Proceedings of the 2005 Winter Simulation Conference
M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, eds.

USING SIMULATION TO ANALYZE R&D VALUE CREATION

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ABSTRACT

As the front-end to product and system lifecycles, research and development activities serve as engines of value creation. By nature, though, R&D involves significant uncertainty. As such, it often is viewed as an investment problem, whereby funds are invested in ventures under risk, with the hope of achieving future value. This paper investigates the use of organizational simulation to analyze the R&D investment problem, focusing on ways to increase value created from R&D. Based on a process-focused model of R&D systems, initial results indicate that using a real options framework to valuate R&D outperforms traditional discounted cash flow (DCF) methods in total value created, but that DCF methods are preferred for return on R&D investment. To complement the process-focused R&D system model, a product-focused model of R&D is specified and integrated with the process-focused model.

1 INTRODUCTION

By nature, research and development activities have highly uncertain outcomes. Yet R&D is crucial to the success of many corporate and government enterprises. Thus, there is strong motivation to manage risk, while at the same time maximize the future payoff from R&D in terms of value created for the enterprise.

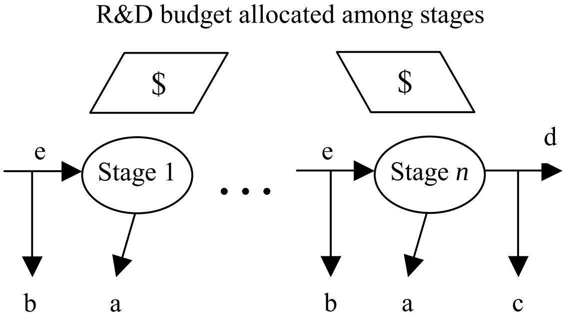
One way to approach this problem is to identify value levers, i.e., those factors that can be manipulated to improve value creation, while at the same time mitigate risk. This paper describes research aimed at identifying and quantifying such value levers. Here, value levers are studied from an enterprise perspective, rather than from the perspective of individual R&D projects. That is, the study of value levers focuses on organizational processes and strategies that enable or facilitate value creation, rather than on best practices in conducting an R&D project. Thus, one useful method in studying value levers is the emerging method of organizational simulation (Rouse and Boff 2005). Organizational simulation draws on the traditional strengths of simulation in analysis of systems with significant risk and uncertainty, but also incorporates advanced decision logic, human interaction and (at its most developed stages) immersive environments.

This paper presents initial work in using organizational simulation models to study value creation in R&D enterprises. The remainder of this paper is organized as follows. Section 2 frames the value creation problem. Section 3 describes a simulation-based approach to addressing the problem and summarizes previous results focusing on the effect of investment valuation and budget allocation methods on total value created. Section 4 presents results focusing on the effect of these potential value levers on total value created per investment dollar. These results are based on a process-focused R&D model; therefore, Section 5 presents an extended model that incorporates a product-focus in its representations. Finally, Section 6 concludes with thoughts on future research.

2 R&D VALUE CREATION

R&D is intended to create future value for an enterprise through innovation, or possibly through transformation. This is accomplished through a staged set of investments, i.e., funding of R&D activities. From this perspective, R&D is a multi-stage investment problem, distinguished by a downstream value payoff from deployment of the R&D results. This research assumes quantitative value that can be in the form of revenue or coast savings. Figure 1 illustrates the multi-stage R&D investment problem.

Obviously, the staged nature of the R&D process mitigates risk. Those lines of R&D that prove unsuccessful can be terminated in early stages, ending prospects of a major financial commitment. This nature of R&D lends itself to conceptualizing R&D activities as real options, similar to financial options (Faulkner 1996, Myers 1984). Funding of an early stage of R&D is analogous to purchasing the right (i.e., option) to continue future work, eventually resulting (hopefully) in a deployed asset. These authors, and others (e.g., Herath and Park 1999, Trigeorgis 1996), argue that computing a project's value using a real options approach is superior to using the more traditional discounted cash flow approach because the options model captures the flexibility inherent in staged investments. While real options may be a superior method for measuring value, this paper studies its effectiveness as a value lever, in the sense that its use may increase the amount of value created by the enterprise over a time horizon, as compared to using discounted cash flow methods.



a – Project fails at current stage
b – Project not funded for next stage
c – Project shelved (not deployed)
d – Technology deployed
e – R&D investment point

Figure 1: Multi-Stage R&D System

In a multi-stage R&D enterprise, the overall R&D budget is allocated over the various stages, and within stages, among technical program areas. Hansen, Weiss, and Kwak (1999) present an approach analogous to line-balancing, in which allocations are proportioned according to expected budget requests at each stage, factoring in the effect of failure at each stage. This approach does not account for market or application risk, though. Budget allocation then is another potential value lever.

