Of Mice or Men: Management of Federally Funded Innovation Portfolios With Real Options Analysis

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***Abstract*—*The aerospace industry is a rich source of innovation and novel technologies. However, structural drivers, such as product complexity and stringent performance requirements, inhibit the uptake of new technologies and present challenges to portfolio management specific to technology-rich environments. Although project risk is often managed through staged funding processes associated with intermediate milestones, this process is typically decoupled from portfolio valuation. In this paper, we use a simple real options binomial tree model to value the National Aeronautics and Space Administration portfolio funded through the Small Business Innovation Research program, accounting quantitatively for the funding stages and future opportunities accompanying technology infusion. For the 2009 portfolio, the average net project investment is $166k, suggesting the important role that early-stage funding plays in launching innovation efforts. We study the staged architecture to offer insight to managers of commercial and public portfolios alike.*

Key words: Real options, SBIR, innovation policy, R&D portfolio, entrepreneurship, government venture capital, aerospace

MANAGERIAL Relevance Statement: We offer a framework for managing a set of early-stage technologies by estimating the portfolio's valuation. The method uses a real options approach appropriate for staged investments in highly skewed environments in which a relatively small number of successes generates the value of the entire portfolio and the risk changes dramatically over time. Furthermore, our sensitivity analysis identifies the key drivers of project and portfolio valuation, providing quantitative insight to a program manager.

1. INTRODUCTION

While technology portfolio management challenges exist in many industries, they are particularly acute in the aerospace community. It is technologically advanced and strategically important because of its size, global nature, innovation capacity, and technological complexity. Adoption of new technology faces significant challenges because of high development costs, limited markets, and complex products conforming to strict performance and reliability standards. The aerospace industry thus represents a rich and important environment in which to study technology portfolio management.

In particular, research and development (R&D) portfolios are complex with sources of uncertainty that include budgets, schedules, payoffs, product performance, and market requirements [1]. Modeling efforts include stochastic analysis [2], multi-attribute value modeling [3], and simulations to constrain the portfolio downside [4]; all require an understanding of the changing nature and level of uncertainty over a R&D project's life cycle and how the risk profile evolves over time. Real options ("RO") analysis provides a framework for accommodating these changing risks. This financial tool has been extended to strategic planning, particularly in environments of uncertainty [5], [6] and in staged decision-making [7], [8]. However, its application in the aerospace industry has been limited. R&D management in the aerospace industry is important particularly because the relevant United States agencies (National Aerospace and Space Administration (NASA) and the Department of Defense (DOD)) suffer from cost overruns with infusion of new technologies [9], [10].

A key resource for early-stage finance is the federally funded Small Business Innovation Research (SBIR) program supporting technology development and applied research in small companies with roughly $2 B of federal investment across all industries. To date, economic research regarding SBIR has focused primarily on the benefits [11]–[13], with less attention directed toward viewing the program's investments as a research portfolio managed under uncertainty.

In this work, we study early-stage technology portfolio management by using the NASA SBIR portfolio as a model system. Examining work funded by this agency allows the use of aerospace industry standards and processes to inform technology valuations at various stages of development. To address the dynamic technology risk, we have employed real options approaches; the SBIR program operates with a staged structure that lends itself naturally to a discrete option tree model at the intersection of early-stage technology development and financial analysis.

We begin with a review of the aerospace industry technology processes and drivers, followed by an analysis of real options approaches to portfolio management and finally, the general context of innovation policy and federally subsidized R&D. We then examine the specialized case of the NASA SBIR program, mapping the architecture to a binomial options tree to estimate the average project's valuation and, by extension, that of a given portfolio. A sensitivity analysis indicates which steps of the process drive the project valuation, and thus that of the entire portfolio, so that the program manager can understand the consequences of potential decisions. Finally, we conclude with the implications for R&D management as well as for the growing field of innovation policy, particularly with respect to mission-driven agencies like NASA.

2. Literature Review

2.1. Management of New Product Development in the Aerospace Industry

The aerospace industry is generally recognized as a nationally strategic industry characterized by complex, advanced technologies with strong links between defense and civil markets and representing a major source of invention [14]. Management challenges include heterogeneity, small production volumes, and high reliability and performance requirements. As the products are highly customized, the industry generates extended product life cycles and a general tendency to launch variants of existing models rather than new products, as well as strongly collaborative and risk-sharing business models [15]–[17].

