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Value-Centered R&D Organizations: Ten Principles for Characterizing, Assessing, and Managing Value

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ABSTRACT

The management of R&D organizations has received considerable attention in terms of the nature of the flow from research to development to deployed technology, as well as planning and managing this flow. R&D strategies, innovation funnels, and multistage decision processes, to name just a few constructs, have been articulated and elaborated. This article builds on this foundation to consider the nature of the value created by this process. An options-based approach is advocated for economic valuation of the products of R&D. Adoption and implementation of this approach is outlined in terms of ten principles for characterizing, assessing, and managing value. © 2004 Wiley Periodicals, Inc.† Syst Eng 7: 167–185, 2004

Key words: R&D; investment & valuation; organizatonal change; value streams; option pricing models; technology management

1. INTRODUCTION

Over the past three decades, we have managed several academic, industrial, and government research organizations, ranging in size from ten or so researchers up to several hundred scientists and engineers. These organizations have served various constituencies, including the larger enterprise, technology markets, and profes-

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sional disciplines. The technologies involved ranged from simulation to software, from displays to decision support.

Internal and external marketing and sales, recruiting and mentoring staff, and managing budgets and cash flow were continual issues, as they are in all enterprises. More specific to R&D organizations were the long-term uncertainties associated with the value of activities and outcomes of our organizations. Often, these activities and outcomes were not central to the overall enterprise's near-term success. This sometimes made it difficult to get the attention of key stakeholders [Rouse, 1985].

To address these challenges, we availed ourselves of the best thinking in terms of the various "generations" of R&D management [Roussel, Saad, and Erickson, 1991; Matheson and Matheson, 1998; Miller and Morris, 1999], as well as articles from *Research Technology Management*, *Journal of Product Innovation Management*, and many other journals. The body of literature in this broad area is very rich.

This exploration led us to become fascinated with the specific issue of attaching value to R&D, particularly economic value. We have also been interested in noneconomic attributes, especially as they trade off versus economic attributes. Central to the question of economic valuation is the fact that the nature, magnitude, and timing of returns from R&D investments are highly uncertain.

It is common to discount the projected financial returns from R&D due to these high uncertainties. This discounting is often severe, ranging from 20% to 50%. To lessen the effects of such severe discounting, people argue for extraordinary returns, i.e., the familiar "hockey stick" projections. This can lead to a war of attrition between discounting bean counters and wild-eyed technologists.

Participation in such conflicts caused us to argue for more explicit treatment of uncertainties rather than burying these effects in the discount rate. Further, it seemed to us that the value of R&D should increase with uncertainties. R&D provides a hedge against uncertainties. Hedges have value and this value should increase with uncertainties and, of course, consequences.

This thinking led us to real options [Amram and Kulatilaka, 1999; Boer, 1998, 1999; Luehrman, 1998], based on the options pricing theories of Black, Merton, and Scholes [Black and Sholes, 1973]. Adoption of an options-based framework caused us to conclude that the value of R&D is in the options created rather than the technology deployed. Deployment depends on options being exercised, decisions for which depend on a variety of factors beyond those associated with R&D. Options have value whether or not they are exercised.

This article describes how we formulated and operationalized an options-based framework for economic valuation of R&D. We have cast this description in terms of ten principles for characterizing, assessing, and managing value shown in Table I. We strongly believe that these principles are more important than particular calculation procedures. As one senior executive told us, "You've got to count the numbers right, but the numbers are not all that counts."

2. CHARACTERIZING VALUE

In this section we address the problem of defining the value of R&D in terms of the roles it plays—or should play—in enterprises, regardless of whether they are private or public sector enterprises. Key roles include creating means for meeting contingent needs and providing means for managing uncertainty. Development of an appropriate portfolio of such means is also a central role of R&D.

Principle No. 1: Value is created in R&D organizations by providing "technology options" for meeting contingent needs of the enterprise. R&D is almost always about the future. R&D organizations may occasionally become involved in today's problems, but involvement in such situations is usually focused on gaining an appreciation for the context in which the future is likely to emerge. To the extent that R&D is focused on solving today's problems, they are performing an engineering function rather than R&D.

There can be substantial pressure on R&D to provide engineering services to operational units. These units usually value this highly because it augments their technical staffs, often with very competent people. R&D also usually likes the subsequent endorsements from the field. Such services doubtlessly add value to today's operations.

Taken to an extreme, however, focusing on these services results in R&D functions, in effect, being shelved and eventually dissipated. As a consequence, the future is taken hostage by the present. Future needs, especially contingent needs, are ignored. This leaves the enterprise ill prepared for the future. Its portfolio of means for meeting future needs will be impoverished.

Even when R&D is kept firmly focused on the future, there can be difficulties assessing success. It is often perceived that success is proportional to the fraction of investments that yield technologies that transition to deployment. The goal is to transition every idea and result to providing value in the enterprise's marketplace or equivalent.

Table I. Ten Principles for Characterizing, Assessing, and Managing Value

No.	Focus	Principle
1	Characterizing Value	Value is created in R&D organizations by providing "technology options" for meeting contingent needs of the enterprise.
2	Characterizing Value	R&D organizations provide a primary means for enterprises to manage uncertainty by generating options for addressing contingent needs.
3	Characterizing Value	A central challenge for R&D organizations is to create a portfolio of viable options; whether or not options are exercised is an enterprise challenge.
4	Assessing Value	Value streams, or value networks, provide a means for representing value flow and assessing the value of options created.
5	Assessing Value	Valuation of R&D investments can be addressed by assessing the value of the options created in the value network.
6	Managing Value	Decision making processes -- governance – are central in managing the flow of value.
7	Managing Value	Organizational structure affects value flow, with significant differences between hierarchical vs. heterarchical structures.
8	Managing Value	Individual and team affiliations and identities affect value flow; dovetailing processes with disciplines is essential.
9	Managing Value	Champions play important, yet subtle, roles in value flow; supporting champions is necessary but not sufficient for success.
10	Managing Value	Incentives and rewards affect value flow; aligning these systems with value maximization is critical.

Total focus on such transitions can lead to dysfunctional behaviors. For example, solely low-risk issues may be pursued. High-risk issues, despite their importance to the enterprise, may be avoided. Creation of knowledge about why ideas failed is perceived to have little or no value. Similarly, creation of skilled people is perceived to have little or no value.

A strong desire to avoid the types of problems outlined above led us to pursue the notion of options [Rouse and Boff, 1999; Rouse et al., 2000]. An option is the right to make an investment decision in the future, contingent on the information available at that time. Put another way, an option is a chit that allows delaying a decision that one would rather not make now, but also would not like to lose the opportunity to make later.

Of course, unlike financial options, an enterprise needs much more than a piece of paper to effectively "own" an option. R&D organizations produce options in terms of knowledge and skilled people, as well as prototypes, patents, etc. Knowledge may be codified in published articles, internal technical reports, and patent disclosures. However, the "shelf life" of such things, and consequently the value of technology options, depends on frequent renewal via ongoing participation in research and professional societies, for example.

From an options perspective, the R&D "scorecard" should not be dominated by the percentage of technology options exercised. Instead, one should also count viable technology options created, some of which get exercised and some of which do not. The key point is that the enterprise needs the right portfolio of options for meeting future needs. R&D should be scored on both its demonstrated ability to provide these options and, obviously, the actual creation of the options.