Portfolio management is potential value lever that incorporates valuation plus risk measurement. Often, this problem is framed as seeking to maximize value, subject to a certain level of risk (or vice versa). Portfolio management has been addressed extensively in the research literature. Methods include simulation-optimization (Cobb and Charnes 2003), data envelopment analysis (Linton, Walsh, and Morabito 2002), efficient frontier analysis using risk-reward (Graves, Ringuest, and Case 2000), and dynamic programming (Childs and Triantis 1999).

Value levers can be distinguished by their relation to enterprise operation vs. enterprise design. The preceding value levers relate mainly to operation. Enterprise design yields its own set of value levers. When manipulated, these levers tend to be transformative in nature. DeSanctis, Glass, and Ensing (2002) study organizational design for corporate research, particularly the conflict between centralized vs. decentralized R&D. Based on empirical studies, they categorize the conditions under which various organizational designs promote the best value creation. Other potential design-related value levers include setting the number of R&D stages, defining the programmatic mix of technical areas, and outsourcing of R&D activities.

To date, simulation has been used mainly in the area of valuation, especially for computation of option values. Here, analytic expressions are available for a limited set of options computations, such as the European call option. This option features a set exercise date, and the Black-Scholes method, for example, can be used to determine its value (Black and Scholes 1973). Monte Carlo simulation is used when the option value cannot be computed analytically (e.g., Boyle, Broadie, and Glasserman 1997). This may occur when the option structure is not amenable to analytic computation, or when the option situation does not conform to the assumptions needed by an analytic method. This second situation is of concern when real options are studied, as opposed to financial options, since real options may not conform completely to the assumptions used in deriving analytic results for financial options, e.g., complete markets and no arbitrage, random walk process for asset variability, etc. (Lander and Pinches 1998).

To date, little research has used simulation to study the overall value creation problem. This research uses discrete-event simulation to identify and quantify value levers in R&D enterprises.

3 SIMULATION USING R&D WORLD

This research seeks to create high-fidelity models of R&D enterprises to study value creation (i.e., R&D World). As an initial effort, a prototype simulation environment has been developed, using ARENA® 7.01. It is a relatively simple flow model designed to exhibit fundamental multi-stage R&D investment system behavior; it is focused on R&D process behavior.

This model has four stages, with the fourth stage being deployment. Stages are modeled as delays, with each stage lasting one year. R&D projects are modeled as entities that arrive to the first stage, and then pass through remaining stages, subject to a probabilistic failure rate at each stage (which decreases with succeeding stages), and to a selection process based on an annual budget constraint for that stage. Each project is, in effect, a line of R&D. It has a budget request for each stage, which increases by a factor of two in each succeeding stage (average request for stage one is 3). Each line of R&D is associated with a future estimated free cash flow associated with its deployment. This is assumed to vary lognormally as a random walk process with volatility *v*, in accordance with assumptions underlying the Black-Scholes method. The interest rate used is 8%.

All proposed projects arriving to a stage within a year are selected from the same budget (average of 60 arriving projects to stage one). The budget at each stage is a fixed percentage of the overall enterprise R&D budget (500). The project selection problem at each stage is posed as a knapsack problem, where item value is computed using a specified method that accounts for (i) current estimated free cash flow, (ii) future budget requests, and (iii) future failure probabilities. The knapsack item cost is the budget request for that stage. The simulation heuristically selects projects based on the ratio of item value to item cost.