Because of the industry's deep interaction with civil applications, public funding is an important driver in technology development. Both DOD and NASA experience significant cost and schedule slippages, particularly in new technology infusion [9], [10]. These over-runs could be mitigated by favoring mature solutions, but this strategy would naturally exclude new, riskier technologies offering the possibility of future value. Since costs increase as a technology advances toward maturity, it becomes progressively more expensive to demonstrate and validate technical performance, potentially inhibiting future funding [18]. This is made more challenging in the aerospace industry, and particularly NASA, by the limited frequency and number of missions, consequently restricting technology development and funding opportunities [19].

Often aerospace technology portfolio evaluation is conducted with a "stage-gate" model, with flow from conception to implementation controlled by a series of gates or decision points where the projects are evaluated and selected to advance to the next level of funding. One study attempted to calibrate the maturities at each gate to development costs [20]. Valuing space technology is further complicated because the government funding process does not take place in an open market with natural price discovery, but instead in a limited marketplace [21].

In general, the aerospace industry is a rich and important source of new technologies. The strong linkages with the civil sector make federal funding an important resource to advance technology development. The portfolios are typically managed through stage-gate models, but they provide limited insight into the technology's ultimate value, motivating the search for another estimation scheme.

2.2. Real Options Approach to Valuation

A common method for R&D managers to analyze prospective projects is a simple net present value ("NPV") analysis that both evaluates a current stream of expected cash flows and discounts them at some uniform rate. However, this method is inappropriate for staged programs with managerial opportunities to discontinue funding after a given phase. In addition, NPV analysis does not account for the reduction of risk as a project advances through the stages, further rendering the uniform discount rate imprecise. A method is needed to account for a staged development program and its risk characteristics.

Real options analysis incorporates the terminology and perspective of financial options, defined as the right but not the obligation to purchase (call) or sell (put) an asset. Myers first viewed strategic planning as management of a portfolio of real options—i.e., the option to expand, contract, defer, abandon, or switch the use of a capital investment [5]—and Trigeorgis and Reuer (2017) discussed the value of these alternatives to make decisions in an environment of uncertainty [6].

Real option implementation is complex in R&D environments with asymmetric risks and skewed distributions, where one strong success compensates for many failures. Furthermore, the risk level changes over time, and so a single discount rate does not reflect this dynamic system. The poor understanding of the system's probabilistic behavior, coupled with the perceived mathematical complexity of RO analysis, has inhibited its wide adoption by R&D management practitioners, despite the capability to differentiate between technical and market risks [22], [23]. Initial studies are promising; Bodner and Rouse determined that real options analysis optimizes portfolio planning, while NPV analysis performs better at optimizing a single project [24]. Datar and Mathews developed an iterative simulation technique for individual projects [25], and the model of Laamanen and Seppä has higher predictive power than the traditional DCF model in valuing venture capital investments [26].

Whereas Miller and Bertus used real options to evaluate out-licensing opportunities for an aerospace manufacturer [27], it has been more commonly applied in the energy industry [28]–[31] and in the pharmaceutical industry [23], [32], [33]. Oriani and Sobrero applied RO to stock market valuation of R&D projects [34], and RO simulations of R&D suggested that the abandonment option had high value [35].

Real options approaches have clear benefits in portfolio valuation, particularly in high technology environments such as the energy generation and pharmaceutical industries. There is strong precedent for using it to value an aerospace portfolio.

2.3. Innovation Policy and the SBIR Program The United States government represents an important source of funding for research and development (R&D) activities; the American Association for the Advancement of Science (2017) reports federal investment of an estimated $147 B in 2017 [36]. Because new companies contribute disproportionately to economic growth [37]–[39] and may struggle to attract private capital [40]–[43], subsidy programs have been developed around the world, [44], [45]; in the United States, the Small Business Innovation Research Program represents $2 B in investment and has been linked to increased entrepreneurial activity, venture capital, company growth, high-tech entrepreneurship, patent generation, and patents acquired from external sources [11], [13], [46]–[49].

Although federal funding could in principle "crowd-out" or displace private investment [12], the subsidy instead allows for the firm to continue research that would otherwise be abandoned [50]. This can be viewed as a real options problem in which the NPV of the abandonment option is no longer the highest value. We therefore can ask the question: What is the actual valuation estimated in a real options approach?

