4-4). In these cases, a naive NPV assessment that ignores options will diverge from an informed, decision tree based NPV. However, decision trees that recognize the value of the option are not able to properly adjust project cash-flows for market risks. The real options method represents an approach that simultaneously recognizes the value of the implementation option and includes the appropriate level of risk adjustment in the project cash-flows.
PROJECT ASSESSMENT: CURRENT PRACTICE

The materials R&D portfolio that this case study uses is managed according to a number of goals. Two important decision drivers are a metric of project value and the balance of the R&D pipeline.

Figure 7-1 presents a chart that is currently used to gauge the value of projects. It compares the expected annual benefits of a successful project to the probability that the project will be successfully developed to the point where it is ready to be implemented. This chart is very similar to the risk-reward matrix (Figure 2-2) that is criticized in Chapter 2 for oversimplifying issues related to project value. In particular, Figure 7-1 indicates nothing about the timeframe over which the benefits will accrue or the cost of implementing the projects. These factors obviously influence the value of the projects. Further, while it is clear that driving projects toward the upper right corner of the chart is desirable, a value-optimizing trajectory is not obvious.

However, Figure 7-1 has several advantageous qualities. First, it concisely communicates that the portfolio of projects is expected to yield significant benefits (millions of dollars per year), and that a large fraction of the projects are expected to work with reasonable likelihood (i.e., the probability of success is greater than 50% for the majority of projects). Second, the chart is based on information that the R&D group can easily assemble. In contrast, most implementation efforts involve a broader cross-section of the firm, so it is more difficult for the R&D managers to gauge the cost of the required resources. Finally, the chart provides a basis for comparing project performance over time; the general objective to drive each project toward the upper right corner of Figure 7-1.

Since Figure 7-1 represents current practice for valuing the R&D projects, it is a useful benchmark that can be compared with the results of the composite valuation process. The specific metric of value that this thesis uses to represent the valuation goal of Figure 7-1 is the probability of success multiplied by expected annual benefits.
Figure 7-1: The Current Basis for Communicating R&D Value

Figure 7-2: Annual Implementation Goals Skew Pipeline to Near-Term
Figure 7-2 characterizes the R&D "pipeline." It shows the time-line over which the R&D projects are expected to be completed, and for each year it indicates the level of investment associated with the projects that are expected to be finished. The total number of projects that are expected to be completed during each year is also noted. The pipeline for the materials portfolio is dominated by projects that are expected to be finished within two years. In part, this is likely a result of an annual implementation target at the company.

The rationale for introducing Figure 7-2 is to indicate that project value is not the sole basis for managing R&D. A variety of issues must also be considered. These include managing the flow of innovation, because organizations face limits to the rate at which they can adopt technology. For this reason, this case study closes by exploring the potential role of the composite valuation methodology within a broader portfolio management process.

**VALUING A PROJECT WITH THE COMPOSITE VALUATION METHODOLOGY**

This section demonstrates how to apply the composite valuation methodology to a single project. It follows the procedure and uses the implementation option framework that Chapter 6 outlines. A spreadsheet model based on this implementation option framework is used to conduct the actual calculations. Appendix C describes the spreadsheet in detail.

This demonstration focuses on Project B which is described in Tables 7-1 and 7-2. After the results of valuing all of the projects in these tables are discussed, Project B is revisited and sensitivity analyses are used to highlight important aspects of the valuation models that this case study compares. Project B was selected for the demonstration because it has some interesting features that are addressed through the sensitivity studies.

**Step 1: Scope of Assessment**

The first step in the composite methodology identifies the uses that will be considered for estimating the value of the project. It focuses on identifying potential applications, end-user segments and scenarios that influence the value of the project. The number of uses that must be valued is equal to the number of unique combinations of these three factors (see Equation 7-1, which is identical to Equation 6-1). For each use, the
source and level of project revenues is likely to differ, as are the timing of costs and decisions (project options).

\[
\text{\# Uses} = \sum_{i=1}^{n} (\text{\# End-Use Segments}_i \times \text{\# Scenarios}_i)
\]  

(7-1)

where \(n\) = \# of applications

For the base case analysis of Project B, only one use of the technology is evaluated, primarily because this matches the data that the company was able to provide for the project. The technology is applied to optimize the structural integrity of engine components and reduce their weight. It is applicable to the entire fleet of passenger vehicles that the company produces, and it is assumed that for the purpose of valuing this technology that this fleet can be treated as a homogenous segment. Also, the value of this project is assumed to remain relatively constant across future operational environments. Therefore, only one scenario is considered. A later portion of this case study explores the complexities created by the need to evaluate multiple technology uses.

**Step 2: Project Data Collection**

The second step of the composite methodology requires the collection of project data for each use of the technology defined during Step 1. This includes costs, benefits, decisions and uncertainties. The timing of cash-flows and decisions must also be defined. When multiple uses are considered, it is possible that some project costs might be shared. This can complicate the valuation process. Two practical approaches to this problem are demonstrated later in this case study, during the discussion of how to treat projects with complex benefits.

**Costs**

Table 7-2 indicates that the annual R&D expense for Project B is $800,000, and that the aggregate implementation cost is $250,000. The data in Table 7-2 represents expectations at the beginning of 1997. Only one year of R&D expenses is expected to be
incurred since Project B is expected to be implementation ready by the beginning of 1998. Consequently, the implementation cost is expected to be incurred at the beginning of 1998.

**Benefits**

Table 7-2 also indicates that the company expects Project B to yield benefits of $35,000,000 per year. This analysis assumes that the benefits accrue starting one year after implementation and continue for five years. The timeframe over which benefits accrue was selected based on discussions with the R&D managers at the case study company.

**Decisions**

This case study focuses on a single R&D decision in addition to the initial choice to begin a project. It evaluates the option to implement a successful technical development. This decision occurs at the end of the R&D phase of a project. If the technology is implemented, the implementation cost is incurred in exchange for the benefit stream. If the technology is not implemented, no further costs or benefits accrue. Figure 6-2 presents the basic decision tree structure that incorporates this choice.

**Uncertainties**

The hybrid real options and decision analysis model and the pure decision tree that this case study uses include three uncertainties: technical, benefit and market (see Figure 6-2). Technical and benefit uncertainties are treated as endogenous influences, and market uncertainty is treated as an exogenous influence.

Technical uncertainty is characterized by the probability of success for each project that Table 7-2 provides. For Project B, this probability is 0.8. This is a subjective estimate that the R&D managers at the company which provided this case study data use to help manage projects. In the decision tree framework this case study uses (Figure 6-2), the option to implement is valued only for technical successes. Projects that are not successful are assumed to be worthless. Chapter 3 discusses possible extensions of this assumption, but they are left for others to pursue.
Benefit uncertainty is characterized by the expected and upper limit of benefits for a project. For Project B, it was already noted that the expected benefits are $35,000,000 per year. The upper limit is $42,000,000 per year. Assuming that the upper limit represents the 0.95 fractile of a lognormal distribution (Z-value = 1.645), a standard deviation of benefits can be estimated using Equation 7-2, which is identical to Equation C-1. Lognormality is assumed because a technically successful project is expected to have potentially unlimited benefits that are greater than zero. For Project B, this standard deviation is 11.1%.

\[
\text{Standard Deviation of Benefits} = \sigma_b = \frac{LN(\text{Upper Limit}/\text{Expected})}{1.645}
\]  

(7-2)

Discrete probabilistic estimates of benefit outcomes can then be developed using a process such as the extended Pearson-Tukey procedure outlined in Appendix A. The implementation option spreadsheet developed for this case study equivalently uses the relationship shown in Equation 7-2 to scale the expected revenues of the project. The expected revenues are calculated during Step 3 of the valuation process. For a detailed description of how these calculations are conducted in the spreadsheet, see Appendix C.

Market uncertainty is characterized differently in the real options hybrid model than it is in the pure decision tree. However, both models relate project revenues to vehicle production. Estimating variations in production volume is the basis that the models use for incorporating exogenous market uncertainties into the valuation.

Market uncertainty is estimated directly for the pure decision tree. Since this thesis primarily aims to demonstrate the mechanics of the composite methodology it develops, a simple linear regression of the form shown in Equation 7-3 is used to estimate expectations. The standard error of the regression defines a range over which production might vary. Appendix B estimates regression parameters for A (2,783,980) and B (15,864) in Equation 7-3 using historical production data (see Table B-2). The standard error is 573,104.
\[ P_t = A + Bt \] \hspace{1cm} (7-3)

where, \( P_t \) = production output at time \( t \)

and \( A \) and \( B \) are the regression parameters

Discrete probabilistic outcomes of market uncertainty are estimated for the decision tree using Equation 7-3, the standard error, and the extended Pearson-Tukey method (Appendix A). Appendix C shows how the spreadsheet model applies the results to adjust project cash-flows. In reality, vehicle production is highly cyclical and complex to model. The results of such a model could easily be incorporated into the composite framework.

In the real options hybrid, vehicle production is correlated with the price of a stock to enable the use of risk-neutral valuation procedures. A regression model relates the value of this underlying asset to future production output is developed in Appendix B (see Table B-3 for results). Equation 7-4 shows the general form of this percentage differences model.

\[ \text{Vehicle Production}_{t,n} = \text{Vehicle Production}_t \times \exp(A + B \times \ln(S_{t,n} / S_t)) \] \hspace{1cm} (7-4)

where, \( A \) and \( B \) vary for different values of \( n \).

Assuming that the underlying stock captures all of the exogenous, market risks of the project, it is then possible to use risk-neutral valuation procedures in the hybrid decision tree. This requires a transformation of the stock price distribution that yields a risk-neutral set of probabilistic outcomes of stock price that can drive the estimate of future vehicle production in Equation 7-4. The transformation is conducted during Step 3 of the methodology.

**Step 3: Transforms of Project Data**

The next step in the methodology transforms some of the project data into forms that are required for conducting the valuation. First, for projects with complex benefits, multi-metric models are applied to transform these benefits into dollar based values. Next, if
the real options approach is used to value the projects, the priced factors that are related to exogenous uncertainties are transformed into risk-neutral distributions. Finally, the project costs and benefits are transformed into expected cash-flows. These expected cash-flows are subsequently converted into conditional outcomes during the valuation process (Step 4).

Transforming Complex Benefits into Dollar Values

Although the benefits of Project B include direct dollar savings through prototype elimination and weight savings, the base case analysis relies on the estimate of the value placed on these benefits by the company that provided the case study data. The role of complex benefit valuation models is explored later in this case study.

Transforming Exogenous Uncertainties into Risk-Neutral Quantities

An analysis of the price dynamics of the stock that drives the regression relationship shown in Equation 7-4 shows that historically the stock provides a 13.2 percent total return and has a volatility of 20.7 percent (see Table B-4 in Appendix B). Dividends comprise 4.5 percent of the returns and growth yields the remaining 8.7 percent.

The model that this case study uses applies the binomial approach to estimate a risk-neutral distribution of the underlying asset (see Chapter 3, Appendix B, and Appendix C). Assuming a risk-free rate of 5 percent, the lognormal, risk-neutral distribution has a five percent expected return and a 20.7 percent volatility. This distribution is used to estimate probabilistic outcomes of production. Because the risk-neutral procedure provides outcomes of the underlying asset that are adjusted for market risks, the resulting project cash-flows can be discounted at the risk-free rate. Appendix B details these calculations in Table B-5 and Table B-6. The results in Table B-6 are used for the case study.

Transforming Costs and Benefits into Expected Cash-Flows

Using the dollar-based estimates of costs and benefits from Steps 2 and 3, traditional financial valuation methods are next applied to obtain a present value of the project revenues and costs. During the decision tree based valuation (Step 4), uncertainties are introduced to the cash-flows, and the influence of options is evaluated.
Because the hybrid of real options and decision analysis conducts risk-adjustments through risk-neutral transforms of exogenous uncertainties, the discounting for this model is conducted using the risk-free rate. For pure decision analysis approaches, an arbitrary discount rate is required. The case study assumes that the risk-free rate is 5 percent and uses an arbitrary rate of 15 percent for the decision tree.

The timing and magnitude of costs is established during Step 2. Therefore, these cash-flows can be discounted directly using standard NPV techniques. Estimating aggregate project revenues requires additional work, but is a reasonably mechanical process. It generally requires estimates of the following factors:

- the dollar value of benefits from Step 2 or 3
- the timeframe over which benefits will accrue
- the unit of influence (e.g., production units influenced per unit of time)

The dollar benefit from Step 2 or 3 must be expressed as the marginal revenue that would result from implementing the technology. Typically a dollar per unit of production or a dollar per year estimate will result. Equation 7-5 (equivalent to Equation 6-2) indicates that this marginal revenue is the difference between increases in value to the end-user and cost to the producer.

\[
R&D \text{ Marginal Revenue} = (\text{User Value}_{\text{New}} - \text{Cost}_{\text{New}}) - (\text{User Value}_{\text{Old}} - \text{Cost}_{\text{Old}}) \quad (7-5)
\]

Once an appropriable marginal influence of the technology is estimated, it is aggregated into an estimate of the present value of expected revenues that would result from the successful implementation of the technology. Equation 7-6 summarizes the present value of project revenues calculation. The variables \(t_1\) (period where revenues start) and \(t_2\) (period where revenues end) define the time from the date of project initiation (\(n\) periods) over which revenues accrue, and \(r\) is the discount rate.
\[ PV(\text{Revenues}) = \sum_{n=1}^{\infty} \frac{\text{Marginal Revenue}_n \times \text{units}_n}{(1+r)^n} \]

For Project B, the estimate of annual benefits ($35,000,000) is already expressed as a marginal revenue. The case study assumes that this stream accrues for five years, starting one year after the implementation date (i.e., two years from the start of the project). The case study treats this estimate as if it were entirely appropriable. Therefore, the expected value of the cash-flows (without uncertainty and decisions) is $102 million when the arbitrary rate is applied and $144 million when the risk-free rate is applied (see Figure C-3 in Appendix C).

**Step 4: Valuing a Single Use**

To value a single use of the project, the discounted cost and revenue information is incorporated into the decision tree structure shown in Figure 6-2. The revenues are adjusted to reflect the influence of uncertainties, and these conditional outcomes are compared to the discounted cost of implementation. The technology is implemented only when the revenues exceed the implementation cost. Equation 6-4 summarizes the calculation. Appendix C details the scaling of the revenue streams and the evaluation of the implementation option. For Project B, the hybrid of real options and decision analysis estimates that the project has a net value of $114 million. The pure decision tree results in an estimate of $86 million (see Figure C-6 in Appendix C). The drivers of this difference are explored in detail during the discussion of the results of valuing all of the projects in the portfolio. Chapters 3 and 4 also provide detailed discussions of the differences between pure decision analysis and real options methods.

**Step 5: Valuing the Project**

In the case of Project B, the single use value is equivalent to the value of the project since only one use was considered. A later section of this case study which discusses the role of multi-metric frameworks treats the issue of how to handle multiple uses.
VALUING THE PORTFOLIO AND COMPARING THE VALUATION MODELS

This first analysis of the portfolio of projects is based entirely on the financial data shown in Table 7-2. The goal is to present a comparison of the valuation frameworks and to explore insights that the composite valuation methodology enables. Four valuation models are considered: 1) the probabilistic expected benefits that characterize Figure 7-1, 2) a naive NPV assessment that ignores options, 3) an informed, decision tree based NPV (the pure decision tree), and 4) a real options and decision analysis hybrid.