Figure 2 depicts the flow of R&D projects through a stage. First, the valuation is computed, using a method selected by the analyst. If the value minus the budget request for the stage is not positive, the project is discarded. Otherwise, it is held until a signal is received from the budget cycle process releasing all projects to be considered in that cycle. Projects are ordered by ratio of value to budget request, and selected if the remaining budget allows the request to be funded. The budget is decreased by the amount of a selected project, and selected projects are sent to R&D. Once finished, projects either succeed or fail based on a failure rate. In the final stage, the estimated free cash flow is realized after successful deployment.

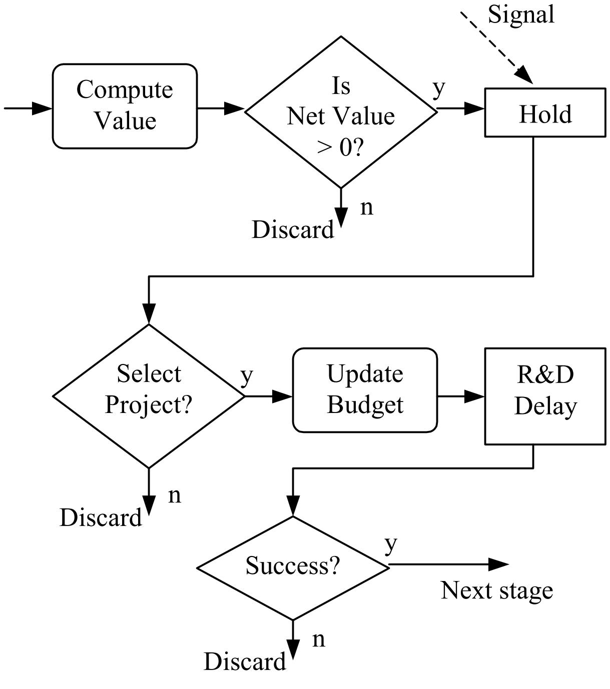


Figure 2: R&D Project Flow through a Stage

This model has been used to study the effect of investment valuation methods and budget allocation across stages on total value created (dependent variable). Total value created *V* is the sum of the value of all deployed R&D lines at the time of their deployment, over a time horizon. Detailed results, as well as further details about the model, are presented in (Bodner and Rouse 2005). These results are summarized in this section. Below is a description of the experimental factors.

- Factor A: The valuation methods studied are net present value using discounted cash flows (factoring in failure probabilities) and real options, framing the next stage as option purchase (i.e., a call option) and the succeeding stages as exercise.
- Factor D: The budget allocation alternatives studied are the line-balancing approach (Hansen, Weiss, and Kwak 1999), considered as the low level, and an alternative that shifts funding upstream, considered as the high level. The low alterative, in the form of percentages, is [13.2, 15.84, 25.34, 45.62], and the high alternative is [19.8, 19.14, 22.04, 39.02].

Additional factors studied include the probability of initial negativity of net present value (factor B, low of 0.33 vs. high of 0.50) the volatility of the asset price (factor C, low of 0.20 vs. high of 0.60). High levels of volatility imply potentially higher upside to increases in estimated free cash flow. Initial NPV negativity is relevant because financials of R&D projects in early stages often evaluate to negative NPV values (e.g., Herath and Park 1999).

This results in a 2^4 factorial experimental design. Overall, ten replications of the each combination of factors were run, with each replication lasting a time horizon *T* of 25 years (after a five year warm-up period to reach steady-state behavior). Conclusions from this experiment include the following:

- Valuating R&D using real options outperforms valuating it using DCF, since more value is created over the time horizon when real options are used. There is a strong interaction effect with initial net present value negativity, whereby options perform much better in environments with high initial NPV negativity. There is a similar, though weaker, interaction effect with volatility, whereby options perform relatively better in high levels of volatility.
- In general, the budget allocation shifting funds upstream (high) outperforms the line-balancing approach. There is a strong interaction effect with volatility whereby this effect is relatively increased with high volatility. There is a weaker interaction effect with NPV negativity, except that

the budget allocation effect is relatively larger with low initial probability of negative NPV. Allocating additional funds upstream appears to promote value creation by providing a better portfolio of projects that can be selected for downstream development and deployment.

