Valuation of Technology Development Using a Novel Workflow Approach to Compound Real Options

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Abstract — A concept study was undertaken to demonstrate how strategic valuation of a micro-sun sensor development could impact decision-making and planning during maturation of technology from proof-of-concept through validation and demonstration. A workflow of activities that retire risk and ensure technology infusion into a targeted system also prescribes a pseudo-decision tree from which comparison of discounted cash flow (DCF) with compound real options valuation is performed to evaluate the strategic value of the maturation phase. The intent is to identify areas where financial modeling may improve decision-making, for integration with technology risk assessment, infusion planning, probabilistic cost estimation, schedule uncertainties and program-level decision tree analysis. DCF and option values expectedly are dominated by assumptions and uncertainty. Nonetheless, the latter preliminarily yields a project value distribution that can exceed DCF by up to $40,000 though typically is below $10,000 for this relatively small $800,000 technology development effort over two years.

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1. INTRODUCTION

A strategic view of the technology development lifecycle is presented, with a case study focusing on technology maturation from proof-of-concept through validation and demonstration. Technology development transforms economic capital, represented by a research and development budget allocation, into strategic capital by creating new investment or funding opportunities downstream. The notion of strategic value captures these additional opportunities (i.e. options) derived precisely from the technology development activities themselves. The total value of a technology development is the sum of economic value *and* strategic value. In other words, the value of development is not represented simply by the allocated budget or aggregated expenditures, rather by the value represented by the options created for its derivative uses during and beyond maturation, given the prescribed infusion target and others that may be manifested (for example, the ability to use the technology in future system trade studies and missions]. In financial parlance, strategic capital generates an *option premium*. Leading companies in diverse industry sectors such as energy, petroleum exploration and production, pharmaceuticals and biotech, and aircraft manufacturing are embracing the use of real options for R&D investment valuation and decision-making [1].

In finance, options are the right but not the right to make an investment. Real options theory is an extension of options theory to non-financial assets. In the R&D domain of an enterprise such as the National Aeronautics and Space Administration (NASA), these non-financial assets might include physical (i.e. real) assets such as flight hardware, software, components, subsystems and complex integrated systems; documents and plans such as proposals, technology assessments, technical reports and project plans, including attendant intellectual property such as patents and copyrights; engineering processes, architectures and designs, including mission concept studies. It is important to realize that the notion of value does not require operating profits or positive cash flow for the application of real options. Options valuation with a simple Black-Scholes model [2, 3, 4] is well established.

Economic and strategic views of technology development are offered by looking respectively at decision-making at the project and at the program levels. A program is defined as a set of interrelated projects, each of which further advances the program towards meeting its overall objective. In so doing, decision tree analysis (DTA) and compound real options valuations both are applied with which to evaluate the economic and strategic value components.

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In order to explore this, consider that an ongoing technology development task has economic value. Current cash flows (i.e. actualized expenditures or obligated costs) drive its worth to a "value investor." *A project manager can be considered a value investor whose interest is the cost of development – a purely economic view.* Without revenues, negative cash flow is equated to the R&D expenditure – a cost item rather than investment. However, cost reductions or savings enabled by a given technology development can be a proxy for revenues and thereby used to yield a measure of net revenue. Of course, this depends on the time horizon over which such offsets to development costs are aggregated.

Consider further that a technology development plan represents a real option. If funded, the option is acquired and, generally speaking, executed throughout the course of the development itself. Real options capture the value of managerial flexibility whereas discounted cash flow (DCF) from DTA, if and when performed in a context of specific technology project investment decision-making, does not.

In other words, using real options, decision-making is not based solely on assets already committed. Rather, managerial flexibility still exists, but volatility (e.g. a proxy to uncertainty in the development and infusion target or application domains of the technology) means that option values improve when returns are less certain, while the value of the underlying development asset decreases. The opportunities for downstream return on investment drives the value of a given technology development to a "growth investor." The following contrasting view to that of a technology project manager thus is offered for a technology program manager. *A program manager is a growth investor and holds a strategic view that transcends a single project and seeks to maximize returns (i.e. future cash flows or their proxies) across multiple opportunities, or projects.* In the options parlance, a technology program is responsible for managing – creating, acquiring, exercising, hedging, abandoning, expiring, trading, etc. – real options as a portfolio.