Major Assumptions

The following analysis uses assumptions similar to those applied during the demonstration valuation of Project B:

- Projects accrue revenues for five years after implementation.
- The risk-adjusted discount rate for the decision analysis and NPV model is 15%, and the risk-free rate used in the real options model is 5%.
- The upper limit of project benefits is 120% of the expected value.
- The regression parameters A and B in Equation 7-3 are 2,783,980 and 15,864, respectively. The standard error is 573,104.
- The case study uses the regression results for \( n = 1 \) in Equation 7-4. \( A \) is not significant, and the correctly estimated \( B \) is 0.253.
- In Equation 7-4, the annual dividend yield of the underlying stock is 4.5% and the annual volatility is 20.7%.

The assumption that benefits accrue for five years is based both on conversations with the portfolio manager and the recognition that the benefits of any technology implementation will erode over time due to competition. Sensitivity analysis is applied during the case study to examine the influence of changes to this assumption.
The risk-adjusted discount rate and the variation of benefits are pure assumptions. The growth rate and volatility assumptions are based on data presented in Appendix B. All of these inputs are candidates for sensitivity analysis.

**Results**

Table 7-3 summarizes the results of valuing projects A through P (the Tier 3 and Tier 2 projects) using the four valuation models, and it ranks the projects according to value predicted by each model. This exhibit and others in the remainder of the case use the following abbreviations to refer to the valuation models:

- **P(s)*Benefits =** the probabilistic expected benefits,
- **NPV =** naive NPV assessment that ignores options,
- **DA =** decision tree based NPV (a pure decision tree),
- **OPT =** real options and decision analysis hybrid.

**Table 7-3: Four Value Based Rankings of the Projects (in $, Millions)**

<table>
<thead>
<tr>
<th>Rank</th>
<th>P(s)* Benefits</th>
<th>NPV</th>
<th>DA</th>
<th>OPT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Project Value</td>
<td>Project Value</td>
<td>Project Value</td>
<td>Project Value</td>
</tr>
<tr>
<td>1</td>
<td>N 100</td>
<td>N 282.5</td>
<td>N 311.3</td>
<td>N 402.7</td>
</tr>
<tr>
<td>2</td>
<td>A 32</td>
<td>A 97.7</td>
<td>A 97.9</td>
<td>A 130.6</td>
</tr>
<tr>
<td>3</td>
<td>K 30</td>
<td>B 85.5</td>
<td>B 85.8</td>
<td>B 114.3</td>
</tr>
<tr>
<td>4</td>
<td>B 28</td>
<td>C 54.4</td>
<td>L 59.1</td>
<td>K 95.6</td>
</tr>
<tr>
<td>5</td>
<td>L 25</td>
<td>E 51.4</td>
<td>K 58.5</td>
<td>L 81.1</td>
</tr>
<tr>
<td>6</td>
<td>E 20</td>
<td>F 39.1</td>
<td>C 54.6</td>
<td>E 75.6</td>
</tr>
<tr>
<td>7</td>
<td>C 18</td>
<td>L 35.6</td>
<td>E 51.8</td>
<td>C 72.9</td>
</tr>
<tr>
<td>8</td>
<td>M 15</td>
<td>K 35.3</td>
<td>F 39.3</td>
<td>F 50.3</td>
</tr>
<tr>
<td>9</td>
<td>P 15</td>
<td>G 29.9</td>
<td>G 30</td>
<td>M 49.6</td>
</tr>
<tr>
<td>10</td>
<td>F 12</td>
<td>M 26.5</td>
<td>M 26.6</td>
<td>P 41.6</td>
</tr>
<tr>
<td>11</td>
<td>G 9.8</td>
<td>H 24.1</td>
<td>P 24.6</td>
<td>G 40</td>
</tr>
<tr>
<td>12</td>
<td>H 8</td>
<td>I 11.3</td>
<td>H 24.2</td>
<td>H 32.4</td>
</tr>
<tr>
<td>13</td>
<td>O 6</td>
<td>O 9.9</td>
<td>O 13.6</td>
<td>O 18.9</td>
</tr>
<tr>
<td>14</td>
<td>I 4</td>
<td>D 8.5</td>
<td>I 11.8</td>
<td>I 15.8</td>
</tr>
<tr>
<td>15</td>
<td>D 2.7</td>
<td>P 1.5</td>
<td>D 8.5</td>
<td>D 11</td>
</tr>
<tr>
<td>16</td>
<td>J 0.9</td>
<td>J 1.2</td>
<td>J 1.3</td>
<td>J 2.1</td>
</tr>
</tbody>
</table>
Table 7-3 illustrates several important points. First, while the project rankings do not match exactly for any of the methods, they are generally close. Most projects are ranked within one or two places of each other. Next, the real options model (OPT) places the highest value on every R&D project. Since the OPT model also represents the most correct way of valuing the project cash-flows, this suggests that the other methods undervalued the projects. Unfortunately, as Chapter 3 points out, there is no way to tell \textit{a priori} if the arbitrary discount rate will under or overvalue an investment. Finally, \( P(S) \times \text{Benefits} \) yields lowest estimate of value. This is not surprising since this metric only includes the value of one year of benefits. However, it may still serve as a useful signal under certain conditions. This issue is explored shortly.

Table 7-4 further clarifies the rankings by separately ordering the projects within their respective R&D tier. For the Tier 3 projects, the rankings match, except for the positions of projects C and E, which vary between the third and fourth ranks. Comparing the estimates of project value obtained using NPV, DA and OPT reveals that the models all yield similar results for these two projects. The rankings of the Tier 2 projects are also close for all of the valuation methods.

Table 7-4 also helps to illustrate that the simple metric of value, \( P(s) \times \text{Benefits} \), can provide similar signals as the more complex methods. It is not surprising that this method yields the lowest estimate of value since it is based on the annual benefits instead of five years of revenue accrual. However, it is interesting that such a simple index tracks with more formal models.

In fact, the \( P(s) \times \text{Benefits} \) metric may be satisfactory for many \textit{relative} comparisons, when projects have low implementation costs compared to expected benefits, a high likelihood of success, and similar exogenous risk characteristics and time horizons. In such cases, the value of the implementation option is limited and, the appropriate level of risk-adjustment is similar. Under these conditions, the \( P(s) \times \text{Benefits} \) metric is essentially a
stripped down NPV metric (i.e., the insignificant cost terms and common discounting factors are dropped). These conditions seem to hold for projects A-J of this particular portfolio.

Part of the appearance of order in Table 7-4 stems from breaking a long list of projects with many minor variations into two smaller lists. However, it is also useful to separate the projects at this point because the next section explores the potential for applying multi-metric models and scenarios to the complex benefits of the Tier 2 projects. In contrast, the valuation of the Tier 3 projects is nearly complete at this juncture, with the exception that some sensitivity analyses are conducted before returning attention to the Tier 2 efforts.

Table 7-4: Rankings within Tiers are Very Similar (Value in Millions of $)

<table>
<thead>
<tr>
<th>Rank</th>
<th>P(s)* Benefits</th>
<th>NPV</th>
<th>DA</th>
<th>OPT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Project</td>
<td>Value</td>
<td>Project</td>
<td>Value</td>
</tr>
<tr>
<td><strong>Tier 3: Current Vehicle Focus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>32</td>
<td>A</td>
<td>97.7</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>28</td>
<td>B</td>
<td>85.5</td>
</tr>
<tr>
<td>3</td>
<td>E</td>
<td>20</td>
<td>C</td>
<td>54.4</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>18</td>
<td>E</td>
<td>51.4</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>12</td>
<td>F</td>
<td>39.1</td>
</tr>
<tr>
<td>6</td>
<td>G</td>
<td>9.8</td>
<td>G</td>
<td>29.9</td>
</tr>
<tr>
<td>7</td>
<td>H</td>
<td>8</td>
<td>H</td>
<td>24.1</td>
</tr>
<tr>
<td>8</td>
<td>I</td>
<td>4</td>
<td>I</td>
<td>11.3</td>
</tr>
<tr>
<td>9</td>
<td>D</td>
<td>2.7</td>
<td>D</td>
<td>8.5</td>
</tr>
<tr>
<td>10</td>
<td>J</td>
<td>0.9</td>
<td>J</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Tier 2: Future Vehicle Focus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>N</td>
<td>100</td>
<td>N</td>
<td>282.5</td>
</tr>
<tr>
<td>2</td>
<td>K</td>
<td>30</td>
<td>L</td>
<td>35.6</td>
</tr>
<tr>
<td>3</td>
<td>L</td>
<td>25</td>
<td>K</td>
<td>35.3</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>15</td>
<td>M</td>
<td>26.5</td>
</tr>
<tr>
<td>5</td>
<td>P</td>
<td>15</td>
<td>O</td>
<td>9.9</td>
</tr>
<tr>
<td>6</td>
<td>O</td>
<td>6</td>
<td>P</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Figures 7-3 and 7-4 use the data from Table 7-3 to illustrate some important differences between the DA and NPV models. These figures compare the difference in value predicted by DA and NPV to the level of uncertainty and implementation cost. Figure 7-3 shows that the DA model converges with NPV for projects with low uncertainty, in this case the probability of success. Similarly, Figure 7-4 shows that DA and NPV converge as the implementation cost becomes less significant. In cases where uncertainty or implementation costs are high, DA provides a higher estimate of value than NPV because the value of the implementation option that NPV ignores is significant. A similar trend results from comparisons of the hybrid OPT model and NPV.

For example, Figure 7-3 and Figure 7-4 both indicate that NPV and DA yield nearly equivalent estimates of value when applied to Project D, which has low uncertainty (P(S)= 0.9) and low relative implementation costs (implement for $250,000 versus annual benefits of $3 million/yr). In contrast, Project K has high uncertainty (P(S)= 0.3) and high implementation costs (implement for $50 million versus annual benefits of $100 million/yr), and the difference between DA and NPV is significant (> $10 million).

*Sensitivity Analysis of a Single Project (B)*

Project B is an interesting project to examine further using sensitivity analyses because it raises some interesting issues related to the practical valuation of R&D projects. In particular, it helps to question the degree of effort that should be placed on quantifying all of the potential benefits of a project. If the goal of an assessment is simply to determine if an individual effort is worthwhile, without considering its relative value compared to other projects, focusing on easily traceable financial benefits alone might be satisfactory. However, if projects are ranked based on absolute value it may be important to consider as many project benefits as possible.
Figure 7-3: Decision Analysis (DA) and Net Present Value (NPV) Diverge as the Probability of Success Decreases (Uncertainty Increases)

Figure 7-4: Decision Analysis (DA) and Net Present Value (NPV) Diverge as the Magnitude of Implementation Costs Increases
Figure 7-5: Sensitivity of the Valuation Models to Benefits Estimates

Project B is interesting because it is one of two Tier 3 projects in the portfolio for which the estimated value of project benefits shown in Table 7-2 is predominantly based on benefits that are not easily converted into dollars. Project J is the other example. In the case of Project B, Table 7-1 indicates that the total expected benefits are $35,000,000 per year. However, only $5,000,000 of this stems from easily traceable financial benefits that result from the elimination of prototyping efforts. It turns out that the bulk of the value of Project B stems from a weight savings credit that is based on an internal factor the company uses.

Figure 7-5 serves two purposes. First, it compares the sensitivity of the valuation models to changes in the estimate of project benefits. Second, by centering the sensitivity analysis around the five million dollar benefit estimate, it inquires if the project is attractive if only traceable dollar benefits are considered. Figure 7-5 suggests that the trends between the models hold, and that Project B appears to be attractive for estimates of benefit value that are far below the traceable dollar estimate.
The issue of practical valuation is raised again during the conclusions to this thesis; however, the point to take from Figure 7-5 and other comparisons of valuation methods throughout this thesis is that context matters. Project B is attractive when valued using only the traceable dollar benefits and any of the four valuation models. While simpler methods do not always value projects properly, this thesis has identified conditions under which such models provide useful signals.

The remainder of the sensitivity analyses that this case develops for Project B focuses on traceable dollar value alone. These analyses are mainly concerned with developing more detailed comparisons of the four valuation models.

Figure 7-6 and Figure 7-7 examine the sensitivity of the models to variations in the probability of success, for two different levels of implementation cost. Both consider success probabilities ranging between zero and one. Figure 7-6 assumes an implementation cost of $250,000 (base case). Figure 7-7 assumes an implementation cost of $10,000,000 (an extreme value selected for illustrative purposes).

Figure 7-6 demonstrates several important points. First, when the implementation cost is $250,000, all four models indicate that Project B has a positive value until the probability of success falls below ten percent. Also, DA and NPV are essentially equivalent. P(s)*Benefits exhibits the same downward trend in value for decreasing probability of success that the other models show, and is constant for all levels of implementation cost.

Figure 7-7 shows that when the implementation cost is large ($10,000,000) all of the models except P(S)*Benefits yield lower estimates of value than in the base case. As expected based on the findings of Figure 7-5 and 7-6, DA and NPV diverge for probabilities of success less than one because the simple NPV model ignores the implementation option. In the base case, this option is not extremely valuable, so the DA and NPV models are close. In this case, the large implementation cost makes the option much more valuable. Since the simple NPV model ignores the option, an important source of project value is excluded from consideration.
Figure 7-6: Sensitivity of the Valuation Models to the Probability of Success for Low Relative Implementation Costs

Figure 7-7: Sensitivity of the Valuation Models to the Probability of Success for High Relative Implementation Costs
Figures 7-8 and 7-9 help to illustrate some important differences between DA and OPT. Both figures examine the sensitivity of the models to the duration of the R&D phase. They also examine the influence of the arbitrary discount rate in the DA model. In both figures, the NPV model would match the results of the DA model because the implementation option is not significant. \( P(s) \cdot \text{Benefits} \) is a constant over the sensitivity regimes of Figures 7-8 and 7-9. Therefore, the figures focus only on DA and OPT.

To start, Figure 7-8 shows that project value decreases for increasing R&D time requirements. This figure assumes that each additional year before the project is ready to implement adds cost to the project, and pushes benefit flows further into the future.

More importantly, Figure 7-8 also indicates that the choice of discount rate for the DA model strongly influences the recommended investment policy. For the base case rate of fifteen percent, DA suggests the project is not financially attractive if the R&D phase is expected to extend beyond nine years. Increasing the discount rate leads to an earlier cross-over point.

When the discount rate is set equal to the risk-free rate, the DA and OPT models still do not correspond. The remaining differences in value stem from the different bases that the two models use to estimate the influence of exogenous market uncertainty. Therefore, in cases where exogenous risks are minimal, discounting at the risk-free rate within a decision tree is functionally equivalent to a real options approach.

The strong sensitivity of the DA model is a concern for two reasons. First, there is no basis for selecting a discount rate when a pure decision tree is used to value a project with embedded options that depend on exogenous market outcomes. This is precisely why options models were developed. Second, in common practice, companies often use discount rates that far exceed even the weighted-average cost of capital (WACC). If such a rate were applied to Project B, the DA model would grossly undervalue the project compared to OPT. This tendency to undervalue projects is likely to arise in many instances where an inordinately large discount rate is applied.
Figure 7-8: The Influence of the Arbitrary Discount Rate in the Decision Analysis Model when Benefits Accrue for Five Years

Figure 7-9: The Influence of the Arbitrary Discount Rate in the Decision Analysis Model when Benefits can Accrue for Longer than Five Years
Figure 7-9 extends the criticism of the arbitrary discount rate that DA requires by examining the sensitivity of the results in Figure 7-8 to changes in project cash-flows. Previously, project revenues were assumed to accrue for five years after implementation. In Figure 7-9, the period over which revenues accrue is twice as long as the R&D phase, with a minimum of five years. Such an assumption may not be unrealistic. Often, long-term R&D yields technology that can be protected through patents and trade secrets. In these cases, the period over which the firm can appropriate rents may be longer than for short-term incremental improvements that might be duplicated or competed away in the marketplace.