Each agency manages its own SBIR program in a highly structured fashion, producing open solicitations for research proposals and selecting the entirety of the coming year's project portfolio at one time. Decisions for the next tranche of investment are similarly made simultaneously for all proposals seeking continuing funding. This two-phase structure is uniform throughout the agencies. At NASA, further funding may follow from another program if the opportunity for infusion into a flight project is sufficiently high, and ultimately that project budget may support final development.

Despite the structured approach, the high intrinsic levels of risk associated with technology development have inhibited valuation analyses of these portfolios, particularly through the use of standard NPV techniques. Thus, SBIR portfolio valuations are typically discussed in terms of the investment budget rather than the potential value. Analyzing the drivers of portfolio value can potentially illuminate different aspects of policy decisions as well as commercial opportunities.

3. Data and Methodology

3.1. Program Structure It is natural to consider the SBIR portfolio as a whole, as breadth has been shown to improve performance [51], as has a sequential investment process [52] and increased flexibility [53]. The NASA SBIR budget for FY 2016 exceeded $150 million and addresses the agency's needs in executing its strategy of earth and space exploration. We will follow a simple real option tree approach to value an average project in the NASA

SBIR portfolio; the program architecture is as follows:

- Phase I: Initial investment in R&D efforts selected competitively from an open solicitation.
- Phase II: Additional funding is available only for selected efforts previously funded in Phase I; funding in this round is awarded competitively.
- Supplemental: Activities funded in Phase II may apply for additional resources from NASA R&D programs.
- Flight: A technology may ultimately be funded for infusion into a flight project by a different NASA funding source.

Because the supplemental and flight funding are derived from sources external to the SBIR program, they represent cash inflows, with infusion representing the final payoff. This analysis could be recalculated from the perspective of NASA as a whole with all cash flows represented as outflows; however, to focus on the SBIR program manager, we view these as positive cash flows generated by development and infusion. In other words, the Phase I and Phase II funding rounds represent cash outflows or investments, analogous to pharmaceutical R&D investments, while the supplemental and flight project funding are similar to out-licensing a pharmaceutical compound. At the end of each stage, the R&D activity is re-evaluated for further funding and thus each stage's end constitutes a decision node.

Table 1. Annual Funding Levels for Phases I and II in the NASA SBIR Program in 2009

Item	Value
Award size	
Phase I	$100 k
Phase II	$600 k
Number of awards	
Phase I	364
Phase II (subset of Phase I)	211
Advancement probability	58%
Budget	
Phase I (% of total budget)	$36.4 M (22%)
Phase II (% of total budget)	$126.6 M (78%)
Total SBIR funding pool	$163.0 M

We will differentiate between the SBIR's two funding tranches, denoted as "Phases", and the entire life-cycle, denoted by "stages." The funding in Phases I and II has varied from year to year. Furthermore, both the number of awards in each cycle and the total budget (evaluated as the product of the number of awards and the award size) have varied from year to year in aggregate as well as for each Phase. In this work, we explore the data of the 2009 award cycle (Table 1).

3.2. Application of the Option Tree

In keeping with the notation of Jägle [32], the project value at each node i is denoted S_i; if it does not proceed further, it has a liquidation value S_i^- (Figure 1).

This architecture lends itself naturally to an option tree approach. The periods of Phases I is 6 months, and Phase II has varied from 18-24 months. We assume Phase II length of 18 months in our calculations and a supplemental funding duration of two years, making the total project duration four years.

Historically, the success rate for Phase I NASA awards is roughly 13% [54]. Projects rejected at the Phase I decision do not contribute to the portfolio value as no cash outflow takes place, and thus these rejected projects are not included here. Analysis begins at the point when a project is selected for Phase I funding. The probability of advancing to Phase II varies from year to year. Of those projects, 25% receive supplemental funding of approximately $2 M from another R&D program. Of those, the final subset reaching the payoff of selection by a flight project and additional funding of $3 M represents 25%; in other words, approximately 6.25% (25% x 25%) of the projects funded in Phase II reach the final payoff. These parameters are summarized in Table 2.