The scorecard should, of course, also include some measure of options exercised. Such metrics should appear on R&D managers' scorecards as well as the scorecards of those responsible for making decisions to exercise options, e.g., managers of product lines and enterprise operations. Failure to have needed options is, by no means, simply a failure of R&D. It often represents a deficiency across the whole value stream, including overall leadership.

Assessing the value of options immediately begs the question of why options are valuable, and how to attach value to contingencies in general. We address this below. First, however, let us explore the assertion that a primary role of R&D is creation of technology options. In particular, is creation of technology options inherently a primary role of all R&D organizations?

What about universities with their focus on big R and little or no D? The problem here is not with the term "option," but with the adjective "technology." Perhaps "knowledge options" should be the phrase. Knowledge options can be exercised downstream, most likely outside academia, to create technology options. Interestingly, knowledge options, without dilution, can provide the basis for a range of technology options.

What about applied R&D organizations where problem solving is the goal, i.e., big D and little or no R? Perhaps the activities of such organizations are better characterized as engineering services rather than R&D. Hence, option creation is less relevant. On the other hand, exercising options may be very relevant. Options that are more inexpensively exercisable tend to be more valuable.

Upstream in academia the goal is knowledge creation, to a great extent for its own sake. Downstream in applications, the goal is problem solving. Midstream, where most R&D organizations operate, the goals are understanding and creating contingent value. These goals are achieved by understanding emerging applications and drawing upon accumulating knowledge.

Within a technology-intensive enterprise, e.g., IBM or the Air Force, R&D organizations may have purview of and influence on the whole value stream. As one looks up and down the whole process, it is important to keep in mind that the meaning of "options" may differ along the stream. Nevertheless, an options-based perspective is useful for viewing the whole process.

Principle No. 2: R&D organizations provide a primary means for enterprises to manage uncertainty by generating options for addressing contingent needs. R&D is a means of managing and often reducing uncertainty. Providing options for addressing contingent needs involves addressing various types of uncertainties beyond the uncertainty underlying the need for contingencies. One may be uncertain about whether or not something is possible, how best to do it, and what one can expect in terms of performance and cost. One also may be uncertain about what functionality will be needed, what levels of performance and cost will be required, and what competitors are likely to do.

To the extent that futures are uncertain with many possibilities, it is better to have options on alternative futures than attempt to invest in all possibilities. These investments should cover the full range of uncertainties just noted. The purpose of these investments is not to eliminate uncertainty, but to have the right portfolio of options.

The value of an option[1] increases with the magnitude of the consequences of exercising the option. This value also increases with the uncertainty associated with these consequences. Finally, value increases with time into the future when the option can be exercised. Thus, the value of an option increases with the magnitude and uncertainty of consequences, and time until these consequences can be obtained.

Balancing these relationships is the fact that the magnitude of consequences is expressed as the discounted cash flow due to exercising an option. The farther into the future one looks, the more highly discounted this cash flow. Thus, to illustrate, an option for a highly uncertain million dollars 100 years in the future will be worth its full net present value of $12. In general, the countervailing forces of increased value due to uncertainty and time and decreased value due to discounting can yield counterintuitive results.

Table II provides a summary of 14 selected case studies of option-based investment analysis that the authors have recently conducted—the Appendix elaborates the ways in which these valuations were formulated and calculated. It is important to note that all of these case studies involved actual investment decisions that were made based, in part, on the option-based analyses. Option "purchase" ranged in cost from $0 to over $400 million. The cost of option "exercise" ranged from $0 to almost $1.7 billion. Expected profits from exercising options ranged form $16M to almost $3.5 billion. Finally, net option values ranged from $8M to over $600M.

It is important to note that the actual investment modeling and analysis were substantially more elaborate than apparent from Table II. The software tool employed, ***Technology Investment Advisor*** [Rouse et al., 2000], enabled modeling technology maturity, production learning, and competitive positions, as well as uncertain parameter values throughout all models. The results of such analyses are probability distributions for the measures summarized in Table II. Only expected values are shown in Table II to illustrate representative results.

The net option value provides a measure of the value created by owning the option beyond the cost of buying the option, e.g., investing in R&D. Thus, this provides a metric of the value or worth of R&D beyond its costs. From Table II, it can be seen that R&D investments provide options on profits 1–4 years later for private sector enterprises and rather later for costs savings for public sector enterprises. The longer times for the public sector are due, in part, to the extended nature of their planning and acquisition processes more than the nature of the technology.

This type of thinking embodied in Table II tends to conflict with how large enterprises typically address and manage uncertainties. Large hierarchical and/or bureaucratic enterprises often are quite risk-averse.

[1] See the Appendix as well as Amram and Kulatilaka [1998], Boer [1998, 1999], Luehrman [1998], Luenberger [1997], and Smithson [1998] for discussions and illustrations of how option values can be calculated for a range of models.

Table II. Example Option-Based Valuations of Technology Investments

Technology	Enterprise Type	Option Purchase			Option Exercise			Net Option Value ($M)
		Investment	Amount ($M)	Duration (Years)	Investment	Amount ($M)	NPV Profit ($M)	
Aircraft (manufacturing)	Private	R&D	0	1	Deploy Improvements	0	16	8
Aircraft (unmanned)	Public	R&D	420	10	Deploy System	72	749	137
Auto Radar	Private	Run Business	6	3	Expand Offerings	16	160	133
Batteries (lithium ion)	Private	R&D	1	2	License Technology	8	220	215
Batteries (lithium polymer)	Private	R&D	8	3	Acquire Capacity	147	581	552
Fuel Cell Components	Private	R&D	18	1	Initiate Offering	144	522	471
Microsatellites	Public	R&D	359	10	Deploy System	614	930	43
Optical Multiplexers	Private	R&D	0	2	Expand Capacity	66	568	488
Optical Switches	Private	Run Business	68	2	Expand Offerings	402	1642	619
Security Software	Private	Run Business	0	3	Add Market Channels	104	416	267
Semiconductors (amplifiers)	Private	Invest in Capacity	24	2	Expand Offerings	412	1035	431
Semiconductors (graphics)	Private	R&D	3	1	Initiate Offering	8	102	99
Semiconductors (memory)	Private	R&D	109	4	Initiate Offering	1688	3425	546
Wireless LAN	Private	Run Business	19	2	R&D	40	268	191

Good decisions that yield bad outcomes are termed failures and decision-makers associated with such failures find their careers thwarted. This situation is exacerbated when an enterprise has little or no real competition.

In our experience, such enterprises do not want options—they want results. Everything promised should be delivered as promised. Nothing that is delivered should be extraneous. Options that are not exercised were bad investments. Unused life insurance, in retrospect, was a poor investment. Organizations with these perspectives delude themselves about uncertainty and how best to manage it.

In contrast, strategic advantage can be gained and sustained by understanding uncertainty better than one's competitors and creating a portfolio of options that provides high-value hedges against these uncertainties. Once contingencies emerge, one can exercise those elements of the portfolio that provide the greatest competitive advantage. Organizational abilities to address uncertainty this way—enabled by R&D—makes uncertainty a factor to be leveraged rather than eliminated.