The point of Figure 7-9 is to show that the arbitrary discount rate in DA can distort estimates of project value and sensitivity trends. The OPT model shows that, at least for a while, the increase in revenues off-sets increases in R&D costs and delays in revenues. The DA model does not always demonstrate the OPT trend. It depends on the discount rate.

Figure 7-10 examines the influence of the market uncertainty drivers that the DA and OPT models utilize. For the DA model, this case study uses a linear regression of historical production data to approximate exogenous project risks. The standard error serves as the uncertainty metric (MSIG in Figure 7-10). In contrast, the OPT model relates production volume uncertainty to the price of a traded stock, and adjusts the expected distribution of outcomes of the traded asset to match expectations in a risk-neutral world. This adjustment accounts for the market risk in the project, and it allows the resulting cash-flows to be discounted at the risk-free rate. The standard deviation of the adjusted distribution serves as the OPT metric of market uncertainty (USIG in Figure 7-10).

Figure 7-10 shows two influences of the market uncertainty metric for the DA model. First, the value of the project increases with the level of volatility (uncertainty). Second, the influence of the market uncertainty increases with the time before implementation. Similarly, the influence of uncertainty also increases with time before implementation for the OPT model. However, in this case, the OPT model indicates that value of the project decreases as uncertainty increases.
Figure 7-10: Sensitivity of the Decision Analysis and Real Options Models to Market Uncertainty

Figure 7-11: Near the Money Options Most Sensitive to Volatility
The increase in the importance of market uncertainty with time before implementation is not a surprising result. However, options are generally thought to increase in value with increasing uncertainty, so the reverse trend in the OPT model is surprising.

Figure 7-11 helps to illustrate these points. It presents the sensitivity of a simple call option to changes in volatility (dC/dSig) as a function of stock price and time to expiration. It considers the effect of a jump in volatility from 0.2 to 0.6, for an option with a strike price of 0.25. Figure 7-11 indicates that near the money call options (S close to K) are the most sensitive to volatility. Since Project B has a strike price of $250,000 and annual benefits of $5,000,000 (five year value > $20,000,000), it is not surprising that the implementation call option shows little sensitivity until the time to implementation approaches ten years.

Figure 7-11 also confirms that increasing uncertainty should yield increases in the value of a simple call option. However, the payoff structure of the OPT model is not as simple as that of a call option on a stock. The level of production output and thereby the revenues in OPT is a non-linear function of the future underlying price, while a simple call option is directly and linearly related to the price of the underlying (see Figure 3-4). As a result, OPT may not always mimic the behavior of a simple call option.

In this particular case, the combination of the non-linear relationship and the risk-neutral valuation procedure in the OPT model leads to a weighted expected output that slightly declines as volatility increases. Since the option is deep in the money, it is exercised across most outcomes. As a result, the decline in expected output reduces the value of the option. This trend could reverse for different risk-neutral growth rates and relationships between the underlying and the driver of cash-flows.

The combined findings of Figure 7-10 and 7-11 also illustrate another problem with using an arbitrary discount rate in a decision tree. One reason that the DA method does not yield results that correspond to OPT in Figure 7-10 is that while volatility varied, the risk-adjusted discount rate was constant. Figure 3-8 indicates that the option beta is related
to the beta of the underlying asset and therefore, its volatility. Changes in volatility require corresponding changes in the risk-adjusted discount factor for DA. Real options models require no such adjustment since they rely on risk-neutral valuation procedures.

These sensitivity analyses, and others like them, could be repeated for any or all of the projects in the portfolio. The major goal of developing these analyses for this case study was to point out important similarities and differences in the various valuation models. Rather than repeating the process for other projects, attention is now turned to examining in more detail some of the Tier 2 projects that offer complex benefits.
A CLOSER LOOK AT PROJECTS WITH COMPLEX BENEFITS

The first part of this case study applied the estimates of project benefits developed by the company that provided the portfolio data to compare four different metrics of project value. This comparison demonstrates that OPT, DA, NPV and P(s)*Benefits yield different estimates of project value, but might provide similar signals under certain conditions.

However, many of the Tier 2 projects in Table 7-1 and Table 7-2 aim to enable complex functionality improvements that could be valued using the multi-metric approaches described in Chapter 5. For example, implementing body technologies (Projects K, L, N, and O) could reduce vehicle weight, but currently these technologies are costly. Therefore, a major goal of these R&D efforts is to improve the production economics of these developmental processes. This might be accomplished by enabling the use of less expensive materials, improving process throughput, or reconfiguring processes to reduce capital requirements. For these projects, the benefit estimates in Table 7-2 represent a complex aggregation of credits for saving weight and adjustments for changes in technology costs.

This part of the case study discusses how multi-metric valuation methods could be applied to such projects. The goal is simply to demonstrate a structured approach to considering the issue, and only stylized valuation examples are presented. To conduct an actual valuation, an assessment of end-user preferences is needed. As a practical matter, it is likely that in an industry the size of automotive, existing company resources (e.g., marketing) could be tapped to help assemble representative data.

The Role of Multi-Metric Models for Valuing Complex Project Benefits

The objective of applying multi-metric assessment methods to value R&D is summarized by Equation 7-5, which defines R&D marginal revenue as the difference between the value of a product or technology to an end-user and the cost of producing this product or technology, before and after a technological advancement is implemented. Rearranging Equation 7-5 to the form shown in Equation 7-7 expresses this marginal revenue as the difference between net increases in end-user value and production cost.
R&D Marginal Revenue = (User Value_{New} - User Value_{Old}) - (Cost_{New} - Cost_{Old}) \hspace{1cm} (7-7)

Multi-metric valuation methods provide a basis for estimating the value of a technology to a set of end-users. When the new technology can be compared to an incumbent, these frameworks provide a dollar-based willingness to pay (WTP) estimate that is equivalent to the difference in end-user values in Equation 7-7 (see Chapter 5). Substituting WTP into Equation 7-7 yields Equation 7-8.

R&D Marginal Revenue = (WTP) - (Cost_{New} - Cost_{Old}) \hspace{1cm} (7-8)

Further, Chapter 1 and Chapter 5 point out that it is not typical for an innovator to appropriate all of the value of an innovation. Instead, the benefits may accrue to a number of parties, including the innovator and the end-user. Equation 7-9 introduces a multiplier that represents the fraction of the net value creation value that is appropriated by the innovator (A_i). A_i will vary between 0 and 1, depending on the relative strength of the party that develops the technology.

R&D Marginal Revenue = A_i \times [(WTP) - (Cost_{New} - Cost_{Old})] \hspace{1cm} (7-9)

Thus, 7-9 indicates that end-users can benefit even when a project only yields cost improvements. This is especially true in highly competitive industries where price competition is severe. While appropriability is not fully considered in this case study, it is an important issue that deserves some attention when devising a technology strategy for a firm. At a minimum, R&D management should look for instances where a project might have an unusually low or high level of appropriability (e.g., patentable, hard to imitate, can implement well in advance of competition).
Integrating Multi-Metric Methods into the Composite Methodology

The composite methodology uses multi-metric methods during Step 3 (Transforms of Project Data) to transform complex project benefits into a dollar value. Equation 7-3 indicates that estimating the potential revenue stream for projects that offer complex benefits requires the assessment of several factors. Multi-metric valuation frameworks yield the WTP metric, but the costs of the incumbent and new technology must also be estimated. Chapter 6 suggests that cost modeling approaches are commonly used for this purpose (also see Clark, Roth, Field 1997). Finally, an estimate of appropriability is required. Unfortunately, this requires a more subjective evaluation.

However, Chapter 6 also suggests that the value of a technology can be contextual (see Equation 6-1). In simple cases where cost savings result from R&D, context may not have much bearing, but the complex cases that the multi-metric methods address may require the evaluation of more technology uses. Therefore, Equation 7-9 may need to be assessed for several scenarios, applications and end-user segments. These uses are identified during Step 1 of the valuation process (Scope of Assessment).

Once a marginal revenue is obtained for each use, Equation 7-6 can be applied to estimate total revenues for each use. The valuation process is then comparable to that for a project that yields directly quantifiable dollar benefits.

Table 7-5 provides an example of the data requirements and calculations for valuing an application of a technology using the composite valuation framework with multi-metric methods. It also notes the relevant step in the composite methodology for each calculation.

Table 7-5 considers one end-user segment and two scenarios. Therefore, it evaluates two uses of the technology.\textsuperscript{14} Table 7-5 indicates that any of the terms in Equation 7-9 can vary between scenarios, and that the value of the application is the probabilistic weighted sum of the uses. The analysis scheme could be further sub-divided into user segments if the revenue drivers are expected to vary between these groups.

\textsuperscript{14} From Equation 6-1: \# Uses = 1 application * (1 user segment * 2 scenarios in segment) = 2
Table 7-5: A Schematic of a Multi-Criteria Valuation

<table>
<thead>
<tr>
<th>Item</th>
<th>Scenario Probability</th>
<th>Scenario Probability</th>
<th>Ai</th>
<th>WTP</th>
<th>Marginal Revenue (Eq. 7-9)</th>
<th>Total Revenue (Eq. 7-6)</th>
<th>Value (OPT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use 1</td>
<td>P(A)</td>
<td>C_{New(A)}</td>
<td>C_{Old(A)}</td>
<td>Ai A</td>
<td>WTP_A</td>
<td>MR_A</td>
<td>REV_A</td>
</tr>
<tr>
<td>Use 2</td>
<td>P(B)</td>
<td>C_{New(B)}</td>
<td>C_{Old(B)}</td>
<td>Ai B</td>
<td>WTP_B</td>
<td>MR_B</td>
<td>REV_B</td>
</tr>
</tbody>
</table>

Step 5: Total Value = P(A) * VAL_A + P(B) * VAL_B

**Factors that Influence the Value of the Tier 2 Project Benefits**

Table 7-1 indicates that a major benefit of the Tier 2 projects is their potential to reduce the weight of vehicles. However, a main objective of these projects is to improve the economics of the technologies. By improving process economics, these R&D efforts aim to make the technologies more attractive for implementing.

Part one of this case study uses the company's estimates of benefit value (see Table 7-2). For the Tier 2 projects, these estimates are based on mixed estimates of credits for weight savings and economic changes. The company's basis for valuing weight savings is related to current cost penalties for exceeding fleet fuel-economy.

Applying a multi-metric approach to the Tier 2 projects focuses the analysis on valuing technology benefits based on the net approducible value that is created. Combined with scenarios, it also considers how external conditions can influence the value of these technology benefits.

One potentially important issue to consider is the value of the weight savings capabilities under different regulatory environments. In a weak regulatory environment, the value of the weight savings depends entirely on the value that end-users place on features that this benefit enables. In a tighter regulatory environment, cost penalties for missing fuel-economy targets create additional incentives for implementing technologies that reduce vehicle weight.

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Table 7-6 presents an analysis scheme that introduces two scenarios for the weight savings related projects. The first scenario represents outcomes under a tight regulatory environment, which closely represents the basis for valuing weight savings that was used during the first part of the case study. This scenario assumes that if the technologies are implemented, the marginal revenue includes a cost avoidance (CA) component in addition to any appropriable increase in end-user value. In contrast, the second scenario assumes that CAFE and other fuel consumption regulations remain at the status quo. While implementing the technologies will yield an appropriable revenue stream, the overall incentive to implement does not include a cost avoidance component stemming from increasingly strict fleet fuel-economy targets.

Table 7-6: Schematic for Valuing Projects that Reduce Vehicle Weight

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario Probability Step 1</th>
<th>User Segments Step 1</th>
<th>Cost Difference Step 2</th>
<th>Ai Step 2</th>
<th>Annual Volume Step 2</th>
<th>WTP Step 2,3</th>
<th>MR (Eq. 7-3) Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight Regulatory Environment</td>
<td>P(TR)</td>
<td>1</td>
<td>CD_{TR1}</td>
<td>Ai_{TR1}</td>
<td>Y_1</td>
<td>WTP_{TR1}</td>
<td>MR_{TR1} + CA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>CD_{TR2}</td>
<td>Ai_{TR2}</td>
<td>Y_2</td>
<td>WTP_{TR2}</td>
<td></td>
</tr>
<tr>
<td>Status Quo</td>
<td>P(SQ)</td>
<td>1</td>
<td>CD_{SQ1}</td>
<td>Ai_{SQ1}</td>
<td>Y_1</td>
<td>WTP_{SQ1}</td>
<td>MR_{SQ1}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>CD_{SQ2}</td>
<td>Ai_{SQ2}</td>
<td>Y_2</td>
<td>WTP_{SQ2}</td>
<td></td>
</tr>
</tbody>
</table>

Table 7-6 also considers two different end-user segments (1 and 2). For each segment the difference in product costs (CD), the appropriability factor (Ai), the production volume (Y), the willingness to pay (WTP), and consequently the marginal revenue (MR) of implementing can differ.

Table 7-6 points out several important issues related to the weight savings focused projects. First, the incentives to implement the technologies are scenario dependent. In particular, the avoidance cost (CA) only occurs in conjunction with implementing the technologies under a tightly regulated environment. Thus, the option to implement has a component of value that is contingent upon this outcome.
In effect, the weight savings related technologies include two options: the implementation option and an insurance option. The insurance option protects the company against being caught in a tight regulatory environment without a workable response. While the implementation option fits a call option analogy, the insurance option is more like a put option. It insures the company against costly external events, much like a put option protects the holder of a stock against a declining share price. The advantage of applying the composite valuation methodology is that it provides mechanisms for valuing this complex option, and a basis for communicating the importance of the projects under different contextual outcomes.

Second, the incentives to implement the technologies can also vary by user segment. Combined with the cost avoidance influence, the overall incentive for widespread use of the technology could differ significantly across the scenarios. For example, suppose that the technologies were used to increase vehicle fuel-economy, regardless of the regulatory environment. Further, assume that any cost differences are nominal, and that End-User Segment 1 in Table 7-6 values fuel-economy increases (MR_{1}>0), but Segment 2 does not (MR_{2}=0). Under these conditions, it is possible that the incentives to implement the technologies would be sufficient to encourage implementations in both segments if the regulatory environment were tight (i.e., CA makes-up for Segment 2's low appreciation of fuel-economy), but only in Segment 1 if the status quo occurred.

Finally, Table 7-6 demonstrates that the value of the technologies within a user segment does not have to be constant across scenarios. Suppose that End-User Segment 1 in Table 7-6 does not care about fuel-economy, but does value other features that reducing vehicle weight enables (e.g., an increase in vehicle performance or functionality). In this case, the appropriate marginal revenue for this segment will differ across the scenarios if the occurrence of a tight regulatory environment forces weight savings to be channeled into fuel-economy improvements. Under the status quo outcome, the technology is valuable because it enables features that the end-user values (MR_{SQ1}>0). Under the tight regulatory environment, technology value stems from the cost avoidance benefit (CA>0, MR_{TR1}=0).
These observations demonstrate why it is difficult to value technologies with complex benefits. A basis for transforming technical advances into dollar values required, and frequently the estimate of value is contingent. An advantage of the composite valuation methodology is that it provides a structured basis for addressing these issues.