We discuss the 2009 portfolio in detail as a model year. We extracted data representing funded projects from the NASA SBIR web site to accurately estimate the probability of advancing from Phase I to Phase II, and the number of awards [54]. The option tree approach requires project values in the event of failure to advance to the next stage; i.e., S_i^- values must be estimated. Boer shows that under modest assumptions for an early-stage opportunity, a residual value of roughly 15-20% can be derived [55], while Ramey and Shapiro generated estimates of roughly 44% at maturity [56]. Our analysis aligns Phases I and

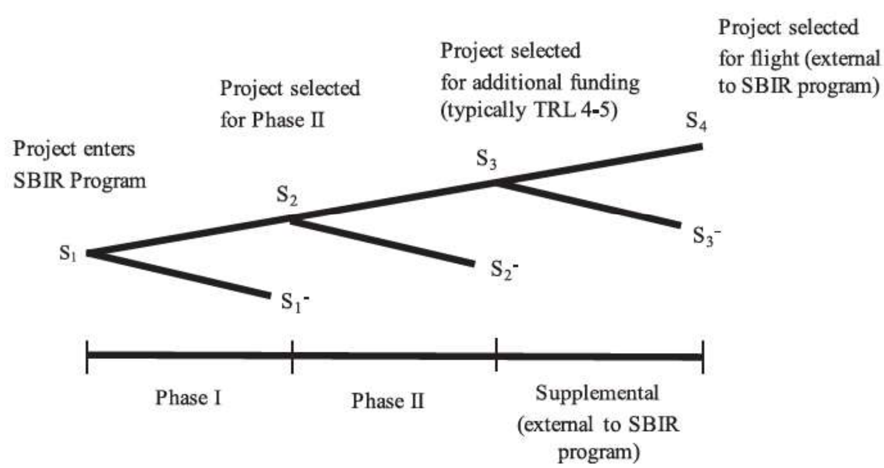

Figure 1. Architecture of NASA SBIR program.

II with Boer's early-stage estimates. At the time of the final funding opportunity, technologies have matured significantly and have higher residual value; indeed, one way to characterize this as an early-stage technology project is to define the liquidation value relative to the cash infusion. These estimates are summarized in Table 3.

3.3. Discounted Cash Flow Analysis

Analysis begins with a straightforward discounted cash flow (DCF) calculation. In the first step, the single period probabilities are mapped onto a binomial option tree (Fig. 2). The tree explores only the two extreme outcomes at each node i: success (S_{i+1}), in where a successful project proceeds to the next stage; and failure (S_i^-), or liquidation. The end point resulting from success at all stages is given by the present value of cash flows at the upper right end of the tree. Project values at inner nodes are calculated by iterating backward through the tree (Equation (1)):

$$S_i = p_i\, S_{i+1}(1 + WACC)^{-t_i} + (1 - p_i)S_i^-(1 + WACC)^{-t_i} + C_i \quad (1)$$

for project value S_i($) at stage i, observed success probability p_i, stage length t_i (years), and stage cash flows C_i. In line with Table 2, stage cash flows equal −$100 k, −$600 k, and $2,000 k in stages 1, 2, and 3, respectively. Evaluation of Equation (1) requires an estimate for the weighted average cost of capital (WACC). One estimate suggests that early-stage cost of capital to the entrepreneur could be 30-45%, depending on the size of the entrepreneur's personal investment [57]. However, noting that this is a non-dilutive investment, we have assumed a value of 25%.

Iteration of this process at all nodes proceeds back to the initial value S_1 as per Equation (1); the DCF analysis of the NASA SBIR data of 2009 is shown in Figure 2 and yields an estimate of negative $120 k.

Table 2. Option Tree Parameters Given by NASA 2009 SBIR Program Architecture

	Phase I	Phase II	Supplemental	Flight
Stage i	1	2	3	Final Payoff
Period duration t_i (years)	0.5	1.5	2	N/A
Single period probability p_i (varies with year)	58%	25%	25%	N/A
Investment outflow ($) (varies with year)	$100,000	$600,000		
Payoff inflow			$2,000,000	$3,000,000

Table 3. Estimated Liquidation (failure) Values for Technology Development Projects in the 2009 SBIR Program

	Phase I	Phase II	Supplemental
Estimated liquidation value	$15,000	$120,000	$500,000
Liquidation value (as % of cash infusion)	15%	20%	25%

