

R&D World: Simulation-Based Analysis of R&D Enterprises

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Abstract

Modern industrial, scientific and military organizations depend heavily on research and development to provide future strategic advantage. Viewed from an input-output perspective, R&D invests resources (funding, people, time) to create value (new products, new capabilities), with the goal of maximizing value in the shortest time possible. Of course, this is challenging, since R&D decision-making is inherently fraught with uncertainty, including uncertain project outcomes and changing market conditions. This paper describes the use of organizational simulation to analyze and improve R&D decision-making. In particular, an options-based framework is used to value R&D projects for purposes of project selection and portfolio management. Specific attention is paid to the problem of allocating funds across a multi-stage R&D process.

Keywords. R&D, project selection, real options, organizational simulation.

1. Introduction

Research and development activities are crucial to the success of many modern enterprises, ranging from corporations, to the military, to scientific concerns. Without successful R&D, an enterprise risks obsolescence of its products, systems and capabilities. Successful R&D can enable future strategic advantage through the deployment of innovative products and systems. In addition, R&D constitutes a significant economic activity, with an estimated \$276.2 billion in U.S. combined government-industry expenditures in 2002 (2.64% of gross domestic product) [13]. The social and economic impacts of these expenditures, while difficult to predict, are likely to be quite large.

R&D typically embodies a multi-stage process, whereby a line of R&D passes through stages such as basic research, exploratory development and then advanced development. In the pharmaceutical industry, for instance, standard R&D stages include discovery, pre-clinical testing and clinical testing (which itself can be divided into three stages) [5, 9]. At each stage, management can decide to continue funding into the next stage, defer funding until the future, or discontinue funding completely. These funding decisions, obviously, have significant impact on the value of output from R&D activities. Traditional approaches to funding R&D use discounted cash flow (DCF) analysis. A growing body of literature suggests that using a real options framework may yield superior results (e.g., [7, 10, 12, 16, 20]). The fundamental reason cited is that options capture the inherent flexibility of this multi-stage process, i.e., ability to discontinue funding at any stage, if the line of R&D loses attractiveness. This is similar, in a call option, to the ability not to exercise the option. DCF assumes all future outlays and revenues in the multi-stage process occur. This is perhaps not attractive in an uncertain environment.

The goal of this research is to understand the effects of valuation methods (options vs. DCF) and budget allocation among R&D stages on R&D enterprise performance. A simulation study is conducted to assess these effects. The remainder of this paper briefly reviews the relevant literature (section 2), describes a simulation model and methodology for analyzing and improving the effectiveness of R&D funding decisions (section 3), presents results of a simulation experiment (section 4), and concludes with thoughts on future research (section 5).

2. R&D Valuation and Real Options

Real options provide an interesting alternative to traditional DCF methods in valuation of R&D projects. Real options are analogous to financial options, except that the underlying asset is not a financial instrument, but rather a "real" asset, such as a product line or system. An option can take the form of a call (option to buy at a later date) or a put (option to sell at a later date). There are variants of each, two primary ones based on whether or not the holder can exercise the option before its expiration date (American vs. European options). Trigeorgis [20] presents a comprehensive discussion of a real options framework in relation to capital budgeting, including R&D. Rouse and

Boff [18] present a set of principles for managing R&D value in this type of framework. The flexibility of options is illustrated in Figure 1.

In the R&D domain, this product line or system exists in the future, not in the present. This phenomenon introduces two types of risk – technical risk and market risk [4]. Technical risk means that the R&D may be unsuccessful. Market risk, on the other hand, means that the result of the R&D, once deployed, may be obsolete or less valuable than anticipated due to competing offerings (or may be more valuable). Amidst this uncertainty, management must be able to value R&D lines, to decide which to fund or discontinue.