APPLYING THE COMPOSITE METHODOLOGY TO A COMPLEX PROJECT

The analysis structure presented in Table 7-6 could be applied to many of the Tier 2 projects in Table 7-1. The following example illustrates how the composite methodology could be applied to value Project N, which aims to reduce the cost of producing the body structure of a vehicle from a material that can enable significant weight reductions. A more detailed benefit assessment is needed to develop an actual valuation. However, this example highlights important issues that influence project value.

Step 1: Scope of Assessment

Table 7-7 presents the information required to value Project N. It includes the two scenarios from Table 7-6, and assumes that each is equally likely. It also considers two end-use segments. The first segment, Luxury/Sport, represents vehicles that are larger in size, and that include many premium features or engineering details. The second group, Compact/Sedan, represents vehicles that are smaller on average than the Luxury/Sport, and that include fewer premium features and engineering details. This oversimplifies common segmentations of vehicles, but is satisfactory for illustrative purposes.

Step 2: Project Data Collection

Costs

Table 7-7 assumes that a successful R&D outcome adds no cost to the vehicles.

Benefits

The major benefit that Project N offers is dramatic weight savings. Implementing the R&D technology in the Luxury/Sport segment is expected to reduce vehicle weight by an average of 250 pounds. Implementing the R&D technology in the Compact/Sedan is
expected to reduce the weight of these vehicles by an average of 125 pounds. Each of these segments is assumed to represent 500,000 vehicles per year.

Table 7-7 also assumes that a combination of industry competitiveness and risk-aversity of end-users with respect to the value of gas savings results in a low appropriability (\(A_i = 0.2\)) when weight savings is used to increase fuel economy. However, when the weight savings is applied in the Luxury/Sport segment to increase performance, a much higher appropriability results (\(A_i = 0.8\)).

**Decisions**

The option to implement a successful technical development remains the major decision that this analysis evaluates.

**Uncertainties**

The uncertainties remain unchanged from the first part of the case study.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario Probability</th>
<th>User Segments</th>
<th>Cost Difference</th>
<th>Ai</th>
<th>Annual Volume</th>
<th>WTP (/lb)</th>
<th>MR/car (Eq. 7-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight Regulatory Environment</td>
<td>0.5</td>
<td>Lux/Sport Cmpt/Sdn</td>
<td>$0</td>
<td>0.2</td>
<td>500,000</td>
<td>$0.6</td>
<td>$30+$337</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$0</td>
<td>0.2</td>
<td>500,000</td>
<td>$0.6</td>
<td>$15+$337</td>
</tr>
<tr>
<td>Status Quo</td>
<td>0.5</td>
<td>Lux/Sport Cmpt/Sdn</td>
<td>$0</td>
<td>0.8</td>
<td>500,000</td>
<td>$1.0</td>
<td>$200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$0</td>
<td>0.2</td>
<td>500,000</td>
<td>$0.6</td>
<td>$15</td>
</tr>
</tbody>
</table>

**Step 3: Transforms of Project Data**

*Transforming Complex Benefits into Dollars*

Table 7-7 assumes that under the tight regulatory environment, weight savings is used to improve vehicle fuel-economy. Chapter 5 presented an estimate of the value of fuel-economy improvements to end-users, based on the NPV of fuel savings over the life of a vehicle. Table 7-7 uses this estimate (\$0.6/lb saved) as the WTP for the tight regulatory environment scenario. In addition, the tight regulatory environment creates an incentive to
implement in the form of an avoidance cost, which is estimated to be $1.35 per pound.\textsuperscript{15} Combined, the sources of value suggest that the marginal revenue for implementing the Project N in the Luxury/Sport segment is $367 per vehicle (Equation 7-3 + CA*weight savings = 0.2*(0.6-0)*250 + 1.35*250), and $352 for the Compact/Sedan segment.

The assumptions are slightly different for the status quo scenario. First, while fuel-economy improvements are assumed to be the most valuable use of weight savings for the Compact/Sedan segment, Table 7-7 assumes that more valuable ($1.0/lb) uses of the benefit are possible in the Luxury/Sport segment. Further, there is no cost avoidance under this scenario. As a result, the implementation revenues are less than in the tight regulatory environment scenario ($200/vehicle for Luxury/Sport and $15/vehicle for Compact/Sedan).

These estimates of benefit value are approximations. Chapter 5 introduces more formal valuation methods that could similarly be applied. This example simply illustrates the potential usefulness of the approaches for helping to value projects. The conclusions to this thesis highlight this potential during a discussion of potential future work.

\textit{Transforming Exogenous Uncertainties into Risk-Neutral Quantities}

The process for modeling revenues as a function of vehicle production and transforming the priced driver of production into a risk-neutral distribution remains unchanged from the first part of this case study.

\textit{Transforming Costs and Benefits into Expected Cash-Flows}

The procedure for transforming costs and marginal revenue into expected current values of benefits remains unchanged from the first part of this case study.

\textit{Step 4: Valuing a Single Use}

The information in Table 7-7 can be applied to value each use of the technology using the spreadsheet model from the first part of this case study. However, since the project has been split into segments, some additional care must be taken with shared project

\textsuperscript{15} CA = (1 lb saved/3000 lb vehicle)*(5% fuel-economy increase/10 % weight reduction)*(27 mpg CAFE average)*($300 million fine/mpg under requirement)/(1 million vehicle fleet) = $1.35
cash-flows such as R&D and implementation costs. Two potential approaches are considered here: 1) assume that the technology will be implemented in either all or none of the segments, add the revenue streams for each segment, value the project under each scenario as shown in the first part of the case study, and sum the scenario probability weighted results, 2) allocate shared costs between segments, value each segment separately for each scenario, and sum the scenario probability weighted results.

The disadvantage of the first approach is that a positive project value indicates that the technology should be implemented in all of the segments, when this may not be economically efficient. The disadvantage of the second approach is that when a particular segment is not valuable, the shared costs that are allocated to this segment are removed from consideration, but realistically may not be avoidable. Combining several approaches helps to identify any such potential errors.

Table 7-8 and Table 7-9 present the requisite project cash-flow inputs for the project valuation model and the resultant real options based estimate of project value using these two approaches to valuing implementation segments. The remaining input assumptions are consistent with those presented in Table 7-2 and the first part of the case study. The last column of Tables 7-8 and 7-9 presents the option inclusive value of implementing Project N in a specific use.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario Probability</th>
<th>R&amp;D Cost (million/yr)</th>
<th>Implement Cost (million)</th>
<th>Annual Revenues (millions)</th>
<th>Value (OPT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight Regulation</td>
<td>0.5</td>
<td>$0.6</td>
<td>$50</td>
<td>$359.5</td>
<td>$588</td>
</tr>
<tr>
<td>Status Quo</td>
<td>0.5</td>
<td>$0.6</td>
<td>$50</td>
<td>$107.5</td>
<td>$162</td>
</tr>
</tbody>
</table>

Project Value = 0.5*($588) + 0.5*($162) = $375 million
Table 7-9: Project Value: Shared Costs Allocate Across Segments

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario Probability</th>
<th>Segment</th>
<th>R&amp;D Cost (million/yr)</th>
<th>Implement Cost (million)</th>
<th>Annual Revenues (millions)</th>
<th>Value (OPT) (millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight Regulation</td>
<td>0.5</td>
<td>Luxury/Sport</td>
<td>$0.3</td>
<td>$25</td>
<td>$183.5</td>
<td>$300</td>
</tr>
<tr>
<td>Tight Regulation</td>
<td>0.5</td>
<td>Compact/Sedan</td>
<td>$0.3</td>
<td>$25</td>
<td>$176</td>
<td>$288</td>
</tr>
<tr>
<td>Status Quo</td>
<td>0.5</td>
<td>Luxury/Sport</td>
<td>$0.3</td>
<td>$25</td>
<td>$100</td>
<td>$155</td>
</tr>
<tr>
<td>Status Quo</td>
<td>0.5</td>
<td>Compact/Sedan</td>
<td>$0.3</td>
<td>$25</td>
<td>$7.5</td>
<td>$3</td>
</tr>
</tbody>
</table>

Project Value = 0.5*($300) + 0.5*($288) + 0.5*($155) + 0.5*($3) = $373 million

Step 5: Valuing the Project

The total value of Project N is the probabilistic weighted sum of each of the technology uses. Table 7-8 estimates that the project is worth $375 million while Table 7-9 estimates it is worth $373 million. In this case, the aggregation of implementation costs and revenues in Table 7-8 leads to a more favorable assessment of the Compact/Sedan segment under the Status Quo environment because it is combined with a segment that is deep in the money. In Table 7-9, this use has annual revenues that are lower than the allocated implementation cost, and the option is only near the money.

Overall, the results in Table 7-8 and 7-9 are of the same magnitude obtained for the project using the estimate of benefits provided by the automotive company, but the value of the project is highly dependent on the regulatory environment. The difference in value if the regulatory environment is tight and if it remains at the status quo predominantly stems from the cost avoidance term (i.e., the put option characteristic of the project).

Similar analyses could be developed for the other weight savings related projects. However, this analysis was primarily intended to be demonstration of how the results of a multi-metric assessment can be integrated with the financial valuation framework of the composite valuation methodology.
To conduct a true valuation of this project, more precise estimates of end-user value, and costs would be needed. A more careful segmentation of product markets might also be considered. Whether or not such a detailed effort is merited is a question that the individual organization must decide.

**EXTENDING THE USE OF THE COMPOSITE METHODOLOGY**

So far, this case study has used project value as the sole basis for ranking projects, and has focused on valuing projects using an implementation option analogy. This last section reflects on how the results of a valuation could be incorporated with an overall R&D management process and how the valuation frameworks could be extended to include other project options.

First, using financial value alone to rank projects is how an exogenous party such as a venture capitalist might view a portfolio. However, as the Tiers of R&D framework points out (Hauser and Zettelmeyer 1996), financial metrics alone tend to be inadequate for managing Tier 2 and Tier 1 efforts. The reason that additional metrics are needed is that valuing the degree to which projects complement the existing capabilities of the firm becomes increasingly difficult as the potential uses of a technology become less well defined. The composite methodology that this thesis develops attempts to capture more of the complementary value, through a more careful examination of project value under different outcomes, but it is unlikely that the metric of value fully captures the complementary and spillover value of a project.

As a result, the metric of value that the methodology yields should be integrated into an overall R&D management process, such as the Tiers of R&D framework. In this role, the methodology can be applied to help assess important portfolio issues. For example, the use of scenarios allows an estimate of project and portfolio value under different outcomes to be assessed (e.g., Project N is much more valuable if the regulatory environment is tight). Examining the influence of these external outcomes helps the organization to assess if it is developing satisfactory compliments to its existing capabilities across a range of potential
futures. Another potential use includes using the methodology to estimate the value of portfolios of projects, and the sensitivity of this value to key projects, outcomes and uncertainties.

Second, this case study focuses on valuing projects using an implementation option analogy. However, Chapter 3 points out many other project options that could also be valued. It also demonstrates that information needs rapidly increase as complexity is added to the valuation frameworks. Extending the financial analysis frameworks to include more decisions and uncertainties is not especially difficult, but the decision to add complexity must be weighed against the increase in data requirements, the resolution of the available data, and the relative importance of the planning effort that the valuation will support. For example, Chapter 4 discusses the use of options analysis at Merck and Kodak, and notes that this set of trade-offs led Merck to settle on real options methods, while Kodak selected decision tree approximations.

SUMMARY OF CASE STUDY

Looking at Tables 7-3 and 7-4, one might infer that there is little merit to using options based approaches to value R&D since simpler methods yield nearly equivalent signals in this case study. However, such a conclusion overlooks several important issues. These include the context of the case study and potential importance of enabling more meaningful comparisons of R&D investments with other objectives of the firm.

First, this case study was heavily weighted by Tier 3 projects. It confirms that in many cases, the value of the implementation option is limited because uncertainty is low and the relative level of implementation costs to benefits is low. Therefore, DA and NPV results are nearly equivalent, and OPT provides a higher estimate of value because a comparatively lower discount rate is applied to the cash flows. Consequently, the ranking of projects based on these models is similar.

In contrast, the implementation option is valuable for many of the Tier 2 projects (N, L, K, P). In these cases, NPV mis-values the project because it ignores the option. DA
mis-values the project because it applies an inappropriate discount rate, but it at least recognizes the valuable contingent decision opportunity. OPT provides the most appropriate valuation since it correctly values the implementation option.

However, the ranking of the Tier 2 projects for the case study still does not vary significantly. In the case of the DA model, this results in part because the implementation costs and the probabilities of success are similar for the project with the most significant options features (i.e., N, L, K, and P). Therefore, the incremental value over NPV that DA reflects is similar for these efforts. This is also the case when the OPT model and NPV are contrasted. Comparing OPT and DA directly, the influence of exogenous market uncertainty was not strong for either model (see Figure 7-10). As a result, these two models yield similar signals.

In a more detailed valuation, or for larger groups of projects, these similarities might not exist, and the influence of market uncertainty in DA and OPT could differ more appreciably. This would lead to potentially different rankings of projects.

Second, and more importantly, the composite methodology provides several important features that enable more meaningful comparisons of R&D investments with other firm wide objectives. The explicit use of real options approaches provides a defensible basis for including the value of R&D options in estimates of project value. Since highly uncertain (risky) projects tend to have the most valuable options, this suggests that wide implementation of options valuation approaches would reveal that risky R&D is much more valuable than often believed. Further, since the composite methodology is designed to accommodate information flows from other assessment processes such as multi-metric valuation models, it provides a legitimate basis for estimating the value of benefits that are often thought to be intangible or complex.

Therefore, this case study should be considered more of a how to conduct a valuation as opposed to a full demonstration of the merits of the methodology. The key points that should be taken from this work are that options matter most when uncertainty is
high, and projects are near the money. The specific form of options model that should be used depends on the dominant form of uncertainty: endogenous or exogenous. If projects are primarily exposed to exogenous risks, the DA approach is suitable. If exogenous uncertainties are important of dominant, using a real options model such as OPT is important, especially if the goal is precise valuation.

Finally, the most compelling argument for using an approach like the composite methodology is that it provides an explicit mechanism for forcing organizations to recognize the value of options. Whether or not a full real options method is applied, it encourages an "Options Thinking" perspective in R&D, and it provides a basis for broadly communicating the value of these options. Consequently, it could become a powerful tool for encouraging healthy undertaking of risks that might otherwise be avoided.
Chapter 8: Conclusions

SUMMARY OF THESIS

The objective of research and development is to create valuable complements to the existing capabilities of the firm. Unfortunately, quantifying the value of R&D is difficult because it is an uncertain and sequential process that often yields complex benefits. These difficulties tend to obscure important sources of R&D value from common valuation methods such as NPV and portfolio matrices.

To improve the valuation of R&D, this thesis develops a composite valuation method that focuses on:

- valuing opportunities to revise R&D projects in response to uncertainty resolution;
- better matching valuation frameworks to project uncertainties (risks);
- integrating methods for valuing complex benefits with financial valuation frameworks.