Standard DCF analysis of 2009 NASA SBIR awards
WACC = 25%
All numbers in $k

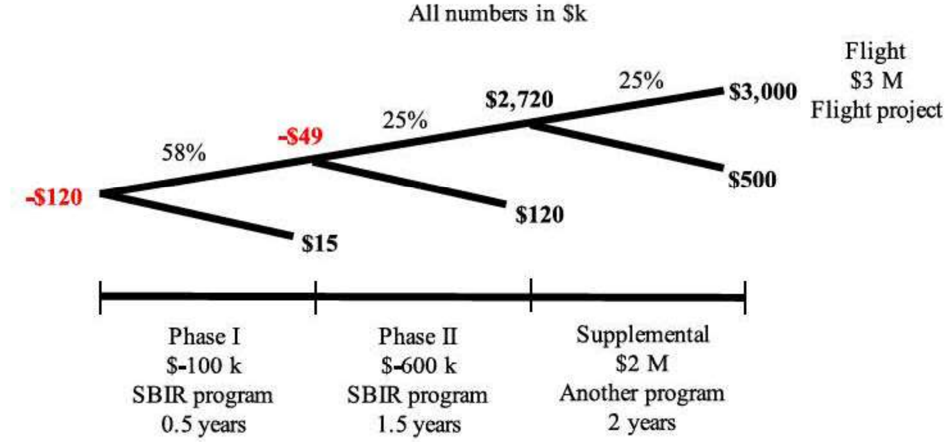

Figure 2. Completed DCF tree (2009 NASA SBIR data).

3.4. Real Options Binomial Tree Approach

Cox, Ross, and Rubenstein developed a model for evaluating options as multiplicative binomial processes [58]; in effect, by adjusting the single-period probabilities and cash flows, future cash flows may be discounted at a risk-free rate. We will use T_i to designate the value of a node using a real options approach, where $T_i^- = S_i^-$; i.e., the liquidation value at each node is equivalent regardless of the specific valuation approach. Therefore, using the new T_i values and the risk-free interest rate r, the risk-neutral probability at each stage (u_i) is given by:

$$u_i = \frac{(1 + r)^{t_i}(S_i - C_i) - S_i^-}{S_{i+1} - S_i^-} \quad (2)$$

After evaluating these risk-neutral probabilities, the procedure of discounting backward through the options tree is repeated to yield the project values at the beginning of each stage, but this time, we use the risk-neutral probabilities and the risk-free interest rate r. In this step we also incorporate the C_i cash flows of each phase and evaluate T_i as follows:

$$T_i = u_i\, T_{i+1}(1 + r)^{-t_i} + (1 - u_i)T_i^-(1 + r)^{-t_i} + C_i \quad (3)$$

Once again, to calculate the current project value at the beginning of each stage, new liquidation values must be evaluated using the stage-specific percentages of Table 2. The resulting T_i values are recorded at the inner nodes of the final real options tree along with the risk-neutral probabilities on their respective branches (Figure 3) to estimate T_1 using the United States Office of Management and Budget five-year maturity rate [59].

The real option tree analysis is shown in Figure 3 and summarized in Table 4. The estimated average project value in the 2009 SBIR portfolio is negative \$166 k. A real options framework allowing for varying risk throughout the project lifecycle suggests that the average project is considerably riskier than our DCF estimate. In other words, a DCF analysis would produce an equivalent negative \$166 k valuation only if the discount rate increases significantly—namely, from 25% to 38%. Furthermore, because it is an input to the RO model, raising the discount rate from the conservative baseline of 25% does not converge simply with the RO analysis; in fact, increasing the WACC widens the discrepancy between the valuations generated by the two models. This suggests that it is difficult to capture the risk dynamics with a simple DCF model.

Figure 4 displays the average portfolio value from 1997 to 2016[1]. We adjust for inflation using the U.S. Bureau of Economic Analysis deflator series [60]. The probability of advancement to Phase II, award sizes, and interest rate vary across years, whereas the cash inflows, time horizons, liquidation values (as a % of project value), and probabilities of advancing to supplemental and flight stages stay constant. The value stays fairly consistent until 2010, decreasing due to increased Phase I and II award sizes from \$100 k to \$125 k and \$600 k to \$750 k, respectively.

3.5. Sensitivity Analysis

We performed a sensitivity analysis to determine the degree of influence of each input on the final project value. Table 5 considers the impact of a 1% relative improvement of each key input parameter. The final column indicates that for the 2009 SBIR program, the most influential drivers are the probability of advancement and the size of supplemental funding, and to a lesser extent the timeline and size of the Phase II award, as well as the WACC. Because of the low probability of success, advancing fewer firms to Phase II increases the portfolio value. The Phase II duration is critical because it takes place so close to the beginning of the process and thus has a higher weight in any NPV-oriented valuation estimate. In this regime of parameter space, WACC estimates have a stronger impact than the risk-free rate of return r. This aligns consistently with a program designed for high-risk (i.e., small, privately held) companies; one can imagine that such a grant program geared toward more established companies might not exhibit the same level of sensitivity toward WACC. The results are generally less sensitive to variations in Phase I parameters.