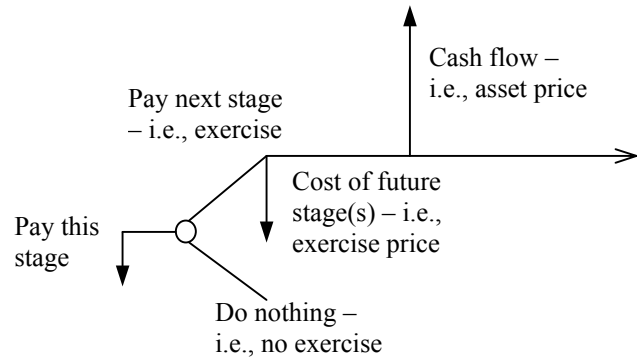


Figure 1. Decision flexibility under real options

This discussion assumes that funding decisions are made using financial criteria. Here, each line of R&D i has n stages, a budget b_{ij} for stage j , a deployment cost $b_{in} = d_i$, a revenue value V_i and an operating cost m_i . Note that V_i and m_i represent post-deployment revenue/cost streams discounted to the time of deployment, and that V_i may represent cost savings instead of pure revenue. At each stage, f_j represents the probability of failure. Valuation under DCF is a straightforward application of discounting future expenditures and cash flows to a net present value (NPV), with failure probabilities included. Under an options approach, the decision to fund a stage of R&D can be modeled as a call option, where the stage budget b_{ij} is the option price, which purchases the right to continue the line of R&D (i.e., exercise at a later stage). The net option value (NOV), then, is computed by subtracting b_{ij} from the option value (which also accounts for f_j). To compute the option value at stage 1 in a system with two stages, the exercise price is b_{i2} , and the asset price is the free cash flow value $V_i - m_i$, discounted to the present. Assuming fixed stage duration, the Black-Scholes method for European options can be used directly [2]. In a system with $n > 2$ stages, the Black-Scholes formulation can be used by framing the option as a commitment for the first $x < n$ stages as purchase of the option, and the remaining $n - x$ stages as exercise [17]. Alternatively, a compound option formula may be used, which expands on the Black-Scholes formulation to value an option on an option [5, 8]. Cox *et al.* [6] present an alternative method for valuating options. Their binomial method assumes a probability at each stage that asset price either increases or decreases by a specific amount, while the Black-Scholes formulations assume that asset price varies over time as a continuous random walk process that is lognormally distributed with volatility v . Of course, real asset values are affected by information flows, which usually are discrete in nature. Pennings and Lint [14] study stochastic jump processes for asset values in multi-media electronics.

R&D activities are constrained by budgets. One goal is to maximize output from R&D activities, subject to this constraint. Typically, the budget is allocated over the stages. This decision is made at the enterprise level, as opposed to the funding decisions for particular R&D lines, which are made at the stage level. In a simple system, budget allocation is analogous to line-balancing. Obviously, under-allocating budget in upstream stages has the effect of starving downstream stages, resulting in unspent downstream funds. Over-allocating funds in upstream stages, on the other hand, results in wasted funding in those stages for projects whose expenses cannot be sustained in later stages. Hansen *et al.* [9] develop a formula for budget allocation that balances allocation according to expected project expenditures at each stage, weighted by the cumulative effect of technical failure.

Most research in real options, including that applied to R&D systems, has focused on techniques to value various types of real options. Little work, if any, has addressed performance assessment of an R&D system that processes numerous lines of R&D lines. This paper describes the use of discrete-event simulation to assess performance under different operating conditions, in particular valuation method and budget allocation among stages.

3. Simulation Model and Methodology

Ultimately, the goal of this research addresses detailed studying of R&D systems for purposes of enterprise improvement and transformation using organizational simulation (i.e., [19]). In particular, this simulation approach is termed "R&D World." This section describes a prototype version of R&D World, implemented to model a simplified multi-stage system. This version models two important R&D system characteristics – project flow through the multi-stage system, and decision-making processes that affect this flow. The goal here is to gain

understanding of fundamental system behaviors prior to using more detailed models. Figure 2 illustrates the system studied, a four-stage system ($n = 4$), with funding decisions at each stage, and the possibility of technical failure.