Chapters 3 through 5 demonstrate the potential of various financial valuation and multi-metric assessment methodologies for improving current R&D valuation practice. Real options and decision analysis are useful for valuing R&D projects that can be revised in response to uncertainty resolution. A mix of real options and decision analysis can accommodate a wide range of project uncertainties. Multi-metric valuation models can translate complex benefits, such as simultaneous cost and performance improvements, into dollar values that the options models require. Scenarios recognize that the value of project benefits can be contingent upon the external operating environment.

Chapter 6 combines these methods into a composite framework that better expresses the complementary contribution of R&D than common valuation methods. This is accomplished by explicitly treating the sequential and uncertain nature of R&D using a combination of options and decision analysis models, and by quantifying the value of complex benefit streams using multi-metric valuation models and scenarios.
A case study based on an automotive producer's investments in advanced materials R&D demonstrates how to apply the methodology to a set of projects, and compares several valuation models. These include a hybrid of real options and decision analysis, a pure decision tree, NPV that ignores project options, and a simple weighted benefits index (the product of the probability of success and the expected annual benefits).

**FINDINGS AND ADVANTAGES OF THE COMPOSITE METHODOLOGY**

The major advantage of the composite approach to valuation is that it provides a legitimate basis for demonstrating that R&D is appreciably more valuable than common valuation methods indicate. This is especially true for many high-risk, long-term investments, such as Tier 2 projects in Hauser and Zettelmeyer's (1996) Tiers of R&D framework.

The composite methodology results in increased estimates of project value because it better expresses the complementary contribution of R&D by using options based models to evaluate opportunities to revise R&D in response to uncertainty resolution. It also extends the reach of financial valuation by providing a basis for integrating the results of scenario analysis and multi-metric valuations of complex benefits into the options models. Because these components are linked in a flexible arrangement, the composite valuation framework is applicable to projects with widely different characteristics.

Effectively, the composite methodology provides a basis for quantifying the strategic value of R&D investments, without abandoning well-understood principles of finance or dollar metrics. Therefore, the results can be also be compared fairly with many other investment alternatives throughout the firm. Since R&D is an option intensive investment, it is likely that such a comparison would demonstrate that R&D is also much more valuable than many firm-wide investment alternatives that are shorter-term and more certain. Therefore, the methodology shows promise for improving the perception of long-term R&D within the firm, in addition to providing an improved metric for guiding R&D investment decisions.
The thesis and case study also result in an improved understanding of the conditions under which the various methods for valuing projects are applicable, and an improved appreciation of trade-offs between resolution and practicality associated with the choice of valuation framework.

For projects that can be revised in response to the resolution of uncertainty, the thesis demonstrates that real options methods provide most correct valuation, if project cash-flows are influenced by exogenous uncertainties, such as the prices of inputs to a process. If project cash-flows are only influenced by endogenous uncertainties, such as the unknown technical feasibility of an R&D project, then decision trees that discount project cash-flows at risk-free rate are suitable. Further, a combination of real options and decision analysis serves as a general model that applies to R&D projects with a wide range of exogenous and endogenous uncertainties. However, in the absence of uncertainty or in cases where uncertainty is extremely limited, NPV that ignores contingent decisions is suitable. For R&D, such low-levels of uncertainty are likely to be encountered only for the most near-term and applied efforts.

The thesis also explores the practical differences between the valuation methods. It raises the question of what is more important, precise valuation or proper signaling. For example, the case study shows that on a relative basis, simple NPV and other indices provide suitable signals to invest or not if uncertainty is limited, or projects are deep in or out of the money. Increasing the level of effort to go from simple metrics to decision analysis or real options will yield a more accurate estimate of value, but not necessarily an improved signal. Similarly, any improvement in the resolution of a value estimate is limited by precision of data, and the practicality of implementing valuation frameworks likely decreases with increasing complexity.

Thus, while the options perspective focuses on important issues (e.g., implementation costs, uncertainty resolution), the choice of a valuation model should reflect a balance between data availability, information needs, organizational context and the
relative importance of the decision. It is therefore understandable that some research organizations prefer the options perspective of decision analysis (Kodak) while others strive for the precision of real options (e.g., Merck).

Finally, the thesis demonstrates how to integrate multi-metric valuation frameworks with the financial models when it is difficult to estimate the dollar value of project benefits directly. The composite methodology also provides a structured basis for considering contextual drivers of project value through the integration of scenario analysis. Again, the objective of including these elements is to improve the ability of the methodology to value the complementary contribution of R&D more completely than established valuation methods.

**ADDITIONAL CONTRIBUTIONS**

This thesis also makes several contributions to the field of real options. First, many practical demonstrations of real options over-extend analogies between projects and simple options models. As a result, they fail to model cash-flows as functions of priced assets. Consequently, the risk-neutral valuation processes that are implicitly used in options models such as Black-Scholes are improperly applied.

The general approach to valuing real options utilized in this work demonstrates the practical application of Kulatilaka's (1993) simulation technique to the R&D valuation problem. This method is simply more proper than force-fitting a project into the Black-Scholes model, or using an arbitrary discount rate in a decision tree or dynamic program. It is also conveniently amenable to a practical division of labor. Finance professionals can focus on identifying priced assets that correlate with drivers of project cash-flows and on developing risk-neutral distributions of these priced factors. R&D professionals can provide the necessary estimates of project costs, benefits and uncertainties that are needed to complete the valuation.

Next, few works have developed practical comparisons of real options and other valuation methods. This thesis points out merits to real options, decision analysis and
simpler metrics of value, and it identifies conditions for applying these methods alone or in combination. The hybrid real options and decision analysis framework that this work develops is a highly flexible method that could be extended to many real options problems that include both endogenous and exogenous risks.

Finally, the integration of multi-metric valuation methods with the financial models is a potentially powerful approach for reaching further into the R&D spectrum to value projects with complex benefits using the common metric of financial worth.

RECOMMENDATIONS FOR FUTURE WORK

Any work faces limitations and leaves potential opportunities for future extension. The major limitation to this work is that financial value is only one metric of R&D, and it is unlikely that any single metric can capture all of the facets of R&D value. The composite methodology this thesis develops strives to improve financial metrics by more completely valuing the complementary contribution of R&D, but it should still be integrated with overall R&D management process (e.g., Three Tiers approach).

Potential extensions to the options portion of the work that could be interesting and useful include expanding the type and number of options considered, exploring the modeling of exogenous risks using several priced factors, and introducing other distributions into the real options and decision tree models. For example, this thesis focuses on the implementation option, but both the R&D and the implementation phases could be expanded to consider multiple decision opportunities.

Finally, this thesis highlights opportunities for integrating multi-metric valuation models with the options models. However, it does not explore the topic of complex benefit valuation to the depth that the uncertain and sequential nature of R&D is treated. Some extremely interesting analyses could result from a more aggressive effort to apply multi-metric frameworks to examine the value of early tier projects, or projects that primarily increase organizational capabilities.
Appendix A: Estimating Discrete Probabilistic Outcomes

Quantifying uncertainties for use in a decision tree requires the estimation of discrete probabilities and outcomes. This can be accomplished in at least two ways. Conducting interviews to assess probabilistic outcomes directly is one approach. Assuming that an uncertain variable fits a specific probability distribution and using statistical descriptors of the distribution to estimate discrete probabilistic outcomes is another.

The advantage of conducting interviews to assess discrete outcomes is that a specific decision-maker's beliefs about the likelihood of certain outcomes occurring are captured. However, the interview process is time consuming and the results are questionable (beliefs do not constitute actualities). Clemen (1991) introduces basic assessment techniques and provides references to additional resources. Merkhofer (1987) presents a method for measuring cumulative distributions.

Although it does not overcome the subjectivity problem, the advantage of assuming the form of the distribution is that data collection efforts are minimized. Only three pieces of information are required: an expected value, a standard deviation and the form of the distribution. Properly framed, this route also might seem more intuitive to individuals charged with developing an estimate of project value. For example, the case study in Chapter 7 relies on estimates of the upper limit of R&D benefits to calculate a standard deviation, instead of asking individuals to estimate the standard deviation directly.

Appendix A introduces two methods for estimating discrete probabilistic outcomes using continuous probability distributions. The first method estimates a limited number of outcomes, while the second breaks distributions into any number of outcomes that is desired. Like many R&D assessment decisions, selecting an approach requires a judgment of whether or not the precision that is sought is commensurate with the level of resolution in the project data. The case study in Chapter 7 and the associated spreadsheet model described in Appendix C utilize these types of discrete approaches to quantify several uncertainties.
EXTENDED PEARSON-TUKEY METHOD

According to Clemen (1991), one simple approach to estimating discrete probabilities and outcomes that works well for both symmetrical and many asymmetrical distributions is the extended Pearson-Tukey method described by Keefer and Bodily (1983). This three-point method assigns discrete probabilities of 0.185 to the 0.05 and 0.95 fractiles of a distribution and a probability of 0.63 to the median.

For example, consider a range of outcomes that fits a standard normal distribution (mean = 0, variance = 1). Since the mean of the normal distribution is also the median, the extended Pearson-Tukey method would assign a probability of 0.63 to the discrete outcome of 0. Then, since the 0.95 and 0.05 fractiles of a normal distribution lie 1.645 standard deviations from the mean, the method would assign probabilities of 0.185 to the discrete outcomes of -1.645 and 1.645.

BRACKET MEDIANS

A potential limitation to the extended Pearson-Tukey method is that it only considers three possible outcomes. The bracket median approach has no such limitation; any number of probabilistic outcomes can be estimated. The procedure and example presented below are based on a description developed by Clemen (1991).

Bracket medians are derived from continuous, cumulative probability distributions. The process defines an interval bounded by two values of an uncertain parameter \( X \), such that \( a \leq X \leq b \). It then finds a value, \( m \), such that \( P(a \leq X \leq m) = P(m \leq X \leq b) \). If the cumulative probabilities of \( a \) and \( b \) are \( p \) and \( q \), respectively, then the cumulative probability associated with \( m \) is \( (p+q)/2 \). By dividing a distribution into \( n \) equally likely brackets, the value of \( m \), for each bracket \( (i = 1 \text{ to } n) \) represents an outcome with probability of \( 1/n \).

For example, consider a cumulative, standard normal distribution. To divide this distribution into three discrete points, the distribution is first divided into three equally likely intervals. The associated cumulative probabilities that define these intervals are given below. Note that it takes \( nr+1 \) cumulative probabilities to describe \( n \) intervals.
\[ P(X \leq x_{0.0}) = 0.0^{16} \]
\[ P(X \leq x_{0.33}) = 0.33 \]
\[ P(X \leq x_{0.66}) = 0.66 \]
\[ P(X \leq x_{1.0}) = 1.0 \]

Then, the corresponding three bracket medians are defined:

\[ P(X \leq m_1) = (P(x_{0.0}) + P(x_{0.33}))/2 = (0.0 + 0.33)/2 = 0.167 \]
\[ P(X \leq m_2) = (P(x_{0.33}) + P(x_{0.66}))/2 = (0.33 + 0.66)/2 = 0.5 \]
\[ P(X \leq m_3) = (P(x_{0.66}) + P(x_{1.0}))/2 = (0.66 + 1.00)/2 = 0.833 \]

Finally, the \( m_i \)'s that correspond to the cumulative probabilities associated with the three bracket medians are quantified. For example, the value -0.975 from the standard normal distribution has a cumulative probability of 0.167. Therefore, this value corresponds to \( m_1 \). Continuing this process for the other two bracket medians leads to the three discrete probabilistic outcomes that are desired:

\[ P(m_1) = P(-0.975) = 1/n = 1/3 = 0.33 \]
\[ P(m_2) = P(0.0) = 0.33 \]
\[ P(m_3) = P(0.975) = 0.33 \]

Figure A-1 shows the cumulative normal distribution, and the three discrete points estimated in this example. A similar procedure could be followed to divide the distribution into any number of discrete, probabilistic outcomes.

\[ ^{16} \text{The probability that } X \text{ is less than or equal to the value } x_{0.0}, \text{ which defines the 0.0 fractile, is } 0.0. \]
Figure A-1: Estimating Three Discrete Outcomes for the Standard Normal Distribution Using a Bracket Median Approach

Table A-1 compares the three-point estimates for the standard normal distribution obtained using the extended Pearson-Tukey method and the bracket median approach. In this case, the Pearson-Tukey method weighs the mean value more heavily and attaches lower probabilities to more far removed outcomes than the bracket median approach. However, both methods yield the same expected value (0) and aim to accomplish the same goal: describe a continuous variable using a limited set of discrete outcomes.

Table A-1: Summary of Results of Two Methods for Discretizing Distributions

<table>
<thead>
<tr>
<th>Extended Pearson-Tukey</th>
<th>Bracket Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(-1.645) = 0.185</td>
<td>P(-0.975) = .33</td>
</tr>
<tr>
<td>P(0) = 0.63</td>
<td>P(0) = 0.33</td>
</tr>
<tr>
<td>P(1.645) = 0.185</td>
<td>P(0.975) = 0.33</td>
</tr>
</tbody>
</table>
Appendix B: Modeling Exogenous Uncertainties

Valuing projects usually requires some consideration of exogenous uncertainties that are correlated with market outcomes. However, the treatment of exogenous uncertainties varies by valuation framework. For example, typical applications of NPV focus on expected outcomes, and apply a risk-adjusted discount rate to adjust expected cash-flows for risk. Unfortunately, this approach overlooks the value of project options that are related to the resolution of exogenous uncertainty. In contrast, decision analysis includes the value of such options, but cannot properly adjust the resulting cash-flows for risk. Finally, real options models recognize the value of the options, and also resolve the discounting problem.

Appendix B explores methods for treating exogenous uncertainties. It specifically develops information that is needed for the project valuation spreadsheet that Appendix C describes and that Chapter 7 applies to value a portfolio of projects. The spreadsheet estimates project value using three different models: NPV that ignores project options, a pure decision analysis model (DA), and a combined real options and decision analysis model (OPT). In this spreadsheet, exogenous market uncertainty is characterized differently in the NPV and pure decision tree models than it is in the real options hybrid. However, in all cases, estimating variations in production volume is the basis for incorporating exogenous market uncertainty into the valuation of the projects that are the subject of Chapter 7.

Exogenous uncertainty is estimated directly for the DA and NPV models. This is accomplished by examining the production history of the case study company. A simple linear regression of the form shown in Equation B-1 serves as the basis for estimating expected production output, and the standard error of this regression serves as an uncertainty metric that describes the range of potential outcomes.

\[ P_t = A + Bt \]  

(B-1)

where, \( P_t \) = production output at time \( t \)

and \( A \) and \( B \) are the regression parameters
The expected value of Equation B-1 is used in the NPV model. The standard error is used to estimate a range of discrete probabilistic outcomes for the decision tree that the DA model uses. Both frameworks then value the projects using an arbitrary discount rate.

The real options model treats exogenous uncertainty using a two-step approach. First, a regression model correlates vehicle production with the price of a stock (i.e., an equilibrium priced underlying asset). Equation B-2 presents the general form of this model.

\[
\text{Production}_{t+n} = \text{Production}_t \cdot e^{(\Delta + \text{LN}(S_{t+n}/S_t))} \quad \text{(B-2)}
\]

where, \(S_t\) and \(S_{t+n}\) are the prices of the stock at time \(t\) and \(t+n\).

\(A\) and \(B\) are regression parameters.

Assuming that Equation B-2 captures the major exogenous risks of the project, a risk-neutral valuation procedure can be applied in the hybrid decision tree. This is accomplished by using the binomial approach to estimate a risk-neutral distribution of future stock prices from estimates of the annual dividend yield and volatility of the stock (see Equations 3-5, 3-9 and 3-11). In turn, the risk-neutral distribution of stock prices drives estimates of production outcomes using Equation B-2. Because these outcomes are adjusted for market risk, the resulting cash-flows can be discounted at the risk-free rate.