4. Discussion

This work represents an analysis of a research portfolio in the context of simple real options approaches, with many implications for portfolio and project managers. The results differ from a standard discounted cash flow technique using typical parameters. The impact of the risks' asymmetric and dynamic nature is addressed explicitly through this method, and the results and sensitivity analysis show the nature of skew (only a few successes generate the value of the entire portfolio), similar to Cochrane's analysis in venture capital [61]. While the parameter values may vary from year to year, the behavior of the entire portfolio can be analyzed by viewing a project life cycle through the lens of real options. The portfolio's net value is driven by the small number of projects that achieve the final funding rounds, consistent with the nature of early-stage investing. In this particular case, the federal funding pool P is given by a sum over all funding tranches i for N_i projects with investment of I_i dollars per round:

$$P = \sum_{i=1}^{2} N_i I_i$$

Table 1 indicates a pool P totaling \$163 M; with 364 projects valued at −\$166 k each, the total portfolio is valued at −\$60.5 M. The sensitivity analysis shows the importance of the Phase II award, with duration, award size, and probability strongly impacting the outcome. Later funding rounds also impact the value, but

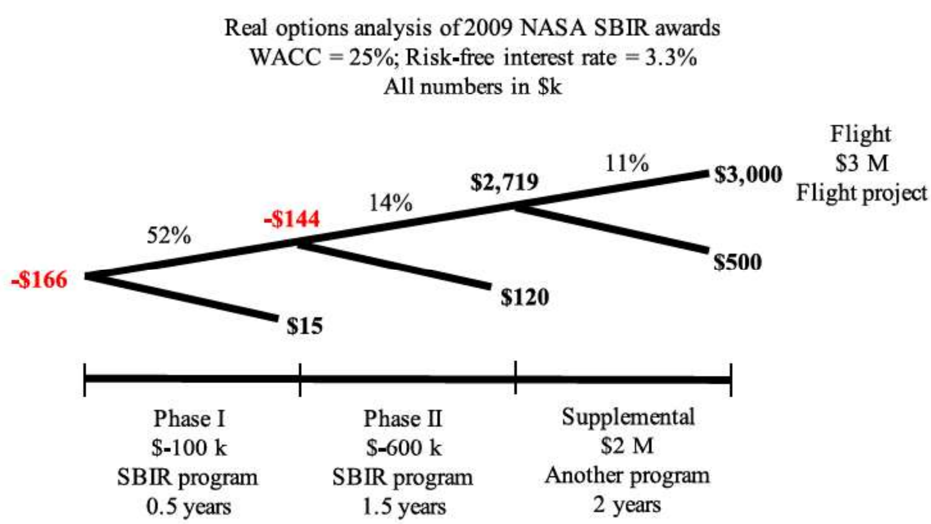

Figure 3. Completed real options tree for 2009 NASA SBIR program.

[1] There was no solicitation in 2013.

other programs fund those stages and thus they are not in control of the program manager. The portfolio manager has several alternatives to increase the portfolio valuation if this is his or her goal.

One important mechanism to increase the project valuation is to accelerate Phase II. Early-stage projects benefit significantly from an accelerated time scale and can quickly be re-assessed for further funding opportunities. Three-month periods matter tremendously for these early-stage development projects (Figure 5). Indeed, this model does not consider the losses incurred by delays in funding and evaluation processes. This consideration affects commercial and subsidized portfolios alike.

The other possibilities pose general challenges in a "mice or men" dilemma—i.e., balancing the resource allocation to a broad set of opportunities in hopes that they will succeed partially, contrasted with concentration in a smaller portfolio of projects in which each has a higher probability of success. For instance, it is possible to restrict further the number of projects proceeding to Phase II, but that would generate fewer recipients by definition. This has important consequences for a technology manager in any organization facing political pressures to prevent a "rich get richer" scenario where only few projects from previously successful recipients are awarded funds. Another option is to adjust the spending by decreasing the Phase II award size because those dollars, invested relatively early, are costly to the portfolio as a whole if the projects do not advance. The potential risk is decreasing the 25% likelihood of uptake by another program because the typical project is now starved and cannot advance as far. This is consistent with studies linking SBIR award size to project success [62].