Real options valuation has been demonstrated in the NASA domain, but in a mission construct [5]. Herein, valuation is undertaken at the technology development task level (i.e. a concise development project without multiple integrated units), within a construct of risk management that focuses on the maturation phase from proof-of-concept to demonstration and validation. In this study, utilization, adoption and infusion of the subject technology in a mission is implicitly intended, but not a direct driver of cash flows for valuation purposes. In this manner, subjective views on potential long-term downstream value (e.g. placing a dollar value on discovering a terrestrial planet outside our solar system) are pragmatically avoided and the valuation window thus framed to the immediate development and its enabling, enhancing or cost-reducing functionality.

2. APPROACH

Decision tree analysis (DTA) is an oft-used approach, and is witnessing increased application in select NASA technology program domains [6, 7] if not yet at the project or task level. DTA helps structure and evaluate contingent outcomes in a development project. However, DTA assumes that the entire project must be "played out" with a commitment to a decision path at time zero. Option valuation is a special approach to DTA that is better suited to valuing sequential, interdependent investments. An options approach provides management with *downside protection* – the option to choose the maximum of the expected value from continuing or the value of abandoning the development This flexibility means that making an investment decision in the future may be less risky than if it were required at the outset of the development. Furthermore, this suggests that a development plan can be changed from its baseline, in the course of the development, in a manner that captures the maximum value as affected by changes in the risk profile of the technology maturation and/or the risk landscape of its programmatic, infusion and application domains. Addressing both unique technical development risks and application domain (i.e. market) risks or volatilities due to competition, supplier relations, program and organizational changes, among other factors are both intrinsic and extrinsic to the development environment.

A real options valuation architecture can be devised from the DTA structure. In fact, under assumptions of zero volatility (i.e. see Black-Scholes model, [2]) real options are equated to decision trees – this provides the unifying structure of this study [see also 4]. A "mock" or pseudo-decision tree can be constructed from a technology development product breakdown structure (PBS) and attendant work breakdown structure (WBS) of the technology development task, capturing single- and multiple-branch parallel and sequential developments, with scheduled milestones (i.e. planned work durations), planned expenditures (i.e. cash flows), future cash flows (i.e. cost reduction or savings) and probabilities of success at each step or tree branch.

Furthermore, and wherein lies the innovation presented in this case study, such a WBS can be constructed by selecting those development activities that are deemed to measurably retire the risks associated with maturation from point-of-concept through validation and demonstration. This process of selecting activities which yield the optimum cost-benefit point on the underlying Pareto front, given available resources is outlined fully in [8]. The novel workflow approach to real options valuation consists of constructing the WBS precisely from this optimized selection of activities and, in turn, constructing the pseudo-decision tree for DCF and compound real options valuation.

The terminology of a pseudo-decision tree is introduced to structure a framework that tacitly represents the underlying decision-making from the above work activities whose

selection was optimized to retire risk, given available resources. Further, the tree provides the basis from which discounted cash flow analysis can be organized and options compounded.

Each decision node is treated as a European call option. At each decision node, with the completion of work elements, the developer has the right, not obligation, to enter or "call in" the next step (i.e. work element) at a specified price (strike price) or planned expenditure. This option is exercised with a (further) investment (I) at the strike price. The price of the underlying security at a given development stage (i.e. decision node) is the present value (PV) of the project, such that:

PV = I + net present value (NPV) of future cash flows.

A European option is one that can be exercised only on its expiration date. Note that if the possibility of finishing development stages ahead of schedule is allowed, an American option would be employed. The intent is to explore this possibility more rigorously at a subsequent stage of this concept study, and represent better the realities of advanced development – some activities will finish earlier than planned, albeit most will likely finish later. This uncertainty is represented by a probabilistic distribution function for the duration of work activities, as explained further below. Further, it is of interest to realize that a work element that extends beyond its scheduled completion date represents an expired option which, by definition has zero value. Thus, the entire valuation approach has to be reset by taking into consideration the nature of the work to re-scheduled completion.

From the DTA framework, technology development therefore can be characterized as a series of real options. Compound [real] options are options in which the underlying security is another [real] option. At the expiration of each option (assuming European options for now without the possibility of an earlier decision point due to completing a development stage ahead of schedule), the owner of the option must make a decision: abandon the option or exercise the option at hand and acquire the next option. The underlying security value [2] at the current stage is the sum of the unique risk-corrected (i.e. deflated) option value of the next stage plus the discount-corrected strike price (i.e. next investment increment). The option premium of the entire development is the discounted initial stage costs. These include all discounted costs aggregated up to the first non-zero option value in the compound series [4].