On the basis of such analyses, the following assumptions are used in the case study:

- For DA and NPV, the regression parameters \(A\) and \(B\) in Equation B-1 are 2,783,980 and 15,864, respectively. The standard error is 573,104.

- For OPT, the regression parameters \(A\) and \(B\) vary with \(n\). For \(n=1\), \(A\) is not significant, and the correctly estimated \(B\) is 0.253. The case study uses this model.

- For OPT, the annual dividend yield of the underlying stock is 4.5% and the annual volatility is 20.7%.
The remainder of Appendix B shows how these inputs are estimated. It also serves as a demonstration of how similar analyses should be approached for other cases.

**MODELING EXOGENOUS UNCERTAINTY FOR DA AND NPV**

The linear model shown in Equation B-1 is used to estimate uncertainty in vehicle production for the model in Appendix C and the case study in Chapter 7. Table B-1 presents the historical vehicle production data used to estimate the model. It also includes stock price data that is used to model exogenous uncertainties for the hybrid real options model.

The yearly vehicle production data in Table B-1 is for cars and light-trucks produced in United States from 1973 to 1996 (from Ward's Automotive Yearbook 1996, 1989, 1981). This data represents the vehicles that the portfolio in Chapter 7 is expected to influence.

Figure B-1 shows that production is cyclic. Much of this cyclical nature of production is driven by external changes in the economy. As a result, simple models of production output, such as Equation B-1, do not provide a high-level of explanatory power. However, the major objective of including the market related uncertainty in the decision tree is to define a range over which production is likely to vary. Since the objective of this thesis is to demonstrate a methodology, the case study uses the simple regression to approximate the influence of exogenous uncertainties in the pure DA model.

Although the case study uses a simple approximation, the methodology could easily accommodate much more complicated models of production output. For example, the real options hybrid requires the exogenous uncertainty to be expressed as a function of price factors. A regression model that correlates production output with an exogenously priced asset is developed in the next section, and fits well within the overall composite valuation framework.
Figure B-1: The Cyclical Nature of Vehicle Production

Table B-1: Annual Production and Stock Price Data

<table>
<thead>
<tr>
<th>Year</th>
<th>Vehicle Production</th>
<th>Year-End Stock Price</th>
<th>Year</th>
<th>Vehicle Production</th>
<th>Year-End Stock Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>2,500,015</td>
<td>$3.91</td>
<td>1987</td>
<td>3,312,461</td>
<td>$18.84</td>
</tr>
<tr>
<td>1976</td>
<td>2,942,051</td>
<td>$5.44</td>
<td>1988</td>
<td>3,330,157</td>
<td>$25.25</td>
</tr>
<tr>
<td>1978</td>
<td>3,790,319</td>
<td>$4.68</td>
<td>1990</td>
<td>2,763,190</td>
<td>$13.31</td>
</tr>
<tr>
<td>1979</td>
<td>3,075,131</td>
<td>$3.56</td>
<td>1991</td>
<td>2,428,942</td>
<td>$14.06</td>
</tr>
<tr>
<td>1980</td>
<td>1,888,457</td>
<td>$2.22</td>
<td>1992</td>
<td>2,829,990</td>
<td>$21.44</td>
</tr>
<tr>
<td>1981</td>
<td>1,937,573</td>
<td>$1.86</td>
<td>1993</td>
<td>3,349,179</td>
<td>$31.69</td>
</tr>
<tr>
<td>1982</td>
<td>1,817,501</td>
<td>$4.22</td>
<td>1994</td>
<td>3,734,282</td>
<td>$27.88</td>
</tr>
<tr>
<td>1983</td>
<td>2,479,158</td>
<td>$7.06</td>
<td>1995</td>
<td>3,453,661</td>
<td>$28.88</td>
</tr>
<tr>
<td>1984</td>
<td>2,958,529</td>
<td>$7.60</td>
<td>1996</td>
<td>3,538,974</td>
<td>$32.25</td>
</tr>
</tbody>
</table>

Note: Year-end stock-prices reflect adjustments for capital charges (e.g., stock-splits)
Table B-2 presents the results of estimating Equation B-1 using the production data in Table B-1. It is not surprising that a straight line does not explain the behavior of the production data. In fact, using the results in Table B-2 does not provide much improvement over assuming that production output is completely random and is described by the mean (2,982,283) and standard deviation (571,622) of the data in Table B-1.

**Table B-2: Results of Directly Modeling Production Output:**

\[ P_t = A + B^t \]

<table>
<thead>
<tr>
<th></th>
<th>(A) (t-statistic)</th>
<th>(B) (t-statistic)</th>
<th>Standard Error</th>
<th>(r^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2,783,980 (11.52)</td>
<td>15,864 (0.94)</td>
<td>573,104</td>
<td>0.03</td>
</tr>
</tbody>
</table>

For the purpose of demonstrating the methodology, this thesis uses the results shown in Table B-2 to approximate the range over which production might vary. Combining Equation B-1 with the standard error yields an estimate of the range over which production can vary. By selecting the appropriate fractiles, the continuous range can be converted into a few discrete points using the extended Pearson-Tukey or similar procedure.

A potentially interesting piece of future work would be to explore the integration of more sophisticated production models with the decision tree model. However, the practical trade-off of developing a complex model versus simply estimating the range of potential outcomes must also be considered.
MODELING EXOGENOUS UNCERTAINTY FOR REAL OPTIONS MODELS

Modeling exogenous uncertainty for the real options model is a two-step process. First, the exogenous uncertainty is related to priced factors. Second, risk-neutral distributions of these priced factors are estimated and applied to drive estimates of production output and project cash-flows.

Regression Model to Relate Priced Asset to Exogenous Uncertainty

The real options model presented in Appendix C and applied in Chapter 7 uses a linear regression model to relate vehicle production to a priced asset. Equation B-2 presents the general form of the model. It relates observed percentage changes in production output over time to observed changes in the price of an underlying asset (S). In this case, S is the price of the company's stock.

Equation B-2 forms the basis for predicting future production output using risk-neutral simulations of the stock price path over time. Since the goal of this work is to demonstrate the steps in an overall methodology, only a single parameter model is developed. It is certainly possible to develop regression models with multiple parameters, and this should be considered for actual implementations of the valuation methodology.

Although it seems likely that the changes in stock prices should be the independent variable in B-2, the relationship between production and stock price is more complex. For example, it is likely that projections of production output will influence the stock price, and that actual outcomes will result in adjustments of expectations. Over short time periods, projected and actual output are probably close, and the stock price and actual production will be correlated. It is even possible that the stock price could lead actual production. Extending this process out over many short time periods leads to a similar conclusion. Thus, the form of Equation B-2 is adopted mainly for convenience, but it is not an unreasonable specification. In a multi-parameter model, relating production to more general indicators of the economic output would eliminate any confusion caused by Equation B-2.
Table B-1 presents the data used to estimate the regression model. It includes year-end, adjusted stock price data from 1973 to 1996, and the production data. The stock price data was collected using Datasync, a financial database maintained by Datasync International, Ltd. (offices in New York and London), and reflects share-price adjustments for capital changes (e.g. stock-splits).

For the case study in Chapter 7, models of Equation B-2 for n = 1 to 6 were estimated. These models allow the current level of production and stock price to be combined with a range of projected future stock prices to estimate a range of future production outputs. Models that span six years were estimated since no project in the example portfolio has an R&D phase that extends beyond this timeframe.

Table B-3 summarizes the results for all six models. First-differencing was used to address serial correlation problems for the models estimated for n = 2 to 6. Standard Wald tests indicated that the regression constant (A) was significant only for n=6. Therefore, the values of B for n = 1 to 5 in Table B-3 reflect the re-estimated model where A is dropped from consideration. Table B-3 also includes t-statistics in parenthesis for each parameter. In all cases, the results are significant at the 95% confidence limit. Figure B-2 shows a graphic example of the fit obtained using the historical data and Equation B-2. The figure presents the case of n=2 (A=0, B= 0.306).

The six models show that the cyclical nature of production is better explained using lagged data (i.e., explanatory power increases for longer lags). A more complex model might consider multiple lags and multiple priced factors, simultaneously. However, for the purpose of demonstration, the case study in this thesis adopt the model for n=1, and uses it to project future production estimates as functions of projected future stock price. To conduct a more true valuation, multiple parameters are likely needed to develop a model that more completely represents the influence of exogenous uncertainties on project cash-flows.
**Table B-3: Regression Parameters for Equation B-2 (for n = 1 to 6)**

\[
\text{Production}_{tn} = \text{Production}_t \cdot \exp(A + B \cdot \ln(S_{tn}/S_t))
\]

<table>
<thead>
<tr>
<th>n</th>
<th>A (t-statistic)</th>
<th>B (t-statistic)</th>
<th>(r^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N.S.</td>
<td>0.253 (2.62)</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
<td>N.S.</td>
<td>0.306 (3.26)</td>
<td>0.55</td>
</tr>
<tr>
<td>3</td>
<td>N.S.</td>
<td>0.382 (3.62)</td>
<td>0.67</td>
</tr>
<tr>
<td>4</td>
<td>N.S.</td>
<td>0.349 (3.14)</td>
<td>0.69</td>
</tr>
<tr>
<td>5</td>
<td>N.S.</td>
<td>0.25 (2.65)</td>
<td>0.71</td>
</tr>
<tr>
<td>6</td>
<td>-0.217 (-2.75)</td>
<td>0.352 (4.76)</td>
<td>0.75</td>
</tr>
</tbody>
</table>

N.S. = Not Significant.

For n = 1 to 5, results are for re-estimated model with constant A dropped.

**Figure B-2: Results of Linear Regression of Vehicle Production**

(for n=2: A = 0, B = 0.306)
Estimating Risk-Neutral Distributions of Priced Factors

Once a model that relates cash-flow drivers to exogenous, priced assets is developed, the next step in the general real options approach is to develop risk-neutral estimates of the potential future prices of this underlying asset. This risk-neutral distribution is then used to drive estimates of cash-flows that can be discounted using the risk-free rate.

Calculating the Volatility and Dividend Yield of a Stock

To develop this risk-neutral distribution, an estimate of the volatility and any dividend payout or equivalent (e.g. convenience yield) of the underlying asset is required. For traded securities, a standard assumption is that the price path follows a time-dependent lognormal distribution. Assuming that this holds for the underlying stock used in this example, Table B-4 illustrates Cox and Rubinstein's (1985) method for estimating the volatility and dividend yield.

Table B-4 presents quarterly stock price and dividend data from 1995 through 1997. The stock prices in Table B-4 were also collected using Datastream, and reflect beginning of quarter prices with capital adjustments. The dividends data was collected from quarterly reports from the case study company, and reflect payments during the quarter.

Column four of Table B-4 converts dividends into a percentage of the stock price. It then averages the results to estimate the expected quarterly dividend yield. Multiplying the result by four quarters results in an annualized estimate. In Table B-4, the annual estimate of dividend yield is 4.5%.

Since dividend payouts reduce the value of a share, any estimate of average growth, which influences the estimate of volatility, must factor these payments back into the share price. Column five of Table B-4 combines the dividend payments with the share price.

Next, columns six and seven of Table B-4 calculate the natural logarithm of the ratio of the current quarter's stock price to the previous quarter's combined share price and dividends. The average of these ratios is the average capital growth rate for the stock. Note
that only \( n-1 \) ratios can be estimated from \( n \) data points. Again, the quarterly result is annualized by multiplying by four. Table B-4 estimates growth to be 13.2%.

**Table B-4: Estimating Dividend Yield, Stock Growth and Volatility**

<table>
<thead>
<tr>
<th>Date (t)</th>
<th>Stock Price (S(t))</th>
<th>Quarterly Dividends (D(t))</th>
<th>Quarterly Dividends (%)</th>
<th>(<a href="t">S+D</a>)</th>
<th>(X= S(t)/<a href="t-1">S+D</a>)</th>
<th>(LN(X))</th>
<th>(Y= (LN(X)-LN(X)ave)^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1/95</td>
<td>$27.88</td>
<td>$0.26</td>
<td>0.93%</td>
<td>$28.19</td>
<td>0.962</td>
<td>-0.038</td>
<td>0.005</td>
</tr>
<tr>
<td>4/1/95</td>
<td>$27.13</td>
<td>$0.31</td>
<td>1.14%</td>
<td>$27.44</td>
<td>1.107</td>
<td>0.102</td>
<td>0.005</td>
</tr>
<tr>
<td>7/1/95</td>
<td>$30.38</td>
<td>$0.31</td>
<td>1.02%</td>
<td>$30.73</td>
<td>1.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>10/1/95</td>
<td>$30.75</td>
<td>$0.35</td>
<td>1.14%</td>
<td>$31.10</td>
<td>0.929</td>
<td>-0.074</td>
<td>0.011</td>
</tr>
<tr>
<td>1/1/96</td>
<td>$28.88</td>
<td>$0.35</td>
<td>1.21%</td>
<td>$29.23</td>
<td>0.947</td>
<td>-0.054</td>
<td>0.008</td>
</tr>
<tr>
<td>4/1/96</td>
<td>$35.00</td>
<td>$0.35</td>
<td>1.00%</td>
<td>$35.39</td>
<td>1.197</td>
<td>0.18</td>
<td>0.022</td>
</tr>
<tr>
<td>7/1/96</td>
<td>$33.00</td>
<td>$0.39</td>
<td>1.17%</td>
<td>$33.39</td>
<td>0.933</td>
<td>-0.07</td>
<td>0.011</td>
</tr>
<tr>
<td>10/1/96</td>
<td>$31.63</td>
<td>$0.39</td>
<td>1.22%</td>
<td>$32.02</td>
<td>0.947</td>
<td>-0.054</td>
<td>0.008</td>
</tr>
<tr>
<td>1/1/97</td>
<td>$32.25</td>
<td>$0.39</td>
<td>1.19%</td>
<td>$32.67</td>
<td>1.007</td>
<td>0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>4/1/97</td>
<td>$31.50</td>
<td>$0.42</td>
<td>1.33%</td>
<td>$31.92</td>
<td>0.964</td>
<td>-0.036</td>
<td>0.005</td>
</tr>
<tr>
<td>7/1/97</td>
<td>$38.44</td>
<td>$0.42</td>
<td>1.09%</td>
<td>$38.86</td>
<td>1.204</td>
<td>0.186</td>
<td>0.023</td>
</tr>
<tr>
<td>10/1/97</td>
<td>$45.63</td>
<td>$0.42</td>
<td>0.92%</td>
<td></td>
<td>1.174</td>
<td>0.161</td>
<td>0.016</td>
</tr>
</tbody>
</table>

Average Quarterly Dividends = 1.1%
Annual Dividends = 4 * 1.1% = 4.5%

Ave. Quarterly Growth = \( \frac{\text{Sum LN(X)}}{(n-1)} \)
\( = \frac{0.031}{3.3\%} \)
Annual Growth = 4 * 3.3% = 13.2%

Quarterly Variance = \( \frac{\text{Sum(Y)}}{(n-2)} \)
\( = (0.11)/10 = 0.011 \)
Annual Volatility = (4 * 0.011) * 0.5 = 20.7%

Notes: Procedure in Table B-1 based on approach presented in Cox and Rubinstein (1985)
Stock-prices are adjusted for capital changes.
Dividends reflect payments that occur during the quarter.