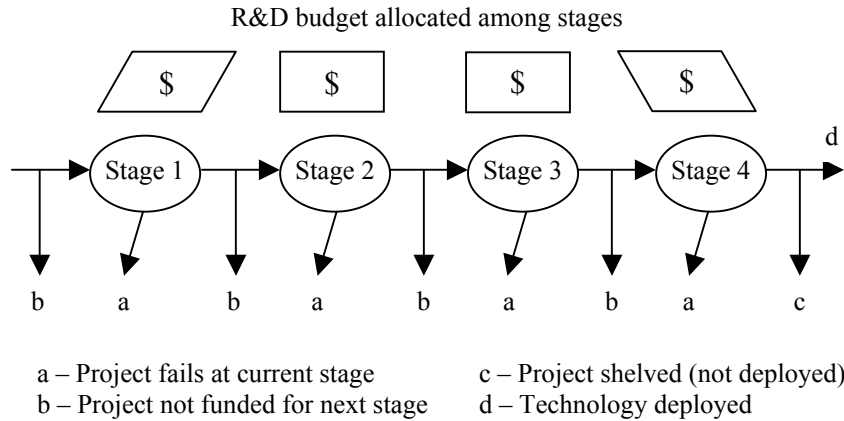


Figure 2. Multi-stage R&D flow

While this system is substantially simplified from a real counterpart, it captures the fundamental nature of R&D as a workflow system, with discrete units of flow (lines of R&D, or projects). As such, it can be modeled with discrete-event simulation, in particular with the process-interaction simulation approach used by most traditional simulation languages. This approach is amenable to modeling flow systems. The caveat here, though, is that complex decision logic is not easily

modeled using the process-interaction approach [11]. In this version of R&D World, the ARENA® simulation package (version 7.01) is used for implementation, due to its ability to model business flow processes. In future models with more complex decision-making, other alternatives will be explored.

Each stage represents one year of R&D, with the last stage representing deployment. Lines of R&D are modeled as entities that arrive to the system, with attributes representing projected cash flows, volatility and technical failure rates. Costs are assumed known in advance, and it is assumed that costs escalate as a project moves forward ($b_{ij} < b_{i,j+1}$). Free cash flow, on the other hand, is assumed to vary lognormally over time, in accordance with the Black-Scholes assumptions. Failure rates are assumed to decrease with increasing stage ($f_j > f_{j+1}$). The annual interest rate r is assumed to be the risk-free rate (needed for the Black-Scholes computations) and the discount rate (needed for DCF computations). Studying the effect of a higher discount rate is an avenue of further research.

R&D lines arrive to the first stage as proposed projects. All those arriving in a particular year are held prior to entering. Likewise, any lines arriving to stage $j+1$ from j in a year are held before entering $j+1$. Here, they are valued, via NPV or NOV. Under NOV, the Black-Scholes method is used. This method involves computing the cumulative distribution function for a standard normal, which is implemented using a numeric approximation [1]. The option is framed by using the next stage as the option purchase, with the remaining stages as exercise. Since each stage has an annual budget, the project selection problem is a knapsack problem, which is NP-hard [14]. In the simulation, selection is done via the well-known heuristic of ranking the R&D lines by descending ratio of value (NPV or NOV) to cost (stage cost). Those selected move to the next stage. Those not selected are discarded.

At the enterprise level, the annual R&D budget is fixed, with the assumptions of (i) no inflation, and (ii) no R&D growth from increased earnings. Budget allocation among stages is static, as well. Unspent funds are not carried over to the next year. Two types of performance metrics are of interest. The primary metric is total deployed value (TDV) over time horizon T . This is measured by summing free cash flow at deployment time ($V_i - m_i$) over all R&D lines i deployed during T . This metric assumes that R&D expenditures are sunk costs. In computing TDV, revenues are realized instantaneously if deployment is successful. The second is yield (Y), computed as total deployed value per dollar of expenditures during T .

4. Experiment and Results

Using the simulation model, an experiment was conducted to determine the effect of valuation method and budget allocation. The simulation was run for a warm-up period of five years to achieve steady-state behavior, and then for a twenty-five year period (T), during which statistics were collected. Ten replications of each run were conducted. The goal is to maximize TDV. Parameters for the R&D system parameters are shown in Table 1. It should be noted that the initial estimate of free cash flow is derived by discounting the annual series C_i . This is the annual cash flow from the deployed project and lasts for six years after deployment.