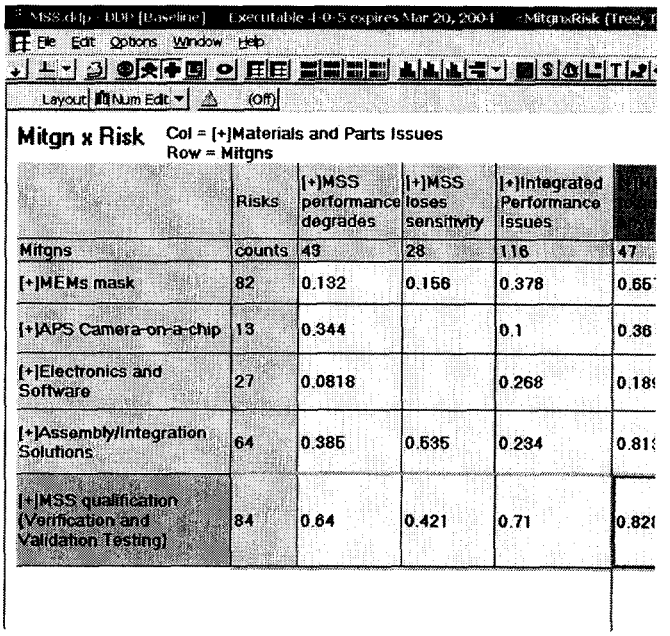
3. Case Study

The subject case study is being carried out as an extension of a Technology Infusion and Maturity Assessment (TIMA) conducted in support of technology development planning for the NASA/JPL Mars Science Laboratory Mission [9].

The MSL mission, planned for launch in 2009, requires sun sensors for spacecraft navigation and will use sun sensors for absolute heading detection of autonomous planetary rovers. The MSS technology under development at JPL represents a possible enabling solution. The MSL project is particularly interested in validating the viability and reliability of MSS packages in accurately determining sun position while effectively withstanding the harsh environment at the Martian surface [9].

The TIMA-derived workflow is shown in Fig.1 Design and fabrication work commences concurrently with electronics and software development. Both lead to packaging and testing activities. The corresponding schedule is shown in Fig. 2, spanning a maturation period of 2 years.

The case study parameters for the valuation are as follows. The total cost of the MSS development and test is estimated at $806,000 with a NPV of $784,320. There is an $80,000 reserve that is not discounted (and not folded into the analysis). The successful rollout of this development signifies that the MSL Project could acquire 4 requisite MSS units at a total estimated cost of $100,000 ($25,000 estimated per unit, averaged including first unit costs) rather than currently available units of $300,000 each for a total of $1,200,000. The reader is cautioned that these dollar figures are not to be interpreted necessarily as true costs outside of this case study analysis, and should be treated purely for illustration purposes of the valuation approach described herein. A discount rate of 5% is assumed throughout.



	Risks	[+]MSS performance degrades	[+]MSS loses sensitivity	[+]Integrated Performance issues	
Mitgns	counts	43	28	116	47
[+]MEMs mask	82	0.132	0.156	0.378	0.65
[+]APS Camera-on-a-chip	13	0.344		0.1	0.36
[+]Electronics and Software	27	0.0818		0.268	0.18
[+]Assembly/Integration Solutions	64	0.385	0.535	0.234	0.81
[+]MSS qualification (Verification and Validation Testing)	84	0.64	0.421	0.71	0.82

Fig. 1. DDP graphical user interface for assessing the effectiveness of mitigations on identified risks, and prescribing the subsequent workflow.