4 TOTAL VALUE VS. YIELD

One view of R&D is that value creation should be maximized using the available budget as a constraint. As seen in the previous section, real options tend to perform better in this regard than DCF. Another viewpoint is that value creation should be managed so as to maximize return on R&D investment. The experiment also can be analyzed using yield as the dependent variable, where yield Y is the total value created per dollar of R&D expended over a time horizon. Table 1 shows experimental results for yield, taken from the same experiment using time horizon T. The figures are averaged over the ten replications. The experimental runs are denoted in the form of factor order A-B-C-D. The table also shows the average total value created and the average percentage of budget expended for each run. It should be noted that, in the spirit of illustrating fundamental behaviors, there is no advanced decision logic to "spend out" budgets.

Table 1: Summary Experimental Results

Run	*V*	*Y*	% Budget
DCF-L-L-L	21,084.67	1.91	88.4
DCF-L-L-H	20,501.59	1.77	92.8
DCF-L-H-L	20,662.09	2.24	73.6
DCF-L-H-H	24,214.06	2.21	87.5
DCF-H-L-L	17,162.43	1.63	84.1
DCF-H-L-H	16,149.03	1.53	84.4
DCF-H-H-L	15,155.27	1.92	62.8
DCF-H-H-H	16,799.31	1.93	69.6
OPT-L-L-L	21,092.44	1.92	88.1
OPT-L-L-H	20,099.98	1.72	93.6
OPT-L-H-L	20,045.68	2.15	74.5
OPT-L-H-H	24,430.80	2.16	90.3
OPT-H-L-L	17,518.85	1.64	85.6
OPT-H-L-H	16,622.20	1.53	86.8
OPT-H-H-L	16,783.27	1.92	69.6
OPT-H-H-H	19,050.93	1.79	85.2

The analysis of variance is shown in Table 2. Minitab® 14 is used for the analysis. Three-factor interactions are not included since none are significant at $p \leq 0.10$.

The following conclusions result from the analysis of variance in terms of yield.

- Here, DCF outperforms real options, with $p = 0.094$ (factor A). This result is an interesting contrast with that from the analysis using total value created. Fundamentally, DCF appears more conservative than options. Options seem to facilitate total value created when presented with a budget constraint, while DCF seems to emphasize return on R&D investment. The conservatism of DCF is further reinforced with analysis of the percent of budget expended. Under options, the average across the eight runs (ten replications) is 84.2%; whereas under DCF, the average percent is 80.4%. Using a paired t-test, the difference between the two is statistically significant with $p \approx 0.00$.
- The line-balancing budget allocation outperforms the other allocation (factor D). This is explained further by the interaction effect with volatility (C*D). The main effect is due mostly to low volatility; under high levels of volatility, there is little difference between allocations. Without high volatility (market risk), the line-balancing approach is appropriate.

Table 2: ANOVA

Source	DF	SS	MS	*F*	*p*
A	1	0.06182	0.06182	2.84	0.094
B	1	2.99373	2.99373	137.58	0.000
C	1	4.53471	4.53471	208.40	0.000
D	1	0.30566	0.30566	14.05	0.000
A*B	1	0.00124	0.00124	0.06	0.811
A*C	1	0.03538	0.03538	1.63	0.204
A*D	1	0.01570	0.01570	0.72	0.397
B*C	1	0.03573	0.03573	1.64	0.202
B*D	1	0.00024	0.00024	0.01	0.917
C*D	1	0.09617	0.09617	4.42	0.037
Error	149	3.24219	0.02176		

These results are based on a relatively simple model of R&D projects and results, and are intended to illustrate fundamental multi-stage R&D behavior and resulting insights. While this model may be applicable to such domains as the pharmaceutical industry, where each experimental drug can be a line of research that proceeds through each stage, other domains may require more complex models, for example ones that allow two R&D lines to be components that feed into another downstream line.

5 EXTENDED MODEL

Enhancements to the prototype version of R&D World have followed two lines. First are enhancements to the model of R&D processes. These are in the form of more advanced and realistic decision logic.