Table 1. System parameters

Parameter	Value/Description	Parameter	Value/Description
Number of entering projects per year t	$N_t \sim \text{Tria}(30, 60, 90)$	Annual R&D budget	\$500 (in millions)
Project cost at each stage (b_{ij}) and avg. project cost at each stage (b_j)	$b_{i1} \sim \text{Unif}(0.5b_1, 1.5b_1)$; $b_1 = 3$; $b_j = \frac{1}{2}b_{j+1}$, $j \leq 1,2,3$; $b_{ij} = \frac{1}{2}b_{i,j+1}$, $\forall i, j \leq 1,2,3$	Annual interest rate (r)	8%
Initial est. project cash flow (annual amount C_i)	$C_i \sim \text{Unif}(0.5C, 1.5C)$; C is an exp. factor	Technical failure rates at each stage (f_j)	$f_1 = 0.4, f_2 = 0.2, f_3 = 0.1, f_4 = 0.05$

In addition to the valuation method (NPV vs. NOV), the experiment looks at three different factors, to determine their effect on performance:

- *Negativity of initial NPV.* In many successfully deployed R&D projects, initial NPV can be negative (e.g., see case studies in [10, 15, 16]). What is the effect of the magnitude of $P(\text{NPV}_i < 0)$ of the entering stream of R&D lines? Two levels are explored (L = 33% and H = 50%). These are determined by varying C in the initial NPV computation, which is the convolution of two uniformly distributed random variables (annual cash flow C_i and stage one cost b_{i1}). Here, C for level L is 15.57; whereas for level H it is 12.95.
- *Volatility.* What is the effect of the level of volatility v , or the variability in asset price over time as an R&D line progresses through its stages? Two levels are explored (L = 20% and H = 60%).
- *Budget allocation among stages.* The line-balancing method [9] accounts for technical risk, but not market risk. With the presence of market risk, what is the effect of differing allocations? Three levels are studied. The baseline allocation is computed using Equation 1 (derived from [9]). P_j = percentage of enterprise budget devoted to stage j . Here, P_j is proportional to the expected budget request at stage j , and inversely proportional to the success rates of current/future stages. Utilizing parameters for expected project budgets and failure rates, the baseline allocation (M) is $\mathbf{P}_M = [0.132, 0.1584, 0.2534, 0.4562]$. Letting $P_1 = \mathbf{P}_M = 0.132$ and $\Delta = [0.5P_1, 0.25P_1, -0.25P_1, -0.5P_1]$, the first alternate allocation (L) is derived as $\mathbf{P}_L = \mathbf{P}_M - \Delta$, and the second alternate allocation (H) is $\mathbf{P}_H = \mathbf{P}_M + \Delta$. Thus, $\mathbf{P}_L = [0.066, 0.1254, 0.2864, 0.5222]$, and $\mathbf{P}_H = [0.198, 0.1914, 0.2204, 0.3902]$. \mathbf{P}_L shifts funding downstream, while \mathbf{P}_H shifts it upstream.

$$P_j = \left(b_j / \prod_{k=j}^n (1 - f_k) \right) / \sum_{l=1}^n \left(b_l / \prod_{m=l}^n (1 - f_m) \right) \quad (1)$$

Summary data obtained from the experiment are shown in Table 2. The first column under each budget allocation level reflects the total value deployed over T , averaged over ten replications. The second column represents yield, similarly averaged over ten replications. Average total expenditures can be obtained by dividing TDV by Y .

Table 2. Summary experimental data

	Budget Allocation L		Budget Allocation M		Budget Allocation H	
	Average TDV	Average Y	Average TDV	Average Y	Average TDV	Average Y
DCF-L-L*	13,689.85	2.24	21,084.67	1.91	20,501.59	1.77
DCF-H-L	11,412.29	1.90	17,162.43	1.63	16,149.03	1.53
DCF-L-H	12,997.46	2.55	20,662.09	2.24	24,214.06	2.21
DCF-H-H	9,837.95	2.13	15,155.27	1.92	16,799.31	1.93
OPT-L-L	13,674.22	2.23	21,092.44	1.92	20,099.98	1.72
OPT-H-L	11,502.80	1.90	17,518.85	1.64	16,622.20	1.53
OPT-L-H	11,944.10	2.30	20,045.68	2.15	24,430.80	2.16
OPT-H-H	10,813.94	2.21	16,783.27	1.92	19,050.93	1.79

* First entry is DCF vs. options; second is level of NPV negativity; third is level of volatility.