Principle No. 3: A central challenge for R&D organizations is to create a portfolio of viable options; whether or not options are exercised is an enterprise challenge. R&D organizations can assure that options are viable—that they are exercisable. This means that knowledge is vetted, codified, and supported with "how to" models, methods, and tools. It also means that people are up to date technically and available if needed. It is also important to have a good understanding of the resources needed for these people to employ the requisite knowledge.

Whether or not viable options are exercised depends on a range of factors beyond the purview and control of a typical R&D organization. Market conditions may not be right. Resources may not be available. Of particular importance, downstream decision-makers may choose to exercise other options, perhaps for technologies that now appear to provide greater competitive advantage.

This raises the question of who decides to exercise options. Other than in small new ventures, it is rare for the creator of technology options to have the discretion to decide to exercise these options. It is much more common for such decisions to be made downstream and/or higher in the enterprise. Of course, R&D should understand these stakeholders and the factors that influence their decisions. This should provide a basis for both making investment decisions and proactively influencing perceptions of emerging technology options.

Further, the R&D management process should provide ongoing insights and opportunities for intermediate decisions to continue, redirect, or terminate investments. As indicated below, typical multistage decision processes also provide for involvement of downstream decision-makers in review of progress towards creating viable options. This results in early "buy in" and can accelerate transitions to deployment [Rouse and Boff, 1998, Rouse, 2001].

Nevertheless, as noted earlier, technology transitions—options exercised—should not be the dominant element of an R&D organization's "scorecard." R&D is primarily responsible for creating viable technology options. Beyond doing good technical work, this requires that R&D have a substantive understanding of the aspirations, opportunities, and uncertainties that the enterprise is facing in the future. R&D needs to provide an appropriate portfolio of options for addressing this future.

Success in addressing the challenges and opportunities of the future cannot be fully planned. The nature of what will be required, the positions of competitors, and the availability of resources are all uncertain. As a result, one needs more than one idea; in fact, one often needs a fairly large number of initial ideas to yield one market success [Stevens and Burley, 1997]. A recent study by the Air Force Scientific Advisory Board found multiple instances of companies needing roughly 300 initial project investments to yield one commercial success [Ballhaus, 2000].

Thus, there is typically a technology "funnel" whereby a large number of initial investments are, over time, whittled down to a few initiatives that receive sufficient investment to have a chance in the marketplace—occasionally one of them achieves market success. Managing a technology funnel is easier if one also adopts an explicit multistage process for managing R&D. The majority of enterprises have such processes, so this idea is by no means novel [Cooper, Edgett, and Kleinschmidt. 1998a].

At the same time, however, we have both experienced large private and public sector enterprises arguing that every investment must lead to a transition to the field. With this emphasis, R&D becomes quite conservative, focused on very incremental improvements that are guaranteed to succeed and the market is guaranteed to buy. These are characteristics of a very mature industry long past its innovative stages.

Ironically, our experiences with such enterprises are that they fall far short of a 100% transition rate. However, given that the leadership and culture are so focused on the 100%, they cannot entertain serious mechanisms for managing the real transition percentages. Consequently, the pipeline becomes clogged with marginally valuable, incremental improvements, and scarce resources are spread among so many investments that critical mass is seldom achieved.

The portfolio of technology options can be portrayed as shown in Figure 1. Return is expressed in terms of NPV (net present value) or NOV (net option value). The former is used for those investments where the lion's share of the commitment occurs upstream and subsequent downstream "exercise" decisions involve small amounts compared to the upstream investments. NPV calculations are close enough in those cases.

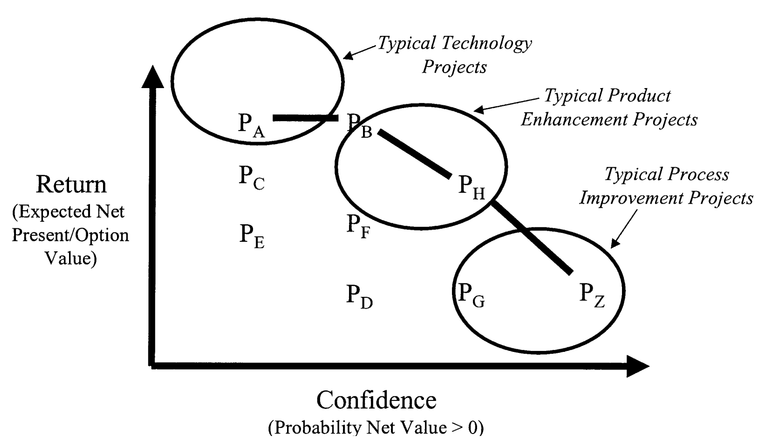

Figure 1. Investment portfolio diagram.

Risk (or confidence) is expressed as the probability that returns are below (risk) or above (confidence) some desired level—zero being the common choice. Assessment of these metrics requires estimation of the probability distribution of returns, not just expected values. In some situations, this distribution can be derived analytically, but more often Monte Carlo analysis or equivalent is used to generate the needed measures.

Figure 1 provides a plot of the economic returns and risks associated with a portfolio of investments. The line connecting several of the projects (P_A, P_B, P_H, and P_Z) in this figure is termed the efficient frontier. Each project on the efficient frontier is such that no other project dominates it in terms of *both* return and confidence. In contrast, projects interior (below and/or left) to the efficient frontier are all dominated by other projects in terms of both metrics. Ideally, from an economic perspective at least, the R&D projects in which one chooses to invest—purchase options—should lie on the efficient frontier. Choices from the interior are usually justified by other, typically non-economic attributes.

A primary purpose of a portfolio is risk diversification. Some investments will likely yield returns below their expected values, but it is very unlikely that all of them will—unless, of course, the underlying risks are correlated. For example, if the success of all the projects depends on a common scientific breakthrough, then, despite a possibly large number of projects, risk has not been diversified. Thus, one usually designs investment portfolios to avoid correlated risks.

While this makes sense, it is not always feasible—or desirable—for R&D investments. Often multiple investments are made because of potential synergies among these investments in terms of technologies, markets, people, etc. Such synergies can be quite beneficial, but must be balanced against the likely correlated risks.

It is important to note that non-economic attributes—not depicted in Figure 1—are also usually important. Considerations such as strategic fit, sustainability of advantage, and leveraging of core competencies are also important concerns when making R&D investments. While such multiattribute assessments are beyond the scope of this article, we recognize their central importance [Rouse, Boff, and Thomas, 1997; Rouse and Boff, 1999; Rouse, 2001].

Finally, it is essential to recognize that options often emerge in an evolutionary manner. Knowledge accumulates and competencies increase over time. At each decision point in a typical multistage R&D management process, the acceptability of progress to date is assessed. In some cases, one now knows that viable options are unlikely and investments are curtailed or redirected. In other cases, it becomes apparent that integrating multiple emerging options will both enable and enhance option value.

Occasionally, "wild card" options emerge that were never sought or envisioned, perhaps reflecting Burke's pinball effect that yields unexpected high-value options for unexpected beneficiaries [Burke, 1996]. As Christensen [1997] elaborates, it is common for enterprises to encounter great difficulty taking advantage these, possibly disruptive, options.

Thus, options are not like certificates that are issued upon purchase. Considerable work is needed once "purchase" decisions are made. Options often emerge piecemeal and with varying grain size. Significant integration of the pieces may be needed before the value upon which the investment decisions were based is actually available and viable.