The project valuation does not consider political or social effects. In a commercial arena, this could represent the organizational impact of having many researchers funded by this program; indeed, a social rate of return was recently estimated as 30-50% for a set of Finnish firms receiving subsidies [63]. The firm response may be nonlinear [64] and the same is likely true of internally funded research and development activities. In both public and corporate settings, the sheer number of awards offers its own political value.

The innovator also faces a real-option problem, with abandoning the project as an alternative. Early-stage firms have been shown to discontinue technology research that fails to attract government funding [50], an alternative that is reasonable if the entrepreneur takes the view of the funding manager and generates estimates of negative valuations. Wallsten suggested that this

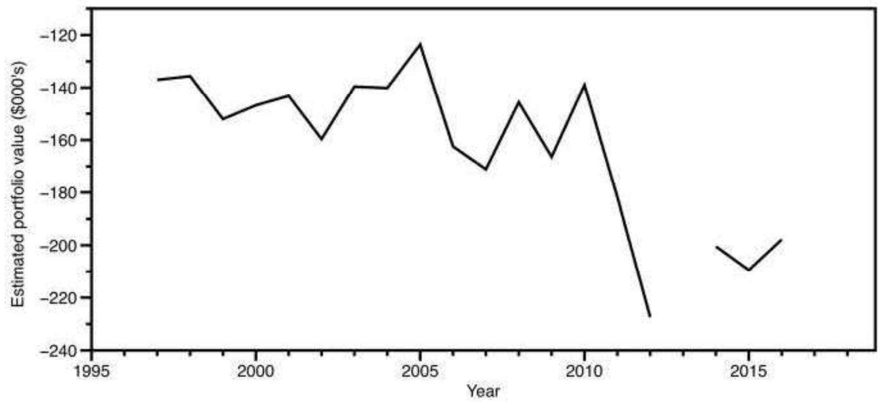

Figure 4. Option valuation for each year's portfolio.

Table 4. Real Options Values of Average NASA SBIR Project for 2009

Item	Value
Risk-free interest rate *r*	3.3%
Number of projects	364
Real options estimated project value	−$166 k

Table 5. Sensitivity Analysis of Real Options Model

Item	Base value	Relative parameter change (%)	Flexed driver	Flexed value	Relative value change (%)
Base ($)				-$166,427	
		Probability of advancement			
Phase II	0.58	−1	0.5742	−$165,603	0.50%
Supplemental	0.25	+1	0.2525	−$164,056	1.42%
Flight	0.25	+1	0.2525	−$165,745	0.41%
		Timelines (years)			
Phase I	0.5	+1	0.505	−$166,327	0.06%
Phase II	1.5	−1	1.485	−$165,091	0.80%
Supplemental	2	−1	1.98	−$165,878	0.33%
		Award size			
Phase I	$100,000	−1	$99,000	−$165,511	0.55%
Phase II	$600,000	−1	$594,000	−$163,105	2.00%
Supplemental	$2,000,000	+1	$2,020,000	−$164,671	1.06%
Flight	$3,000,000	+1	$3,030,000	−$165,609	0.49%
		Liquidation values ($)			
Phase I	$15,000	+1	$15150	−$166,343	0.05%
Phase II	$120,000	−1	$118,800	−$166,172	0.15%
Supplemental	$500,000	+1	$505,000	−$166,018	0.25%
		Discount rate			
WACC	0.25	−1	0.2475	−$164,744	1.01%
Risk-free rate r	0.033	+1	3.333%	−$166,338	0.05%

possibility may manifest with the same signal as a crowding-out effect [12]. The negative valuation suggests that it is unlikely that this subsidy crowds out private funding, instead creating social benefits through the award as well as meeting the returned science goals of the NASA missions. In the commercial context, this is equivalent to investing in early-stage technologies and simultaneously meeting additional strategic objectives, such as providing access to funding for more researchers.

The changing project valuation driven by the duration of Phase II funding is non-trivial to an early-stage technology. In the commercial context, this strongly impacts project value, whereas in the federally subsidized small business, a six-month delay in funding can create a significant cash flow crisis. It is therefore critical to ensure that the funding stages are efficiently managed to provide value to both the funder and the recipient.