Clearly, outcomes from allocation L are significantly different than those from the others. Under L, budgeted funds are not fully expended. The average expenditure during T , in fact, is \$5,513, compared to full expenditure of

\$12,500 (\$500 per year over 25 years). Clearly, downstream stages are starved by L's reduced upstream funding. Budget is much closer to being expended fully under allocations M and H (\$9,802 under M and \$10,788 under H). Therefore, the budget allocation L is not considered in this analysis. Since this paper concentrates on TDV as an output measure, TDV is the response variable in the analysis of variance. While the effect of factors on Y is of interest, it is discussed more fully in [3]. This leaves a 2⁴ factorial experiment for analysis. The ANOVA, using Minitab® 14, is shown in Table 3. Only those three-factor interaction effects significant at $p < 0.1$ are included.

Table 3. ANOVA

Source	DF	SS	MS	F	p
Valuation method (A)	1	9,583,039	9,583,039	3.35	0.069
NPV negativity (B)	1	850,546,261	850,546,261	297.43	0.000
Volatility (C)	1	29,844,117	29,844,117	10.44	0.002
Allocation (D)	1	43,714,488	43,714,488	15.29	0.000
A*B	1	18,924,955	18,924,955	6.62	0.011
A*C	1	5,791,963	5,791,963	2.03	0.157
A*D	1	846,993	846,993	0.30	0.587
B*C	1	24,317,907	24,317,907	8.50	0.004
B*D	1	11,880,499	11,880,499	4.15	0.043
C*D	1	146,964,391	146,964,391	51.39	0.000
B*C*D	1	8,514,094	8,514,094	2.98	0.087
Error	148	423,227,004	2,859,642		

Interestingly, most main effects and two-factor interaction effects are significant. For valuation and budget allocation decision-making, the following conclusions are drawn from this analysis (for more detail, see [3]).

- In general, the options valuation method (A) outperforms a DCF approach. However, the interaction effect between valuation method and NPV negativity (A*B) shows that options outperform DCF in an environment with high probability of negative initial NPV. This confirms results in the literature that describe successful R&D projects with initially negative NPV.
- As expected, the negativity of initial NPV (B) has a dramatic effect on total deployed value, as a higher negativity reduces TDV. The interest here, though, is on its interaction effect with other factors.
- The budget allocation effect (D) shows that a policy of allocating more funds upstream outperforms a policy of line-balancing, and the volatility effect (C) shows that increased volatility improves TDV. Moreover, allocation and volatility (C*D) have a significant interaction effect. With high volatility, budget allocation H performs better, whereas allocation M performs better with low volatility. Market risk, as represented by volatility, plays a key role in budget allocation decisions. It is better to invest funds in a portfolio of upstream possibilities that may create value downstream; if they do not, then they can be terminated at a later stage. This is likely sensitive to the ratio of project budgets at each stage.
- Although the A*C interaction is not strong, it does provide some evidence that options perform better than DCF under high volatility.
- The NPV negativity and allocation interaction (B*D) shows that, while allocation H outperforms M in both NPV negativity levels, the difference is more pronounced when initial negativity is low.
- A mild interaction exists between NPV negativity, volatility and budget allocation (B*C*D). For allocation H, R&D systems with high volatility outperform those with low volatility, with the effect being more pronounced when NPV negativity is low. The opposite is true for budget allocation M, although for M the volatility effect is small.

5. Discussion and Future Directions

This paper has demonstrated a number of interesting results for multi-stage R&D systems in relation to valuation method and budgeting policy, as well as system characteristics such as volatility and initial NPV. Currently, a simplified R&D system is modeled to gain insight into fundamental system behaviors. The insights gained here hopefully generalize to more complex systems. Future research involves modeling more complex and realistic systems to ascertain this, as well as to identify additional system elements that impact R&D value. In addition, more

complex decision logic needs to be implemented in the R&D World models, including compound options, options other than pure call options (e.g., defer option), and managerial heuristics (e.g., managing end-of-year spending). Such complex decision logic, especially human decision-making, requires more sophisticated use of organizational simulation modeling. As this research moves forward, the following questions are of interest:

- What is the effect of multi-year stages, with out-year budget commitments? What is the best way to make and manage such commitments?
- This system assumes that project budgets double as an R&D line moves to the next stage. What is the effect of other ratios? What is the best ratio as a function of other factors?
- What is the response surface for the budget allocation decision as a function of other factors?
- What is the effect of modeling a different distributional form of free cash flow variation (including jumps)?
- What is the effect of more complex R&D lines (e.g., lines that start in stage j using technology or patents purchased elsewhere, lines that join at stage j to move forward as a single line, etc.)?

Acknowledgments

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