3. ASSESSING VALUE

We have characterized the value of R&D in terms of providing options for meeting contingent, uncertain needs of the enterprise. We now need to consider the processes whereby enterprises create value and how these processes result in a flow of options. This will provide a framework for discussing how value can be managed.

Principle No. 4: Value streams, or value networks, provide a means for representing value flow and assessing the value of options created. It is useful to think of value in terms of both how technology options are created and how they are consumed. On the creation side, the focus is on R&D processes that yield viable options and the quality, productivity, and innovation associated with these processes [Rouse and Boff, 2001, 2003].[2] On the consumption end, the concern is with how technologies make possible functionality that is embodied in products, systems, and services that provide capabilities that enable achieving the effects of interest to the marketplace or other constituencies.

R&D organizations should attempt to maximize the yield and minimize the time to create the portfolio of technology options needed by the enterprise. This affects the "purchase price" of the options. The "exercise price" and the resulting cash flows are strongly affected by how the technologies underlying the options flow to market impact. R&D often cannot directly impact the elements of the value stream subsequent to option execution. However, R&D may be able to deliver more "exercisable" options if the nature of downstream processes is understood.

[2]Rouse and Boff [2001, 2003] elaborate and operationalize the quality, productivity, and innovation attributes of value and their relationships to value strategies.

Value streams can be represented as networks of connected nodes with inputs, outputs, resources, and controls [Rouse and Boff, 2003]. Upstream nodes produce options for downstream nodes. Value at any node can be assessed by "rolling back" the value associated with eventual downstream outcomes in terms of cash flows due to profits and/or cost savings.

An example value network is shown in Figure 2. In this example, drawn from the authors' earlier work [Rouse and Boff, 2003], one can see repeated "kernels" associated with programmatic investments, R&D execution, and technology deployment. Programs fed each other, often in somewhat unpredictable ways. For the context of this example, namely investments in intelligent tutoring systems, two different subnetworks, one for the U.S. Air Force and another for the U.S. Navy, resulted in significant value, in this case for public high schools across the United States.

A key distinction in such representations is between end users and next users. End users are the eventual beneficiaries of the enterprise. Next users are those immediately downstream from you who accept the options you create as inputs, add value, and then pass on options to their next users downstream from them. Your key customers are your next users rather than the end users.

When next users cross organizational boundaries, they are also referred to as transition agents. In some cases, they are explicitly tasked to transition or transfer technology. Their role is to understand both sides of the boundary. This involves, for instance, understanding the perspectives of both discipline-oriented researchers and business-focused product line managers. Often, significant translation is needed to balance the two perspectives.

As reasonable as the notion of next users seems, it conflicts with the culture of many large enterprises, in both public and private sectors. The intensity with which the defense community, for example, focuses on the "warfighter" leaves many next users very much under-served and, ultimately, undermines supporting the very end users for which so much passion is felt.

Consequently, R&D organizations may attempt to satisfy today's end users whose felt needs usually involve today's needs and deficiencies. For example, today's pilot is unlikely to envision accomplishing one of his or her current tasks without an aircraft. He or she will ask for higher thrust engines rather than a way to sight targets without moving the aircraft.

In responding to such forces, R&D organizations become engineering services organizations. This may provide significant value to operating units, at the very least in terms of staff augmentation. However, it undermines the R&D function and diminishes the possibilities for the R&D organization to create the portfolio of technology options needed for the enterprise to realize its future aspirations.

Value stream mapping can be very useful for understanding how value flows from initial R&D investment decisions to impacts in markets and for other constituencies [Rouse and Boff, 2003]. It can help to assure that all the elements of a value stream are aligned with maximizing yield and minimizing time until these impacts. It also provides a means for reengineering processes that are not adding value as they should.

In terms of option values, value streams should be redesigned to:

- Decrease costs of purchasing options, decrease costs of exercising options, and/or increase returns of exercising options.

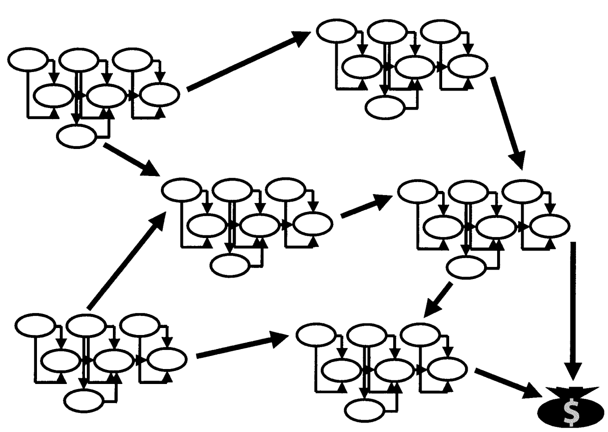

Figure 2. Example value network (based on Rouse and Boff [2003]).

- Decrease time until options are viable, if uncertainties can also be reduced in a manner that provides sustainable competitive advantage.
- Decrease the extent to which competitors and adversaries can create and sustain options that provide them competitive advantage.

Note that redesign in pursuit of such objectives can often be enhanced by mapping and analysis of competitors' value streams.

Principle No. 5: Valuation of R&D investments can be addressed by assessing the value of the options created in the value network. In order to appropriately allocate resources, one needs to attach value to the flows in the value streams or value network. This need for valuation has several important characteristics:

- It is multistage, with many contingent decisions.
- It is multiattribute, with both economic and noneconomic attributes.
- It is multistakeholder, with differing levels of importance of attributes.
- It must address substantial uncertainties across these characteristics.

We have addressed the multiattribute, multistakeholder aspects of this valuation problem elsewhere [e.g., Rouse and Boff, 1999; Rouse, Boff, and Thomas, 1997]. Both economic and noneconomic value can be addressed using multistakeholder, multiattribute utility models. The theory underlying these models and the practices for applying these models are well developed. There are issues of the relative importance of different stakeholders' perceptions. However, there is much experience in wrestling with these issues.

From an options-based perspective, a central issue concerns assessing the economic value of a network of contingent decisions over time, laced with substantial uncertainties. In the context of R&D, these decisions primarily involve purchasing options that, when exercised, yield other options. Cash flow, in terms of profit and/or cost savings, does not come until technology is deployed in products, systems, and services.

Traditionally, economic value is expressed in terms of Net Present Value (NPV) of cash flows created by an investment. These cash flows are the differences between returns and costs that, in the case of R&D, are almost always negative. Beyond the obvious fact that "money is not everything," the NPV approach presents two key difficulties.

One difficulty is that NPV calculations assume that all viable contingencies will be exercised, perhaps with associated probabilities. Yet, in reality, many alternatives are, quite rationally, not pursued once the time for their possible pursuit arrives. The returns and costs of these alternatives should not be included in the NPV calculation. The problem, of course, is that you do not know in advance which alternatives will not be pursued. Using Net Option Value (NOV) rather than NPV avoids this difficulty.

The second difficulty, particularly for public sector investments, involves defining "returns." Defense investments, for example, do not yield profits for the public that invests in these capabilities. These investments yield desired military capabilities and effects. Taking these desires as requirements or "givens," one can characterize the returns on investing in a new technology in terms of potential cost savings in meeting given requirements with this technology.

This presents difficulties when a new technology enables previously unavailable capabilities and effects. In this case, a baseline must be fabricated that provides that capability and effects without the new technology. For example, we recently used the costs of operating manned aircraft as a baseline for assessing investments in unmanned air vehicles. As might be imagined, the credibility of the baseline has a very significant impact on the credibility of the overall analysis.