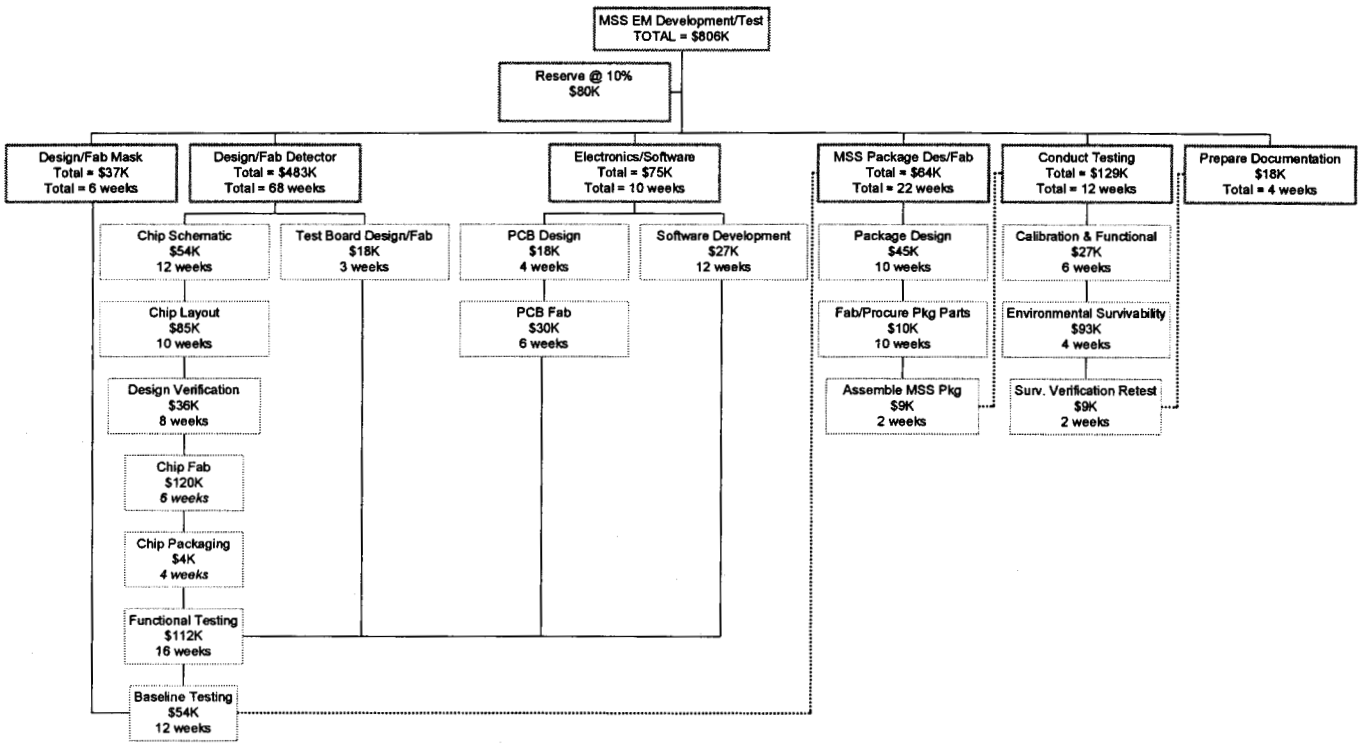
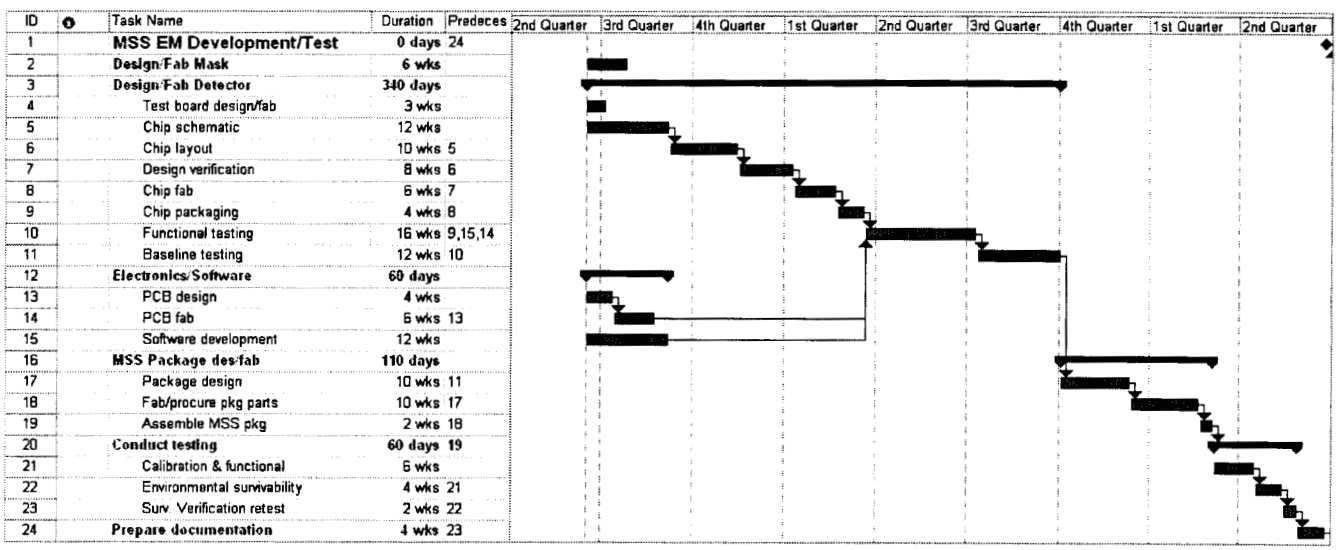


Fig. 2. Constructed from Table 3 of the Micro-Sum Sensor Technology Roadmap for Mars Science Laboratory Technology Infusion and Maturity Assessment (TIMA) Report [9] to construct this workflow diagram, or pseudo-decision tree, with elicited costs and development durations.