- A basic capability for management of out-year budget commitments has been implemented. Often, R&D stages exceed budget year cycles in duration. Thus, an R&D manager would need to commit funds past the current budget year, when budgets for future years may be uncertain. Management of these commitments is important in terms of value creation and risk mitigation. The current model allows a project to have up to three years, with a cost for each year. The ARENA model tracks the current year's budget and current expenditures from that budget. In addition, it computes estimated budgets for the next two years, and tracks commitments from the estimated budgets resulting from funded projects. Various methods to forecast estimated budgets and to manage commitments can be tested to prove their effectiveness.

- A basic capability to handle unfunded priorities has been implemented. Year-end funds often are spent to fund borderline promising projects not funded in the regular budget cycle, especially if there is more than one review cycle per budget cycle. Unfunded projects from each review cycle are kept in a HOLD block and released at the end of the budget cycle. If any funding remains, projects can be selected in the same manner as those during the regular review cycles. Whether to leave year-end funds specifically for this purpose, and how much to leave, are interesting questions for value creation and risk mitigation.

The second type of enhancement focuses on the representation of the results of R&D, i.e., R&D "products" or "assets." In this context, the term R&D "product" or "asset" can be considered as the result (or planned result) of some stage of R&D, as opposed to a consumer product that may be deployed into the marketplace based on R&D. To reinforce this distinction, the term "RDP" is used here for R&D product. A finished RDP may be at a stage where it can be deployed, or where it can be used as a component in a future R&D effort. Of course, this product model must account for "work-in-process" and planned/proposed R&D (i.e., R&D projects). This conceptualization is based on the notion of value streams, as defined in (Rouse and Boff 2003).

This representation addresses the following R&D product characteristics:

- Different types of RDPs (e.g., technical reports, patents, technologies, prototype systems or prototype consumer products);
- Different status possibilities for RDPs (e.g., planned, proposed for funding, in-progress, available, retired);
- Different generations of an RDP, caused by evolving technology;
- Precedence relationships between different R&D products (e.g., one RDP may be a component required for another RDP to be developed at a future stage);
- Interactions between RDPs (e.g., mutual exclusivity);
- A value network that incorporates RDPs in various stages and their precedence relationships; and
- Changes to the value network during model execution (e.g., failure or success of an R&D project, a new planned RDP in response to a competitive threat).

Figure 3 shows example precedence relationships in a value network. Nodes represent R&D products. In the figure, shape indicates node type (e.g., a technology or a sub-system). Color indicates status (e.g., gray indicates proposed for funding, while white indicates planned). Gates represent complex precedence relationships. An AND gate denotes that all preceding nodes are prerequisite, while an OR gate denotes that one of the preceding nodes is prerequisite. The notion of technology generations is represented, as well.

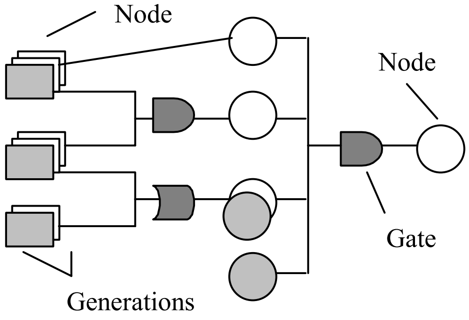


Figure 3: Example RDP Precedence Relationships

From an investment perspective, the notion of precedence relationships is appealing, because it identifies the opportunities for investment and the downstream value enabled by each opportunity. An opportunity may have more than one downstream value possibility. Using this representation, the value for each opportunity (or combination of opportunities) can be computed, using a discounted cash flow or options-based approach, for example.

Consider an investment decision where three candidate projects are available, any one of which is sufficient prerequisite for the following stage of R&D. This precedence relationship consists of an OR gate. Management may want to invest only in the RDP most likely to be successful, or most likely to bring largest value. On the other hand, management may want to hedge its bets and invest in multiple RDPs, with the option to terminate the others if one proves successful first. Consider the example data in

Table 3, representing three such investment alternatives, with the expected payoff from the enabled RDP as 100. The NPV is computed without time value of money. At first glance, alternative 1 is most attractive. Since these are not mutually exclusive, one could invest in alternatives 1 and 2. Even without an early termination option, this is more attractive than alternative 1, with a value of 62.