Options-based framing of R&D investment decisions involves valuation of a portfolio of options, subsets of which are linked in multistage processes. The Black-Scholes formulation mentioned earlier, often augmented with heuristics and sensitivity analyses, enables closed-form calculation of option values. In situations where the underlying assumptions, e.g., lognormality of volatility, cannot be justified, numerical solutions of the requisite partial differential equations, binary lattice models, or Monte Carlo simulation can be employed, albeit with considerably more effort [Luenberger, 1997; Smithson, 1998].

It is important to note that options-based thinking has considerable value beyond the calculations outlined here. Elaboration of contingencies and associated uncertainties greatly improves the framing of investment decision problems. Responding to valuation in this manner, R&D organizations are often quite nimble in identifying and formalizing downstream contingencies much more broadly than typically motivated by traditional valuation methods. These conclusions are based on observations by many of the executives and senior managers involved with the assessments summarized in Table II.

This principle—as well as these conclusions—also applies in situations where a corporate parent or customers pay for the R&D of interest. R&D organizations in such situations are, in effect, selling options to sponsors. The key argument here would be that the R&D budget is substantially less than the value of the option provided. Hence, the Net Option Value would be attractive and the sponsor should "buy" the option.

One might argue that the costs of securing the R&D sponsorship, e.g., bid and proposal monies, can also be seen as option purchase costs. In this case, the sponsor would exercise the option by, for example, awarding the R&D contract. However, option-pricing models typically assume that options are exercisable by the purchasers of the options. A nonstandard formulation would be needed to address probabilistic exercising of options by other than those purchasing the options.

4. MANAGING VALUE

Thus far, we have elaborated the characterization of the value of R&D in terms of option creation for the enterprise. R&D budgets are used to "purchase" options for potential cash flows (profits and/or savings) if exercised elsewhere in the enterprise. We have also discussed the methods and tools needed to assess value—value stream mapping, option pricing models, and multiattribute models.

The first set of five principles provides the foundation for adoption of an options-based view of value. However, they are not sufficient for success. Beyond impressive foundations, an enterprise also has to execute successfully. A second set of five principles, elaborated in this section, provides the underpinnings for successful execution.

It should be noted that this second set of principles relates to the systems management elements of systems engineering. Success often requires that well-engineered systems also be well managed. To assure this, we must incorporate systems management principles into the systems engineering body of knowledge.

Principle No. 6: Decision-making processes—governance—are central in managing the flow of value. Processes for investment decision-making and investment management have a significant impact on value created and subsequent benefits to the enterprise. Good decision processes result in better decisions for two reasons. First, the right attributes and tradeoffs are considered at the right time. Second, all stakeholders understand how decisions are made, how to influence decisions, and how final decisions emerge. This greatly improves buy in.

Inadequate or inappropriate decision processes can undermine value creation by allowing poor decisions, resulting in ineffective allocations of investment resources. Misunderstood decision processes can result in a lack of individual and organizational commitment to decisions. At an extreme, a variety of dysfunctional myths can emerge [Rouse, 1998]. For example, management may feel that they have consensus, the right processes, and "just" have to execute when, in fact, throughout the organization people do not know how to influence decisions, are carrying out processes that are not value-centered, and face considerable execution hurdles.

It is common for organizations to have difficulty agreeing to decision-making processes, employing these processes with a degree of integrity, and communicating decisions in the context of these processes. It is also quite natural for stakeholders to attempt to work around decision processes to assure their interests are supported. To the extent that this succeeds, it undermines disciplined processes and precipitates cynicism among stakeholders.

Such difficulties are common in R&D organizations where traditions of authority and value-centered decision-making are often in conflict. Strong leadership can be of great help in adopting and succeeding with a value-centered approach. However, to the extent that such leadership preempts value-based governance processes, the approach will be undermined and its benefits diminished.

An identified best practice within R&D organizations involves using multistage decision processes with specified criteria and objectives at each stage [Cooper, Edgett, and Kleinschmidt, 1998a, 1998b; Rouse and Boff, 2001]. Early stages, when investments are relatively small, usually involve more qualitative criteria with modest target levels. Later stages, where investments can be very substantial, typically have many more quantitative criteria with challenging target levels. For such processes to be adopted and embraced, they need to be well articulated and supported. They also need to be used, both in terms of making decisions as advertised and communicating decisions in the context of this process.

More specifically, if options created is a desired outcome at each stage of the process, then arguments for continued investment should be couched in terms of net option values. If this is expected from proponents of investments, then methods and tools such as discussed earlier should be provided. Finally, investment decisions should be communicated in the context of options-oriented metrics.

If all proposals for new or continued investment are evaluated in a common manner, then portfolio plots such as shown in Figure 1 are possible and quite useful. There are, of course, always additional noneconomic attributes of importance, but the ability to represent comparisons in this way, enables more focused discussion and debate of key tradeoffs across economic and noneconomic attributes.

It is also important to consider the relationships of decision-making processes to issues that are broader than just the attributes of alternative investments. Decision processes are needed for agreeing on organizational visions, goals, and values. The quality, productivity, and innovation of value streams are likely to affect overall satisfaction of end users, next users, and stakeholders in general. The morale and "psychic income" of researcher staff members and managers are also considerations. Investment decisions also must be made with regard to organizational processes to support R&D and other functions.

Principle No. 7: Organizational structure affects value flow, with significant differences between hierarchical vs. heterarchical structures. Value is maximized, both in magnitude and time, when it flows through efficient organizational processes. Such processes minimize the number of steps between upstream and downstream next users, and eventually end users. It is desirable that steps with little or no value added be eliminated. However, the nature of organizations can make this difficult.

Organizations can be viewed in several ways. Organizations receive inputs and produce outputs. For R&D organizations, these inputs and outputs often are in the form of information. Structural relationships within and across organizations define the extent and content of information flows. Such flows influence the extent to which R&D organizations can deeply understand future enterprise aspirations, as well as communicate and support the options created by R&D processes.

Organizational structure also affects decision-making. Hierarchical structures are useful for leadership and goal setting. Such structures, however, can impede value flow to the extent that higher levels are designed to make decisions in lower level processes. Hierarchical requests for approvals and resources add time and uncertainty while also consuming resources in themselves. In this way, the magnitude and timing of value are decreased and delayed, respectively [Rouse and Boff, 2003].

Heterarchical structures, in contrast, enable efficient horizontal flow of value. Authority for approvals and resource allocations reside at the level of the value streams. Higher levels communicate the vision and elaborate the goals but do not specify how goals are to be achieved. Value flow is monitored, but intervention is rare as authority for corrective actions also resides as the level of the value streams.

Leaders in such organizations have more influence than power. They also must carefully consider and articulate the vision and goals. Design and communication of incentives and rewards are also key leadership roles. These types of leadership roles are difficult to perform well, and are not natural traits for those steeped in more authoritative models of leadership.

Organizational structure also affects the control of resources—human, financial, and physical. This is useful in that resources usually need "homes" to be stewarded appropriately. However, it can also lead to "silos," associated with functions, disciplines, or regions. This limits the flow of resources to where value can best be added.