For a large company with a strong financial history, the lower WACC will improve the valuation. A secondary effect is that those companies would also likely be less sensitive to changes in the program's structure, both in terms of investment amounts and timing. For those organizations, this approach can provide important visibility into risks associated with "make or buy" decisions involving small companies. Small companies with a higher WACC are subject to more risk. From the public perspective, this analysis indirectly addresses the opportunity cost associated with the SBIR program; the same projects could be managed by larger, established companies with cheaper capital, improving the discount rate.

While the methodology holds, the quality of the estimate is obviously driven by the model's fundamental assumptions. The probability of advancement at each of the later stages of investment was estimated by experts, not calculated. Liquidation values were also approximated and are themselves stochastic, with probability distributions affected by the nature of the specific technology and the quality of the research team.

This analysis points to many future avenues for research. One path would be to study technology evolution on a finer scale by studying the actual technical progress, shedding light on the effectiveness of early-stage technology funding. This could form the basis of an interesting optimization study modestly advancing the entire portfolio compared with advancing a few select projects. This analysis could be repeated in other industries; for instance, portfolios of mission-driven funding agencies, such as the National Institutes of Health, could be analyzed to estimate the impact in the health care sector. Further research could examine the role of the specific technology in attracting private capital; the venture capital industry has skewed strongly toward software in the last twenty years [65], motivating further study of subsidies in manufacturing-oriented sectors.

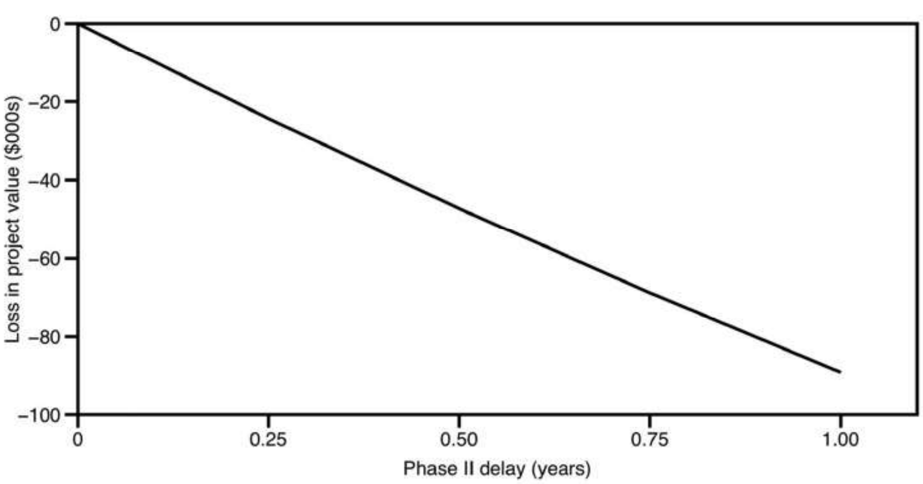

Figure 5. Modeled variation of loss in project value with Phase II duration.

5. Conclusion

In this study, we used a publicly funded portfolio to model a generic staged investment process and created a stochastic model to estimate its value. While similar studies have been conducted in the energy industry, less attention has been paid to the aerospace industry, and thus we illuminate portfolio management in an important and technology-rich sector of the economy. By focusing on early-stage technologies (with low liquidation values at early decision nodes), we shed new light into the forces driving transformation of that sector.

Despite general difficulty in valuing early-stage technology projects, we were able to marry an appropriate valuation structure with validated input parameters to estimate an average value for a project supported by the NASA SBIR program. The methodology exercised here can easily be applied to other innovation programs with structured staged funding. Our analysis indicated that both the conventional DCF approach and a simple stochastic RO method resulted in negative valuation estimates. The RO approach did not require sophisticated mathematics, and the required inputs of success probabilities at each node and project liquidation value can be reasonably well estimated. This approach is powerful to indicate the important drivers in structuring a staged funding program.

The "mice or men" nature of early-stage investing becomes obvious in balancing the desire to spread risk among many projects; the cost of having many projects is explicitly identified here. An important insight is that the two stages of funding did not equally influence the project value; all the structural elements of the later stage—duration, timing, and tranche size—had a stronger impact on project value. This indicates where managers should allocate time and attention. Another critical finding is that this methodology incorporates the liquidation value as the technology advances; this should capture the value added by each funding step and allows for "apples to oranges" comparisons of disparate technologies. Like any method, the RO approach is limited by the accuracy of the inputs; however, a sensitivity analysis conducted in parallel allows for both a qualitative understanding of the portfolio and a quantitative identification of the key drivers.

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