Table 3: Example OR Gate Investments

Alternative	**Cost**	**Failure Rate**	**NPV**
1	20	0.20	60
2	10	0.40	50
3	25	0.30	45

The OR gate relationship can also be used to represent the outcome of a call for proposals (the desired planned RDP), which generates a number of proposed-for-funding RDPs, from which one or more may be selected, depending on budget.

Clearly, the value network representation requires a relatively complex data model, for which the process-interaction formalism underlying ARENA, including global variables and attributes, is not well-suited. A generic relational model has been formulated to address these needs. This initial relational model contains the tables shown in Figure 4. The table `RDPs` provides data on each RDP, with its type, technical area, generation, status, estimated cost per year, estimated duration (if planned or proposed for funding) and estimated free cash flow value (if it is deployable). In an enterprise with project-specific volatilities, the RDP may have an individual volatility, as opposed to a common volatility for all projects. The table `Gates` details which type of gate is used (AND, OR or none). Here, "none" means that there is a simple one-to-one precedence relationship. The table `Parent-Child` is used to relate each pair of RDPs that have a precedence relationship. It includes a reference to the gate that links the two RDPs. The "parent" RDP is downstream and relies on the "child" RDP's completion. Each of these three tables contains only numeric data, consistent with ARENA's ability to handle only numeric values.

The remaining tables provide semantic meaning for various numeric values. For example, a numeric value of 2 for Status in the `RDPs` table means "Proposed for Funding." Thus, the Status_Types table has an entry [2, "Proposed for Funding"]. These semantic values can provide customization for application in particular domains or industries (e.g., technical areas).

This model can be implemented using most relational database management systems. The current RDP model is implemented using Microsoft® Access, since the existing ARENA models can read/write to Access. The ARENA model captures the structure of the R&D enterprise, with its business processes and decision points, and it captures the dynamic behavior of R&D projects as they move through various stages. The Access database, on the other hand, captures the less dynamic structure of the current RDP portfolio, which includes developed results, and downstream value possibilities. The interaction between the two is provided via ARENA's ability to read/write to Access using Microsoft ActiveX® Data Objects (ADO) technology, which allows SQL queries to a database. A query is embedded in a RECORDSET dataset within an ARENA FILE module. Each RECORDSET has a query for a particular table in the database file reference by its FILE module.

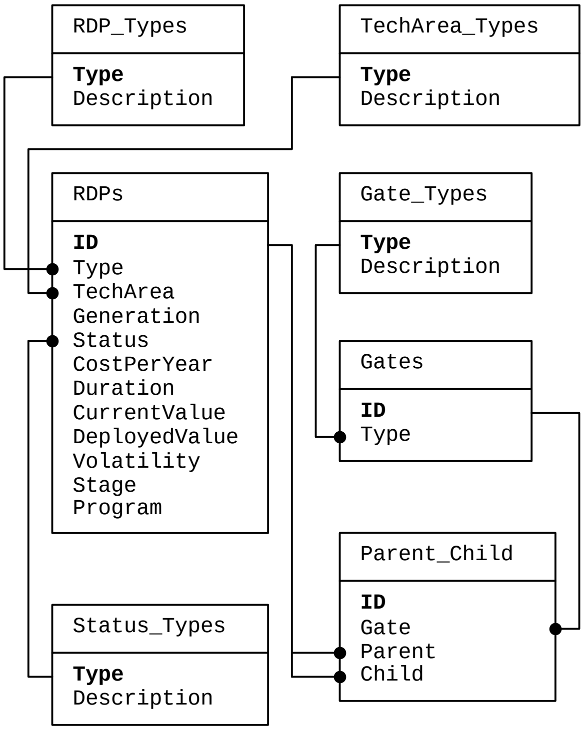


Figure 4: Relational R&D Product Model

For example, one might initialize a simulation model run with an existing value network, stored in the value network database (ValNetDB). ARENA would need to read entries from the table `RDPs`, and create entities for proposed projects. An entity can be created that loops through an ARENA READ block using a FILE RECORDSET that reads sequentially through the table RDPs (using ARENA's ability to read Access tables directly, rather than ADO in this case). If the status is proposed for funding, the entity is sent through a SEPARATE block to create a new project entity to be sent to the R&D process model, and the original entity returns to loop through the READ block to retrieve the next record. If the status is not proposed for funding, the original entity simply returns to the READ block.