These tendencies can be countered by matrixing resources across organizational boundaries. The decision processes discussed above can be used to reallocate resources periodically. Such reallocations can be driven by where the greatest option values are likely to be created. This approach typically results in those who seek resources making their arguments in terms of options and their value. This is, of course, exactly what one would like them to do.

These implications of organizational structure can also be expressed in terms of who can direct what initiatives, who gets to review proposals and progress, and who determines rewards. Organizational structure and the allocation of authority should assure that execution of these managerial responsibilities is aligned with creating options for achieving enterprise aspirations.

For R&D organizations, the above considerations are manifested in terms of how information and knowledge flows, funding decisions are made, resources are allocated, and research outcomes assessed [Rouse and Boff, 1998]. There is no best organizational structure for these activities. Nevertheless, structure should be derived from strategy. To this end, organizational structure needs to be designed to support the way in which options are best created and nurtured in the enterprise environment of interest.

Both descriptive and prescriptive approaches to organizational structure are needed. One must be able to understand the ways things work now in order to define the gaps between "as is" and "to be" as we discuss later. It is also important to recognize that the "best" structure may not be simply a variation within the reigning organizational paradigm. Thus, an improved hierarchy may be inferior compared to a more heterarchical structure, for example.

Kimberly [1986] suggests relationships between organizational design and innovation by considering the organization as a user, vehicle, and/or inventor of innovation. Further, the organization itself can be an innovation. This is complicated by the nature and context of R&D organizations [Miller, 1986; Jain and Triandis, 1990] and their relationships to overall enterprises. Typical R&D cultures with strong external, professional identities, as well as more inwardly directed personnel, can make organizational redesign more challenging and change difficult to sustain.

Principle No. 8: Individual and team affiliations and identities affect value flow; dovetailing processes with disciplines is essential. R&D is often pursued by people with similar disciplinary backgrounds, e.g., scientists and engineers from particular disciplines. People in finance or marketing often work together in other aspects of enterprise value streams. The professional affiliation and identity that this encourages can be very important for professional development and knowledge sharing.

However, this affiliation and identity can also limit people's abilities to fully understand next users and end users' perspectives and needs. For this reason, it is useful to also encourage affiliation with overall value streams and associated processes. This can be fostered by providing education and training focused on enterprise value streams, as well as creating opportunities for value stream participants to meet and get to know each other.

Dovetailing processes with disciplines is important, but it can be very difficult. University education typically does a poor job at supporting cross-disciplinary perspectives. Academic faculty members are often among the most discipline-bound professionals. The best-performing students have often fully assimilated this trait.

Consequently, it is essential to be very intentional in providing value-centered education and training. This should include material on the nature and functioning of enterprise processes. Next users and end users of processes should be explicated, including the options they need and those they create. Supporting information flows should also be outlined and explained.

In addressing this principle, a balance must be managed between understanding and identification with enterprise aspirations, and affiliation and interaction with sources of disciplinary knowledge and best practices. Overemphasis on the former typically results in less then fully competent, but nevertheless enthusiastic researchers. Overemphasis on the latter tends to foster first-rate researchers, although they may at times have a somewhat cynical view of the organization.

Creating this balance is not a problem to be "solved." One should maintain awareness of how the underlying tension is evolving. If the situation evolves to either extreme and persists, it can be very difficult to reestablish a more productive balance. In this sense, perhaps unfortunately, the extremes tend to be fairly stable situations while balance takes continual effort.

Principle No. 9: Champions play important, yet subtle, roles in value flow; supporting champions is necessary but not sufficient for success. Well-designed organizational processes can often sustain incremental value improvements. However, quantum and often disruptive improvements are frequently facilitated by champions that pursue "the cause" regardless of organizational hindrances [Christensen, 1997]. Champions are noted for formulating innovation strategies, finding resources, and sustaining commitment through implementation [Rouse and Boff, 1994].

On the other hand, champions cannot convert bad ideas to good, and seldom succeed without recruiting others to share responsibility and communicate the benefits of ideas more broadly. Thus, while champions may be necessary for disruptive change, they are seldom sufficient. They can be essential catalysts but rarely the sole cause of success [Markham and Griffith, 1998].

Managing value requires that champions be encouraged and supported. An explicit mentoring process can help foster champions. Recognition of champions and their contributions can also help. Once champions emerge for particular initiatives, it is also important to provide ongoing encouragement and support, ranging from visibility with leadership to additional resources.

Nevertheless, it is important that champions not be viewed as the only essential ingredient in success. Organizational processes, especially decision processes, should be designed to empower and support champions. Such processes should also be capable of sustaining initiatives when, for instance, champions depart. There are elements of succession planning that are relevant here.

Organizations seem to have natural tendencies to let champions work things out, often resulting in their having to work around current organizational processes. This is certainly better than watching initiatives fail. However, a more proactive and eventually more successful approach is to redesign and support processes based on lessons learned by champions. This will also encourage people to become champions.

More broadly, one needs to create an environment that encourages champions, while also attracting and hiring the rights kinds of people [Jain and Triandis, 1990]. There needs to be the right mix of unencumbered visionaries, respected thought leaders, and competent value managers to play the roles of idea generators, gatekeepers, and coaches, as well as champions. The overall climate should encourage creative imagining and farming of options, including how they can be realized. This all must be designed in the context of typical R&D professionals and organizational cultures, including typical driving forces [Miller, 1986].

Principle No. 10: Incentives and rewards affect value flow; aligning these systems with value maximi-

zation is critical. People respond to incentives. When incentives are aligned with maximizing value flow, people pay much more attention to providing their next users with viable options. In contrast, when incentives and rewards are not aligned—or are not realigned—with value streams, people "march to old drummers" in order to garner rewards.

It is important to balance recognition and rewards for individuals and teams associated with value processes. Individual excellence is, of course, important, but excessive stress on individual disciplinary accomplishments can undermine an organization's value orientation. In an R&D organization, this could mean giving all authors full credit for a jointly-authored research paper rather than trying to assess who did what.

The key is to develop metrics that are both individually and organizationally oriented. Balanced scorecards [Kaplan and Norton, 1996], or equivalent, can be developed for both overall value processes and individual contributions to these processes. Incentives and rewards can be linked to some combination of these two types of metrics.

Whatever is measured, recognized, and rewarded will get attention. Careful design of value streams will not yield desired results without developing and implementing a measurement system that links individual and organizational performance to these value streams. A key is to relate recognition and rewards to value outcomes, e.g., options created, rather than just well intended activity.

More specifically, measures should be carefully chosen to reflect value goals and strategies, as well as the consequent nature of value streams. From this perspective, an R&D value scorecard is quite different than what one might devise for manufacturing or customer service [Rouse and Boff, 2001]. It is also important to assure that personnel are educated with regard to such measurement mechanisms and trained in their use.

One particularly difficult aspect of implementing this principle involves getting seasoned middle managers to adopt new approaches. Such people are often quite skilled at succeeding in terms of the old metrics. A useful tactic is to recruit thought leaders from this population to participate in the team(s) defining new measures and scorecards. This enables early understanding of objections and use of these thought leaders to help devise countermeasures.

Enterprise strategies fall victim to two primary failures [Rouse, 2001]. The first is a failure to execute—the strategy is all talk and no walk. The second is a lack of alignment between what the enterprise wants to become and how it incentivizes and rewards stakeholders. This tenth and last principle, therefore, is critical to avoiding value strategies being just a concept rather than a real way forward.