Column eight of Table B-4 calculates the squares of the differences between the average growth rate and the log-ratios. Summing and dividing by \( n-2 \) yields an estimate of the quarterly variance. Note that sample standard deviations are usually calculated using a factor of \( n-1 \), but there are only \( n-1 \) ratios, so \( n-2 \) is the required factor. Multiplying the variance by four and taking the square root yields the annual volatility estimate (20.7%).

Examining stock data over more or different time periods will yield different results.

For example, in its most recent annual report, the case study company uses an annual
volatility of 22.1% and dividend yield of 4.8% to values outstanding stock option liabilities. While these values are still close to the values estimated in Table B-4, there is no guarantee that either volatility or dividend yield will remain constant over time.

**Estimating a Risk-Neutral Distribution of Stock Prices**

To develop a risk-neutral distribution of stock prices, a method such as the binomial approach that Chapter 3 discusses is applied. As an example, this appendix applies the binomial approach and the data in Table B-3 to estimate three probabilistic outcomes of a stock price one year in the future. It uses the January 1, 1997 price of $32.25, since this corresponds to the current value of the stock at the time the case study portfolio was being evaluated at the company. The case study in Chapter 7 uses this as the starting date for its analyses. It also assumes that the risk-free rate is 5%, and that the volatility estimate of 20.7% from Table B-4 applies.

First, the values of u and d are estimated using Equation 3-9:

\[ u = \frac{1}{d} = e^{\sigma \sqrt{tn}} = e^{0.207 \sqrt{1/2}} = 1.16 \]

\[ d = 0.86 \]

The time period \((t = 1 \text{ year})\) is broken into two intervals \((n)\) because this will yield three possible outcomes of the stock price (i.e., the binomial model yields \(n+1\) outcomes).

Next, the risk-neutral probabilities are estimated using \(u\), \(d\), and \(r\) (see Equation 3-5). However, since the step size is one-half of a year \((tn = 1 \text{ year}/2 \text{ intervals})\), the risk-free yield for one-half of a year \(1.05^{0.5} = 1.025\) is used to calculate these probabilities.

\[ p = \frac{r-d}{u-d} = \frac{1.025-0.86}{1.16-0.86} = 0.55 \]

\[ p' = 1-p = 0.45 \]
Figure B-3: Schematic of Example Two-Step (Three-Outcome) Binomial Tree (where, \( \text{div} = \text{Annual Dividend Yield} \), and \( S, u, d, p, p', \) and \( t \) are defined in the Text of Appendix B)

Three possible stock prices result from the possible combinations of upward and downward price movements in two steps. These are \( \text{Suu} \), \( \text{Sud} \) and \( \text{Sdd} \). The corresponding probabilities of these outcomes are \( p^2 \), \( pp' \), and \( p^2 \). However, more than one pathway to some outcomes is possible. This is the case for \( \text{Sud} \), which can result from an upward movement during the first interval and a downward during the second, or a downward movement during the first interval and an upward during the second (i.e., \( \text{Sud}=\text{Sdu} \)). The number of pathways to an outcome is generalized as the combinations of \( j \) upward movements over \( n \) intervals:

\[
\text{Combinations} = \frac{n!}{(j!(n-j)!)}
\]  
(B-3)

So, for \( \text{Sud} \), \( n = 2 \) and \( j = 1 \), and the combinations are \( 2!/(1!(2-1)!) = 2 \). Only one pathway to either \( \text{Suu} \) or \( \text{Sdd} \) exists. Therefore, the outcomes and corresponding probabilities (shown in parenthesis) are \( \text{Suu} \) (\( p^3 \)), \( \text{Sud} \) (\( 2*pp' \)), and \( \text{Sdd} \) (\( p^2 \)).
Finally, the stock price must be adjusted for dividend payouts (see Equation 3-11). Thus, \( S \) is replaced with \( S^*(1\text{-annual dividend yield})^t \), with \( t = 1 \). For this example, this results in a dividend-adjusted, starting stock price of $32.25 \times (1-0.045)^1 = $30.80.

Figure B-3 schematically represents the two-step binomial distribution this example calculates. It indicates the spread of prices over time and the influence of dividends. It also shows the corresponding probabilities for each step in the tree. Estimating the three outcomes at \( t=1 \) is the objective.

Table B-5 shows the numerical results of applying a two-step binomial tree to estimate a three-outcome, risk-neutral distribution of stock prices for one year in the future. Note that the weighted sum of outcomes ($32.34) is a 5\% (risk neutral) return on the dividend-adjusted, starting stock price ($30.80). The risk-neutral probabilities in the binomial are constructed to force the expected return to match expectations in a risk-neutral world. Consequently, cash-flows which are contingent upon the underlying asset described by the risk-neutral distribution can be discounted using the risk-free rate.

**Table B-5: Results of Applying a Two-Step Binomial Tree to Estimate a Three-Outcome, Risk-Neutral, Stock Price Distribution**

<table>
<thead>
<tr>
<th>Risk-Neutral Price Outcome</th>
<th>Probability (P)</th>
<th>Weighted Outcome (P*Outcome)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suu (1-div yld) = 32.25(1.20)(1.20)(0.957) = $41.22</td>
<td>pp = 0.52 \times 2 = 0.30</td>
<td>$12.37</td>
</tr>
<tr>
<td>Sud (1-div yld) = 32.25(1.20)(0.84)(0.957) = $30.80</td>
<td>2pp' = 2(0.52)(0.48) = 0.50</td>
<td>$15.26</td>
</tr>
<tr>
<td>Sdd (1-div yld) = 32.25(0.84)(0.84)(0.957) = $22.98</td>
<td>p'p' = 0.48 \times 2 = 0.20</td>
<td>$4.71</td>
</tr>
</tbody>
</table>

Sum of Weighted Outcomes = $32.34
Sum/(S(1-div yld)) = $32.34/$30.80 = 1.05

A similar approach to the example developed in Table B-5 can be used to estimate any number of outcomes for any future time. For example, the spreadsheet model that is described in Appendix C and applied to the case study in Chapter 7 uses a four-step binomial tree to estimate a five-outcome risk-neutral distribution of stock prices. For a volatility of 20.7\% and time to expiration equal to one year, the resulting values of \( u \) and \( d \) from
Equation 3-9 are 1.11 and 0.90, respectively. The risk-free rate for one-fourth of a year is $1.05^{0.25} = 1.012$. Therefore, $p = 0.53$ and $p' = 0.47$ (see Equation 3-5).

Assuming the current stock price is $32.25 and the dividend yield is 4.5%, Table B-6 summarizes the resulting risk-neutral price distribution.

**Table B-6: A Five-Outcome, Risk-Neutral Price Distribution Using Four-Step Binomial Model for Time to Expiration = 1 Year, Annual Volatility = 20.7%, Annual Dividend Yield = 4.5%, and Current Stock Price = $32.25.**

<table>
<thead>
<tr>
<th>Risk-Neutral Price Outcome</th>
<th>Probability (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suuuu (1-div yld) = $32.25(1.11)^4(0.955) = $46.59</td>
<td>$pppp = (0.517)^4 = 0.08$</td>
</tr>
<tr>
<td>Suuud (1-div yld) = $32.25(1.11)^3(0.90)(0.955) = $37.88</td>
<td>$4pppp' = 4(0.517)^3(0.483) = 0.28$</td>
</tr>
<tr>
<td>Sudd (1-div yld) = $32.25(1.11)^2(0.90)^2(0.955) = $30.80</td>
<td>$6pppp'p' = 6(0.517)^2(0.483)^2 = 0.37$</td>
</tr>
<tr>
<td>Sudd (1-div yld) = $32.25(1.11)(0.90)^3(0.955) = $25.04</td>
<td>$4pppp'p'p' = (0.517)(0.483)^3 = 0.22$</td>
</tr>
<tr>
<td>Suuud (1-div yld) = $32.25(0.90)^4(0.955) = $20.36</td>
<td>$ppp'p'p' = (0.483)^4 = 0.05$</td>
</tr>
</tbody>
</table>

Appendix C details how the model that is used in the Chapter 7 case study applies this approach to value the projects. However, it essentially multiplies the expected project benefits by the ratio of probabilistic future production and current production to simulate increases and decreases in project revenue due to exogenous market influences.

The discrete outcomes of stock price in Table B-5 are used in Equation B-2 to estimate the discrete outcomes of future production volume. Each risk-neutral price outcome in Table B-5 represents a possible $S_{t,n}$ in Equation B-2. The starting value of the stock price ($S$), $32.25 in the examples, serves as $S_t$. Since the estimates of production volume are based on risk-neutral drivers, cash-flows modeled based on these outcomes can be discounted at the risk-free rate.

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Appendix C: An Implementation Options Spreadsheet Model

Appendix C introduces an R&D valuation spreadsheet which is used to value the projects in the example portfolio discussed in Chapter 7. The spreadsheet uses a decision analysis (DA) model and a real options and decision tree hybrid (OPT) to value projects that include an implementation option. Chapter 6 introduced these models. Both models include three uncertainties: technical, benefit and market. Technical and benefit uncertainties are treated as endogenous influences, and market uncertainty is treated as an exogenous influence. The spreadsheet also estimates a simple, no-options NPV.

The spreadsheet is divided into several major sections. These include stages Inputs, Regression Parameters, Intermediate Calculations, Conditional Revenue Estimation, and Project Valuation.

MODEL INPUTS

Figure C-1 presents the Inputs section of the spreadsheet. This summarizes the information that is needed to estimate the options value of an R&D project using the hybrid (OPT) and the pure decision analysis (DA) models. The Inputs section is divided into three sections: Projected Costs and Benefits, Uncertainties and Other Inputs. Each cell in the spreadsheet has a label to its right that this appendix uses to refer to the input. The inputs that are displayed in Figure C-1 correspond to the data for Project B that the case study in Chapter 7 describes.

The Projected Costs and Benefit Inputs include the R&D costs, the implementation cost of the project, and the expected benefits. The R&D costs and project benefits are expressed in annual amounts, while the implementation cost is treated as a lump payment at the beginning of the implementation phase. In Figure C-1, R&D costs (RDCOST) are $800,000 per year, the implementation cost (IMPCOST) is $4,000,000, and the expected benefits (BENEFITS) are $35,000,000 per year.
### INPUTS

**Projected Costs and Benefits**
- R&D Cost (\$/yr) $800,000 RDCOST
- Implementation Cost $250,000 IMPCOST
- Dollar Benefits (\$/yr) $35,000,000 BENEFITS

**Uncertainties**
- Probability of Technical Success 0.80 PSUCCESS
- Upper Limit of Benefits (\$/yr) $42,000,000 BENRANGE
- Starting Value of Underlying Asset 32.25 UNDSTART
- Dividend Yield 4.5% UNDDIV
- Volatility of Underlying Asset 20.7% UNDSIG

**Other Inputs**
- Discount Rate 15% DRATE
- Risk-Free Rate 5% RFRATE
- Current Year 1997 YEAR
- Date of R&D Completion 1998 FDATE
- Current Production Volume 3,000,000 PRODSTART
- Analysis Timeframe (Years) 6 TIMEFRAME

---

**Figure C-1: Inputs to the R&D Valuation Spreadsheet**

Next, the Uncertainties Inputs describe technical, benefit and market uncertainty factors in the DA and OPT models that will commonly change for different projects or assessment cycles. The probability of success (PSUCCESS) defines the likelihood that a project yields technically workable results. Benefit uncertainty is characterized by the BENRANGE input, which is the upper limit of potential benefits. By assuming a specific distribution of benefits, this upper limit ($42,000,000 per year in Figure C-1) and the expected value of benefits ($35,000,000 in Figure C-1) can be applied to define a standard deviation and enable the estimation of other outcomes.

The final three Uncertainty Inputs are used by the OPT model to estimate a risk-neutral distribution of stock prices that drives the estimate of exogenous influences on project cash-flows (see Chapter 3 and Appendix B). The current value of the underlying
asset (UNDSTART), a dividend yield (UNDDIV) and a volatility of the underlying (UNDSIG) are sufficient to describe the price dynamics. The values of UNDDIV and UNDSIG in Figure C-1 correspond to the estimates developed in Table B-4 of Appendix B, and the value of UNDSTART is the same as that used in Appendix B to estimate risk-neutral distributions (Tables B-5 and B-6).

Other Inputs include a discount rate, the risk-free rate, the start and end dates for R&D, a baseline production volume and the total analysis timeframe. The NPV and DA models use the discount rate (DRATE) to calculate the present value of the R&D and the implementation costs, and the expected benefits. The risk-free rate (RFRATE) is applied in OPT. The R&D start date (YEAR) and end date (FDATE) define the time interval over which R&D is conducted. The current production volume (PRODSTART) defines the baseline production output. The analysis timeframe (TIMEFRAME) defines the total number of years for which project cash-flows are included in the valuation.

**REGRESSION PARAMETERS**

The Regression Parameters section of the model is much like the Inputs section, but is kept separate because these factors are not likely to change on a project by project basis. These Regression Parameter inputs are derived from regression analyses such as those presented in Appendix B, and describe relationships that are used to conduct a valuation using the DA or OPT models. Changing these inputs requires a re-estimation of the models in Appendix B. Implementing different forms of regression relationships requires more extensive spreadsheet revisions.

Figure C-2 presents the Regression Parameters that the spreadsheet uses. The first three define a linear regression that the DA model uses to characterize market uncertainty (see Equation B-1). DACONST is the constant and DACOEF is the coefficient of this relationship. DASTDERR is the standard error of the regression, and is used to estimate deviations from the expected outcome. All three values in Figure C-2 match the results shown in Table B-2 of Appendix B.
REGRESSION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DA Production Constant</td>
<td>2783980</td>
</tr>
<tr>
<td>DA Production Coefficient</td>
<td>15864</td>
</tr>
<tr>
<td>DA Production Standard Error</td>
<td>573104</td>
</tr>
<tr>
<td>OPT/DA Production Volume Constant</td>
<td>0</td>
</tr>
<tr>
<td>OPT/DA Production Volume Coefficient</td>
<td>0.253</td>
</tr>
</tbody>
</table>

Figure C-2: Regression Parameters Used to Model Market Uncertainties

The last two inputs to the Regression Parameters section describe a simple linear regression model that the OPT model uses relate variations in the price of an underlying asset to changes in production volume (see Equation B-2). The OPT model uses this relationship to modify project cash-flow estimates such that the risk-free rate is applicable. OPTCONST and OPTCOEF are the constant and coefficient of a linear relationship that relates production volume to the price of the underlying asset. Appendix B details the development of the regression model and the estimation of these parameters. The results in Table B-3 of Appendix B (for n = 1) correspond to the values shown in Figure C-2.

INTERMEDIATE CALCULATIONS

After project data is entered into the spreadsheet, it conducts several intermediate calculations before valuing the project. Figure C-3 highlights these calculations. First, the time before the implementation decision (IMPYR) is estimated as the difference between the expected R&D completion date (FDATE) and the present date (YEAR).