Alternatively, when an R&D project (for example, the RDP with ID 21) finishes a stage successfully in the simulation model, its representation in the ValNetDB needs to be updated. That is, the Status field within the `RDPs` table needs to be changed from in-process to available. This can be accomplished by using a WRITE block that invokes a RECORDSET with the following query, and passes a new value for Status to be written to the returned record:

```
SELECT RDPs.[Status] FROM [RDPs] WHERE ID=21.
```

Given an RDP that is proposed for funding, it is useful to be able to compute its value. One factor needed is the value of downstream, planned RDPs. Assuming only one downstream RDP to simplify the query, and an ID = 5 for the proposed RDP, the value can be obtained from a READ block that invokes a RECORDSET with the following query:

```
SELECT Value FROM RDPs WHERE ID = (SELECT
PARENT FROM PARENT_CHILD WHERE CHILD = 5).
```

One frequent phenomenon in R&D enterprises occurs when market pressures force an enterprise to start development of a new system or product to be deployed. This may require upstream R&D activities, resulting in a pull dynamic. In military R&D, this may be a new weapons system that needs to be developed in response to an emerging threat. In industry, this may be a new consumer product to be introduced in response to a competitor's offering. In the Access `RDPs` table, the ID is an autonumber field. To add a new RDP record, the next autonumber for ID can be obtained with a READ block that invokes a RECORDSET with the following query:

```
SELECT COUNT(ID) FROM [RDPs].
```

Then, assigning the value obtained to variable N, a WRITE block can be used to write a new record to the `RDPs` table using a RECORDSET that invokes the following query and writes the new information to the $(N + 1)$th record in table `RDPs`:

```
SELECT     RDPs.[Type],     RDPs.[TechArea],
RDPs.[Generation], RDPs.[Status], RDPs[Cost],
RDPs.[Duration], RDPs.[Value] FROM [RDPs].
```

For this to be truly useful, it is clear that at least two conditions must be met. First, the ARENA/Access model must have some representation of the outside world, so that competitive threats can be made to “arrive” in the simulation. Second, if a competitive threat generates an upstream network of prerequisite nodes, there must be some kind of “model intelligence” to set up this network structure and node characteristics. This model intelligence would need to embody the specifics of the domain being modeled. Both these requirements are avenues for further research.

Thus far, an initial RDP model has been developed and integrated with ARENA. With a large-scale model, there is concern about the computational effects of frequent database read/write transactions. As this work progresses, this issue will be explored and addressed.

6 CONCLUSION AND FUTURE WORK

This paper has presented a process-focused model of R&D enterprises, as well as a complementary product-focused model. The process-focused model represents R&D business processes and the progress of R&D projects through the enterprise to their (hopeful) deployment. The product-focused model, on the other hand, represents the complex nature of R&D products, including investment possibilities and planned R&D products, which have downstream value potential. Combined into a single model, this represents an important step toward analysis of complex R&D systems using organizational simulation (R&D World).

Initial results from the process-focused model indicate that real options provide a better valuation method than net present value in terms of total value created, but that net present value outperforms when considering return on R&D investment. NPV tends to be more conservative in preservation of investment capital. This is an interesting and perhaps fundamental result. Results are also presented concerning the effect of budget allocation, as well. Future work will address further validation with additional experimentation, and further experimentation to see whether the effect holds in more complex systems. Clearly, more complex valuation methods are required for complex RDP models. The framework for real options analysis provided by Trigeorgis (1996) provides a solid starting point for this avenue of research. In addition, the initial relational RDP model will need enhancement.

In addition, future work will address other questions, such as the effect of different methods of managing out-year budget commitments, different methods of managing year-end spend-out and unfunded priorities, different budget request structures for R&D projects, and different distributional forms of free cash flow variability over time.

Overall, this research thrust addresses business processes, product lifecycles and advanced decision logic of R&D systems – the “enterprise physics” aspect of organizational simulation. As part of a broader effort, it would be of interest eventually to incorporate human interaction, advanced visualization and competitive strategy/gaming environments.

ACKNOWLEDGMENTS

This work has been funded by the Tennenbaum Institute at Georgia Tech and by Singapore’s Ministry of Defence.

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