5. ORGANIZING FOR VALUE

Given the ten principles outlined in this article and summarized in Table I, how should one go about creating a value-centered R&D organization? More specifically, how can one design or redesign such an R&D organization in a particular enterprise? This section outlines an overall design process. Some of the difficulties encountered in pursuing this process are then discussed, including a variety of best practices for addressing these difficulties. These insights are based in part on the broad literature on R&D organizations [e.g., Rouse and Boff, 1998; Rouse, Thomas, and Boff, 1998], as well as previous efforts in developing and applying methodologies for design of enterprises, organizations, systems, products, and processes [Rouse, 1991, 1992, 1993, 1994, 1996, 1998, 2001].

5.1. Overall Design Process

The design of a value-centered R&D organization can be pursued using the following general steps:

- Define desired enterprise outcomes
- Design processes for achieving these outcomes
- Design measurement system for processes
- Design structure for managing processes
- Design incentives and rewards to maximize value

These design tasks should be performed using the ten principles for generating alternatives and addressing tradeoffs.

This approach seems quite reasonable, especially if one were designing an R&D organization "from scratch." However, most of the applications of the principles outlined here have involved existing R&D organizations that were aspiring to creating greater value for their stakeholders. In these situations, it is usually very difficult to start from scratch.

As shown in Table III, the value principles can be applied in these cases by first assessing the "as is" organization from the perspective of these principles. The "as is" organization's strengths and weaknesses can be characterized in terms of deficiencies in satisfying principles. It is important to determine the specific nature of deficiencies rather than just their existence.

The next step is to define the "to be" organization in terms of deficiencies remedied. This should include specific programs of action to yield significantly greater conformance with the value principles. It is also impor-

Table III. Template for Supporting Organizational Design or Redesign

<table>
<tr><th>Principle</th><th>As Is</th><th>To Be</th></tr>
<tr><td>Value is created in R&D organizations by providing "technology options" for meeting contingent needs of the enterprise</td><td rowspan="10">Strengths, Weaknesses & Deficiencies</td><td rowspan="10">Programs to Remediate Deficiencies</td></tr>
<tr><td>R&D organizations provide a primary means for enterprises to manage uncertainty by generating options for addressing contingent needs</td></tr>
<tr><td>A central challenge for R&D organizations is to create a portfolio of viable options; whether or not options are exercised is an enterprise challenge</td></tr>
<tr><td>Value streams, or value networks, provide a means for representing value flow and assessing the value of options created</td></tr>
<tr><td>Valuation of R&D investments can be addressed by assessing the value of the options created in the value network</td></tr>
<tr><td>Decision making processes -- governance – are central in managing the flow of value</td></tr>
<tr><td>Organizational structure affects value flow, with significant differences between hierarchical vs. heterarchical structures</td></tr>
<tr><td>Individual and team affiliations and identities affect value flow; dovetailing processes with disciplines is essential</td></tr>
<tr><td>Champions play important, yet subtle, roles in value flow; supporting champions is necessary but not sufficient for success</td></tr>
<tr><td>Incentives and rewards affect value flow; aligning these systems with value maximization is critical</td></tr>
</table>

tant to define a time frame for accomplishing these changes and measures of success.

5.2. Defining "As Is" and "To Be"

At least conceptually, the principles as described earlier are fairly straightforward. More concretely, however, it can be difficult to map these general principles to a particular R&D organization. As surprising as it may seem, it can be somewhat difficult to determine how an R&D organization currently provides value.

This determination begins with identification and characterization of the organization's current activities, the inputs to and outputs from these activities, and how the value of these inputs and outputs are assessed. This can require significant effort, as people, especially researchers, do not necessarily think about their work this way. They just do what they do.

The typical project orientation of R&D organizations provides a means for getting started a bit easier. Beginning with a review of the portfolio of ongoing and recently completed projects, consider how the cases were made to initiate these projects and the outcomes promised in the proposals outlining these cases. The task plans associated with projects are also useful. Compile answers to the following questions:

- What problem and/or opportunity are being addressed?
- Why was this problem/opportunity thought to be important?
- What outcomes were promised in the proposal?
- What tasks were outlined for delivering these outcomes?
- How were these tasks to be performed?
- On what did performance of these tasks depend?
- What outcomes have been delivered thus far?
- Who were the recipients of these outcomes?
- What value do they attribute to these outcomes?
- What difficulties have been encountered thus far?

By focusing on proposals and progress reports, one can assess how the organization makes the case for resources and reports ongoing outcomes. For projects that have been completed, one can assess the perceived value of the final outcomes.

The key here is not to assess every project, which may be daunting in large organizations. Instead, review a large enough sample to obtain a thorough sense of how people in the organization think it functions. Reading between the lines, one can also identify or infer several other characteristics that underlie value streams:

- "Synaptic" linkages among elements of the organization in terms of information complied, created, and shared
- Transition agents that cross organizational boundaries, what specifically is transitioned, and how this is achieved
- Extent to which transitions—and value—depend on a confluence of options, stakeholders, and information
- Impacts of timing relative to broader context-specific considerations such as budget cycles, changes of leadership, etc.
- Sources of impedances that hinder transitions and affordances that foster transitions
- Means of facilitation and other organizational support for expediting and assuring the success of transitions

The results of such an analysis of ongoing and completed projects will be a set of "puzzle pieces" in an overall picture of how the organization functions, as well as several inferences regarding underlying mechanisms. These results should be viewed as hypotheses to be tested by presentation—independently—to a sample of organization members and asking for their review, comments, and suggested corrections and refinements.

We hasten to note that this may not result in the "truth." However, it will provide an invaluable starting point. Beyond assuring that one is "in the ballpark," this process will also help to foster buy-in from important stakeholders—people in the organization. It is essential that key members of the organization perceive that the assessment and resulting characterization make sense.

Given this characterization, one next needs to assess the extent to which the organization operates according to the ten principles for value-centered R&D organizations outlined in this article. Such as assessment will inevitably be fairly qualitative. This will likely be sufficient, as the types of changes that are typically entertained tend to be compelling without complete quantification.

5.3. Designing Action Plans

The process just outlined usually results in identification of a variety of deficiencies. Stated as observations, examples include:

- We are so focused on helping business or operational units now, that we don't know if we are doing the right things for their futures.
- Assessment of value is difficult because our "next users" have no data or projections of the impacts of what they ask us to provide.
- There are many activities dictated by the broader enterprise for which we can find no value added relative to our role in the enterprise,
- Our incentive and reward systems are not aligned with how we can best provide value, and we may be unable to unilaterally change these systems.

Such observations, as well as a typical variety of more mundane conclusions, provide a rich basis for developing action plans.

The overall process outlined earlier focuses on filling gaps to remediate deficiencies. Some changes are likely to be straightforward. However, some of the types of change illustrated in the above list cannot be initiated unilaterally. These changes require that broader stakeholders embrace an options-based view of the R&D organization.

This suggests that action plans include both overt and covert elements. Some things one can make happen immediately, e.g., require that all proposals include an options argument. There may be other changes, e.g., ceasing non-value-added activities, for which it may be much more difficult to gain approval. Nevertheless, changes that require external approval may be essential to becoming a value-centered R&D organization.