Next, the spreadsheet calculates the present value of the expected project cash-flows using both the risk-adjusted discount rate and the risk-free rate. The results from applying a risk-adjusted rate are used for the DA and NPV models. The OPT model uses the risk-free discounting results, and separately adjusts these for exogenous risks. The results from applying the risk-adjusted rate to R&D costs, implementation cost and project revenues are listed as RDPV, IMPPV, and BENEVP in Figure C-3. RDRF, IMPRF and BENERF are the results from applying the risk-free rate.
INTERMEDIATE CALCULATIONS

Time to Implementation (years) 1.0 IMPYR

*Expected Cash-Flows: Risk-Adjusted Discounting*
- PV (R&D Project Costs) ($800,000) RDPV
- PV (Implementation Costs) ($217,391) IMPPV
- PV (Revenues) Total $102,022,112 BENEPV

*Expected Cash-Flows: Risk-Free Discounting*
- PV (R&D Project Costs) ($800,000) RDRF
- PV (Implementation Costs) ($238,095) IMPRF
- PV (Revenues) Total $144,315,889 BENERF

Benefits Lognormal Standard Deviation 11.1% LOGSD

*Intermediate Market Uncertainty Calculations for DA*
- Upper Bound of Production (0.95 fractile) 4,123,336 UPPROD
- Expected Production Volume 3,180,580 EPROD
- Lower Bound of Production (0.05 fractile) 2,237,824 DNPROM

*Intermediate Market Uncertainty Calculations for OPT*
1) *Binomial Model Inputs*
   - Binomial Upward Multiplier (u) 1.11 U
   - Binomial Downward Multiplier (d) 0.90 D
   - 1+ Risk-Free Rate of Interest 1.012 R
   - Binomial Upward Probability (p) 0.53 P
   - Binomial Downward Probability (1-p) 0.47 P'
   - Stock Price Adjusted for Dividend Payouts $30.80 SLESSDIV

2) *Discrete Stock Outcomes and Probabilities*
   - Suuuu $46.59 Suuuu
   - Suuud $37.88 Suuud
   - Suudd $30.80 Suudd
   - Suddd $25.04 Suddd
   - Sdddd $20.36 Sdddd
   - Puuuu 0.08 Puuuu
   - Puuud 0.28 Puuud
   - Puudd 0.37 Puudd
   - Puuddd 0.22 Puuddd
   - Puuuu 0.05 Puuuu

3) *Discrete Production Outcomes*
   - PRODUuuu 3,293,143 PRODUuuu
   - PRODUuud 3,124,875 PRODUuud
   - PRODUudd 2,965,204 PRODUudd
   - PRODUddd 2,813,693 PRODUddd
   - PRODdddd 2,689,923 PRODdddd

Figure C-3: Intermediate Calculations in the Spreadsheet Model
To calculate these present values, the model assumes that the annual cost of R&D is incurred for each year between the current year and the implementation date. R&D implementation cost is incurred at the beginning of the implementation year. The expected project revenues (BENEFITS) accrue starting the year after implementation until the date when the analysis is ended, which is defined by the timeframe input.

Next, the model calculates factors that are used to characterize benefit and market uncertainties. First, a standard deviation of the project benefits (LOGSD) is calculated assuming that project benefits are lognormally distributed, and that the upper limit of benefits (BENRANGE) represents the 0.95 fractile of this distribution (Z-value for 0.95 fractile = 1.645). Then, the project benefits input (BENEFITS) is related to BENRANGE and the standard deviation of the distribution as shown in Equation C-1. The model uses the lognormal assumption because it assumes that any cases where the project does not yield positive benefits are accounted for by the probability of technical success metric (PSUCCESS). Therefore, successful projects are assumed to always have positive benefits.

\[
\text{LOGSD} = \sigma_b = \ln(\text{BENRANGE}/\text{BENEFITS})/1.645
\]  

(C-1)

Then, the model estimates a range of potential production outcomes for the DA model using the regression relationship developed in Appendix B (see Equation B-1). In Figure C-3, UPPROD, EPROD and DNPROD represent future potential production outputs that correspond to the 0.95 fractile, mean, and 0.05 fractile of a normal distribution. As such, the extended Pearson-Tukey approach outlined in Appendix A can be used to assign probabilities to these outcomes. Ratios of these estimates are later used to adjust the project benefit estimates for the DA model.

Next, the model uses the binomial procedure to calculate a risk-neutral distribution of stock prices that drive the probabilistic estimates of production output. First, the basic inputs to the binomial model are estimated. These include the upward and downward
multipliers (U and D), the risk-free rate of interest for the interval (R), the risk-neutral probabilities (P and P') and the dividend-adjusted stock price (SLESSDIV). Appendix B demonstrates these calculations using Equations 3-4, 3-8 and 3-10. The values of these parameters in Figure C-3 correspond to the estimates used in Appendix B to develop a five-outcome risk-neutral distribution (see discussion of Table B-5).

The model then estimates discrete outcomes of the risk-neutral stock price, by multiplying SLESSDIV by U and D for all combinations of upward and downward jumps. The five results are listed in Figure C-3 as Suuuu, Suuu, Suudd, Suddd, and Sddd. The associated probabilities are Puuuu, Puuud, Puudd, Puddd, and Pdddd, which represent multiples of the risk-neutral probabilities, multiplied by the number of pathways in the binomial tree to the result. The values in Figure C-3 correspond to the results shown in Table B-5 of Appendix B.

After the risk-neutral distribution of stock prices is estimated, the model applies a regression relationship developed in Appendix B (Equation B-2) to estimate associated production volumes. These are listed as PRODSTART, PRODuuuu, PRODuuud, PRODuudd, PRODuddd and PRODdddd in Figure C-3. Ratios of these estimates are later used to adjust the project benefit estimates.

CALCULATING CONDITIONAL REVENUES

Once the Intermediate Calculations are complete, the spreadsheet incorporates the uncertainty information into a projection of conditional project revenues. Then, it evaluates the option of implementing the project for each of these states.

Figures C-4 and C-5 summarize the calculations for the DA and the OPT models. Each represents the branch of a decision tree that stems from a technical success, for a tree such as that shown in Figure 6-2. Each figure lists the probability of success (PSUCCESS) and the calculated estimate of the present value of expected benefits (BENEPV for DA and BENERF for OPT). The trees then adjust these expected flows to account for benefit and market uncertainty.
<table>
<thead>
<tr>
<th>P(Success)</th>
<th>PV E(Benefits)</th>
<th>P(Benefit)</th>
<th>Benefit Outcome</th>
<th>P(Market)</th>
<th>Market Outcome (S)</th>
<th>PV Implement Implement?</th>
<th>Net Value (S-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.185</td>
<td>$122,426,534</td>
<td>0.63</td>
<td>$129,795,796</td>
<td>0.185</td>
<td>$168,266,582</td>
<td>($217,391)</td>
<td>1</td>
</tr>
<tr>
<td>0.185</td>
<td></td>
<td>0.63</td>
<td>$91,323,009</td>
<td>0.185</td>
<td>$129,578,404</td>
<td>($217,391)</td>
<td>1</td>
</tr>
<tr>
<td>0.8</td>
<td>$102,022,112</td>
<td>0.63</td>
<td>$139,365,194</td>
<td>0.185</td>
<td>$107,500,854</td>
<td>($217,391)</td>
<td>1</td>
</tr>
<tr>
<td>0.63</td>
<td>$101,397,406</td>
<td>0.63</td>
<td>$75,636,513</td>
<td>0.185</td>
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</tr>
<tr>
<td>0.8</td>
<td>$116,853,182</td>
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<td>$90,135,909</td>
<td>0.185</td>
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<tr>
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<td>$85,018,426</td>
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</tr>
<tr>
<td>0.105</td>
<td></td>
<td>0.63</td>
<td>$63,418,756</td>
<td>0.185</td>
<td>$63,301,365</td>
<td>($217,391)</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure C-4: Contingent Revenues and Implementation Decisions for Pure Decision Analysis Model**

<table>
<thead>
<tr>
<th>P(Success)</th>
<th>PV E(Benefits)</th>
<th>P(Benefit)</th>
<th>Benefit Outcome</th>
<th>P(Market)</th>
<th>Market Outcome (S)</th>
<th>PV Implement Implement?</th>
<th>Net Value (S-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>$190,101,142</td>
<td>0.37</td>
<td>$171,170,449</td>
<td>0.08</td>
<td>$180,387,632</td>
<td>($238,095)</td>
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</tr>
<tr>
<td>0.185</td>
<td>$173,179,067</td>
<td>0.37</td>
<td>$154,124,916</td>
<td>0.185</td>
<td>$162,424,232</td>
<td>($238,095)</td>
<td>1</td>
</tr>
<tr>
<td>0.08</td>
<td>$154,124,916</td>
<td>0.37</td>
<td>$149,402,563</td>
<td>0.08</td>
<td>$157,447,599</td>
<td>($238,095)</td>
<td>1</td>
</tr>
<tr>
<td>0.185</td>
<td>$149,402,563</td>
<td>0.37</td>
<td>$134,524,724</td>
<td>0.185</td>
<td>$149,164,468</td>
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<td>0.8</td>
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<td>0.05</td>
<td>$141,768,609</td>
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</tr>
<tr>
<td>0.105</td>
<td>$120,263,241</td>
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<td>$127,650,977</td>
<td>0.05</td>
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</tr>
<tr>
<td>0.185</td>
<td>$120,263,241</td>
<td>0.37</td>
<td>$118,868,367</td>
<td>0.105</td>
<td>$132,014,682</td>
<td>($238,095)</td>
<td>1</td>
</tr>
<tr>
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<td></td>
<td>0.37</td>
<td>$112,794,605</td>
<td>0.105</td>
<td>$125,031,094</td>
<td>($238,095)</td>
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</tr>
<tr>
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<td>0.37</td>
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<td>0.105</td>
<td>$118,630,272</td>
<td>($238,095)</td>
<td>1</td>
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<td>($238,095)</td>
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<td>0.37</td>
<td>$107,031,191</td>
<td>0.105</td>
<td>$106,793,096</td>
<td>($238,095)</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure C-5: Contingent Revenues and Implementation Decisions for Hybrid of Real Options and Decision Analysis**
First, benefit uncertainty is incorporated using a the three-point extended Pearson-Tukey approach that Appendix A outlines to develop estimates of discrete probabilistic outcomes. This method assigns a probability of 0.185 to the 0.95 and 0.05 fractiles of a distribution, and a probability of 0.63 to the median. Rearranging Equation C-1 and using the estimate of the standard deviation of benefits (LOGSD), the probabilistic outcomes are estimated as follows:

\[
\text{Outcome}_Z = \text{BENEPV} e^{Z\sigma_b} \quad \text{for the DA model in Figure C-4} \quad (C-2)
\]

\[
\text{Outcome}_Z = \text{BENERF} e^{Z\sigma_b} \quad \text{for the OPT model in Figure C-5} \quad (C-3)
\]

The appropriate Z-values for the 0.05, and 0.95 fractiles are -1.645 and 1.645, respectively.

For example, the 0.95 outcome for the DA model (Figure C-4) is calculated as follows:

\[
\text{Outcome}_{0.95} = 102,022,112 \times \exp(1.645 \times 0.111) = 122,426,534
\]

The median value is calculated using the following relationship for a lognormal distribution:

\[
E(X) = \exp(Y_{\text{ave}} + 1/2 \ \text{Var}(Y))
\]

\[
\text{Median}(X) = \exp(Y_{\text{ave}})
\]

where, \( X = \ln(Y) \), and

\[
\text{Var}(Y) = \text{Variance}
\]

Therefore,

\[
\text{Median}(X) = \frac{E(X)}{\exp(1/2 \ \text{Var}(Y))} \quad (C-4)
\]

Thus, for the DA model, the median estimate is \( \text{BENEPV}/\exp(0.5 \times \text{LOGSD}^2) \). The OPT model estimates the median as \( \text{BENERF}/\exp(0.5 \times \text{LOGSD}^2) \).
This leads to three discrete probabilistic benefit outcomes in each model. For example, in Figure C-4, the three conditional benefit outcomes are $122,426,534, $101,397,406, and $85,018,426. These correspond to the 0.95 fractile, median and 0.05 fractile of the benefits distribution. The extended Pearson-Tukey approach assigns these outcomes probabilities of 0.185, 0.63 and 0.185, respectively.

Market uncertainty is incorporated into the cash-flows of the DA and OPT models by multiplying the probabilistic benefit outcomes by ratios of the future production volume estimates shown in Figure C-3 (e.g. UPProD for DA, PRODuuuu for OPT) to the current production volume (PRODSTART).

For example, in Figure C-3, the stock price outcome Suuuu is $46.59 and has an associated probability Puuuu equal to 0.08 and a production outcome PRODuuuu equal to 3,293,143. The current production output (PRODSTART) is 3,000,000. The OPT model estimates the market influence by multiplying a conditional benefit outcome by the ratio of the production outcome to the current level (Equation C-5).

\[
\text{Market Outcome}_{uuuu} = \text{Benefit Outcome} \times (\text{PRODuuuu/PRODSTART}) \quad \text{(C-5)}
\]

Thus, in Figure C-5, the median benefit outcome ($143,432,208) is multiplied by the ratio (PRODuuuu/PRODSTART) = (3,293,143/3,000,000) to yield the market outcome of $157,447,590. Similar ratios are used to estimate the other contingent outcomes in the OPT and DA models.

**VALUING THE PROJECT**

Once all of the conditional project revenue streams are defined in the DA and OPT models, each outcome is compared the appropriate discounted implementation cost (IMPNPV for DA and IMPRF for OPT). Discounted implementation costs are used because the conditional revenues are already expressed in terms of present values.
Figure C-6: Valuation Results from the Spreadsheet Model

If the conditional revenue exceeds the implementation cost, the project is implemented, and the implementation cost is subtracted from the conditional revenue. Otherwise, implementation does not occur, and no implementation cost is incurred, nor is revenue obtained. In this case, Figures C-4 and C-5 indicate that Project B is deep in the money (i.e., benefits far exceed implementation costs), and that it is always favorable to implement successful technical developments.

Total project value is obtained by rolling the results of these comparisons back through the tree, multiplying by the appropriate probabilities, and subtracting the R&D costs (RDNPV for DA and RDRF for OPT). Chapter 6 discusses this process, and summarizes it in Equation 6-4.

The model also calculates a simple NPV using Equation C-6.

\[
NPV = RDNPV + IMPNPV + PSUCCESS*BENE PV
\]  

Figure C-6 shows the valuation results for the example project described by the inputs in Figure C-1. All three models indicate that the project is financially attractive. The DA and NPV results are nearly equivalent. The source of the slight difference between these results is the small faction of implementation costs that NPV assumes will be spent in cases
where a technically success does not result. However, the real options model (OPT) suggests that these first two models have undervalued the project. The case study in Chapter 7 provides a detailed example of how the spreadsheet can be used. It also examines key sensitivities of the NPV, DA and OPT models in the spreadsheet.
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James Edwin Neely III was born in Troy, New York on February 9, 1968, and grew up in Butler, Pennsylvania. After graduating from Butler Area High School in May 1986, he attended Alfred University and earned a B.S. in Ceramic Engineering (May 1990). Subsequently he earned a S.M. from the Massachusetts Institute of Technology (MIT) in Materials Engineering (February 1992), and then worked at IBIS Associates, a materials industry focused management consultancy, in Wellesley, Massachusetts. He returned to MIT during September of 1994, and soon thereafter entered the interdisciplinary Technology, Management and Policy doctoral program. After he completes his Ph.D. (June of 1998), J. and his wife Shawn Shores will move to Cleveland, Ohio where he will begin working as an Associate with the Consumer and Engineered Products group of Booz-Allen & Hamilton, a general management consultancy.