These observations beg the question of who is leading the transformation to becoming a value-centered enterprise. If R&D is the driver, there are more subtleties to negotiate. If top management is the driver, the whole process can be pursued much more directly and aggressively. This suggests, obviously, that R&D executives should focus on selling the CEO, or equivalent, rather than covertly fostering such changes despite the chief executive.

5.4. Executing Action Plans

Action plans only deliver value when plans are executed, results are measured, and remedial adaptations made. This obvious statement conflicts with the organizational reality of business as usual. Articulating project proposals and outcomes in terms of option values may be difficult for audiences accustomed to hearing of budgets and milestones. Initially at least, it may be necessary to tell the story both ways.

It is important to keep the momentum by constantly articulating the value story, explaining and advocating an options-based view. This can be facilitated by illustrating specific outcomes and the option values attached to these outcomes. It is important to keep in mind that options-based thinking is not necessarily natural. For example, the idea that options have value even when not executed can take people some time to digest.

It is essential to value-centered planning that potential outcomes be cast in terms of possible value provided. The expected outcomes of action plans need to be monetized in terms of Net Option Values. Measures of risk can be derived from probability distributions of Net Option Value. Taken together, these two metrics enable portfolio plots. Such plots will, with time, become a central element of the organization's strategic dialog.

Indeed, we have found that this impact on the dialog is more important than the numbers. Returns and risks are, of course, good topics for strategic discussions. Just as important, however, are debates about alternative futures, the options needed to realize these futures, and how these options can be created. Being a primary provider of these options, R&D inherently plays a central role in such debates.

Implementing and managing change is a challenging undertaking in itself. There are numerous difficulties associated with gaining and maintaining momentum. Delusions that execution will be straightforward are common, as are delusions of having changed already [Rouse, 1998]. For R&D organizations, recognition of having succumbed to various delusions often comes far too late to be able to remediate these problems and react to an already-changed environment.

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APPENDIX: FORMULATION AND CALCULATION FOR OPTION-BASED VALUATIONS

The option-based valuations in Table II were the results of a systematic process of framing downstream options, estimating input data needed, calculating option values, and performing sensitivity analyses to assess impacts of modeling and input uncertainties. This appendix elaborates these steps of this process.

A.1. Framing Options

This step begins with consideration of the effects sought by the enterprise and the capabilities needed to provide these effects. In the private sector, desired effects are usually profits, perhaps expressed as earnings per share, and needed capabilities are typically competitive market offerings. Options can relate to which technologies are deployed and/or which market segments are targeted. Purchasing options may involve R&D investments, alliances, mergers, acquisitions, etc. Exercising options involves deciding which technologies will be deployed in which markets and investing accordingly.

In the public sector, effects are usually couched in terms of provision of some public good such as defense. More specific effects might be expressed in terms of measures of surveillance and reconnaissance coverage, for instance. Capabilities would then be defined as alternative means for providing the desired effects. Options in this example might relate to technologies that could enable the capabilities for providing these effects. Attractive options would be those that could provide given effects at lower costs of development, acquisition, and/or operations.

A.2. Estimating Input Data

Option-based valuations are economic valuations. Various financial projections are needed as input to option calculations. Projections needed include:

- Investment to "purchase" option, including timing
- Investment to "exercise" option, including timing
- Free cash flow—profits and/or cost savings—resulting from exercise
- Volatility of cash flow, typically expressed as a percentage

The analyses needed to create these projections are often substantial. For situations where cash flows are solely cost savings, it is particularly important to define credible baselines against which savings are estimated. Such baselines should be choices that would actually be made were the options of interest not available.

A.3. Calculating Option Values

The models employed for option-based valuations were initially developed for valuation of financial instruments. For example, an option might provide the right to buy shares of stock at a predetermined price some time in the future. Valuation concerns what such an option is worth. This depends, obviously, on the likelihood that the stock price will be greater than the predetermined price associated with the option.

More specifically, the value of the option equals the discounted expected value of the stock at maturity, conditional on the stock price at maturity exceeding the exercise price, minus the discounted exercise price, all times the probability that, at maturity, the stock price is greater than the exercise price (Smithson, 1998). Net Option Value equals the option value calculated in this manner minus the cost of purchasing the option.

Thus, there are Net Present Values embedded in the determination of Net Option Values. However, in addition, there is explicit representation of the fact that one will not exercise an option at maturity if the current market share price is less than or equal to the exercise price. As mentioned earlier, sources such as Amram and Kulatilaka [1998], Boer [1998, 1999], Luehrman [1998], Luenberger [1997], and Smithson [1998] provide a wealth of illustrations of how option values are calculated for a range of models.

It is important to note that the options addressed in this article are usually termed "real" options in the sense that the investments associated with these options are usually intended to create tangible assets rather than purely financial assets. Application of financially derived models to nonfinancial investments often raises the issue of the extent to which assumptions from financial markets are valid in the domains of nonfinancial investments. This concern is usually addressed with sensitivity analysis.

A.4. Performing Sensitivity Analyses

The assumptions underlying the option-pricing model and the estimates used as input data for the model are usually subject to much uncertainty. This uncertainty should be reflected in option valuations calculated. Therefore, what is needed is a probability distribution of valuations rather than solely a point estimate. This probability distribution can be generated using Monte Carlo simulation to systematically vary model and input variables using assumed distributions of parameter/data variations. As noted earlier, the software tool employed for the analyses summarized in Table II—***Technology Investment Advisor*** [Rouse et al., 2000]—supported these types of sensitivity analyses.

These analyses enable consideration of options in terms of both returns and risks. Interesting "What if?" scenarios can be explored. A question that we have frequently encountered when performing these analyses is, "How bad can it get and have this decision still make sense?" This question reflects a desire to thoroughly understand the decision being entertained, not just get better numbers.

A.5. Examples from Table II

Consider the example of semiconductor memory in the second row (from the bottom) of Table II. For $109M of R&D, this company "purchased" an option to deploy this technology in its markets 4 years later for an expected investment of approximately $1.7B. The expected profit was roughly $3.5B. The Net Option Value of over $0.5B reflects the fact that they bought this option for much less than it was worth.

In the second row (from the top) of Table II, a government agency invested $420M in R&D to "purchase" an option on unmanned air vehicle technology that, when deployed 10 years later for $72M, would yield roughly $750M of operating savings when compared to manned aircraft providing the same mission effects. The Net Option Value of $137M represents the value of this option is excess of what they invested.

It is instructive to compare these two examples intuitively. For the semiconductor memory investment, the option value of over $600M (i.e., the R&D investment plus the NOV) represents roughly one third of the net present difference between the expected profit from exercising the option and the investment required to exercise it. This is due to considerable uncertainties in the 10+-year time period when most of the profits would accrue. In contrast, for the unmanned air vehicle technology investment, the option value of roughly $560M represents over two thirds of the net present difference between the expected cost savings from exercising the option and the investment required to exercise it, despite the returns occurring in a similar 10+-year time frame.

This may seem counterintuitive. However, the quotient of expected profit (or cost savings) divided by the investment required to exercise the option is quite different for these two examples. This quotient is roughly 2.0 for the semiconductor memory option and 10.0 for unmanned air vehicle technology investment. Thus, the likelihood of the option being "in the money" is significantly higher for the latter. This is why the option value is one third of the net present difference for semiconductor memory and two-thirds for unmanned air vehicle technology.

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