ID		Task Name	Duration	Predeces
1		**MSS EM Development/Test**	0 days	24
2		**Design/Fab Mask**	6 wks	
3		**Design/Fab Detector**	340 days	
4		Test board design/fab	3 wks	
5		Chip schematic	12 wks	
6		Chip layout	10 wks	5
7		Design verification	8 wks	6
8		Chip fab	6 wks	7
9		Chip packaging	4 wks	8
10		Functional testing	16 wks	9,15,14
11		Baseline testing	12 wks	10
12		**Electronics/Software**	60 days	
13		PCB design	4 wks	
14		PCB fab	6 wks	13
15		Software development	12 wks	
16		**MSS Package des/fab**	110 days	
17		Package design	10 wks	11
18		Fab/procure pkg parts	10 wks	17
19		Assemble MSS pkg	2 wks	18
20		**Conduct testing**	60 days	19
21		Calibration & functional	6 wks	
22		Environmental survivability	4 wks	21
23		Surv. Verification retest	2 wks	22
24		**Prepare documentation**	4 wks	23

Fig. 3. See Table 3 of the Micro-Sum Sensor Technology Roadmap for Mars Science Laboratory Technology Infusion and Maturity Assessment (TIMA) Report [9] to construct this schedule based on task durations and development phasing/predecessors.

The TIMA study leading to the MSS maturation activities (see Fig. 1), based on an optimized cost-benefit analysis of requirements attainment, yields an accepted residual risk level which is the consensual outcome of implementing the selected group of mitigations (i.e. PACTs in DDP parlance – acronym for preventions, analyses, controls and tests and used generically herein to refer to the development or risk retirement-derived work elements in the workflow) – see report [8] and DDP references [10, 11, 12]. The study herein assumes that the effectiveness of any given mitigation on elicited risk elements reflects the product of the inherent effectiveness *and* the likelihood of successful PACT implementation. For example, a 72% PACT effectiveness may be an 80% effectiveness PACT with a 90% likelihood of successful implementation. Fig. 1 represents a segment of the DDP software tool graphical user interface for assessing the effectiveness of mitigation work elements on risks. This process, along with a corresponding cost-benefit analysis of all possible mitigation combinations and their aggregate effectiveness across all risks to requirements attainment, is the underlying basis from which the workflow is constructed (Fig. 2).

Instead, if the assumption is made that the selected development tasks indeed have a less than 100% probability of success, this establishes a work flow diagram or mock decision tree that collects costs of failure (i.e. abandonment) branches. Changing these percentages from 100% requires a risk-adjustment to the expectation value of the overall development. The risk-adjustment represents the effective likelihood of success from development start to roll-out (i.e. along a successful development path).

The model set-up for compound real options valuation is as follows. Work element durations, t, taken from TIMA are modeled as lognormal distributions with mean t, σ of 0.1t and truncation below t- σ /2. Point cost estimates, c, from TIMA are modeled as lognormal distributions with a mean 0.1c, σ of 0.1c and a shift of c- σ /2 and no truncation. Work element durations and costs are correlated +1.0 in the model. Probabilities of success are *all* modeled as normal distributions with a mean of 1 and σ of 0.05, with truncation above 1.0. Volatilities are all modeled as lognormal with mean of 0.3, σ of 0.3 and a shift of +0.2 with about 90% of the values falling between 0.2 and 1.0. The cost savings (i.e. acquisition cost of commercial sun sensors currently on the market) is modeled as a triangular distribution with a maximum and most likely value of $1.2K (e.g. 4 times $300K) and a minimum value of $900K to allow for the assumption of price reduction over the course of this development (over 2 years). The roll-out cost (i.e. future acquisition cost of 4 micro-sun sensors) is modeled as a lognormal distribution with a mean of $100K, σ of $25K and truncation below $100K – thus assuming that the TIMA projection is very likely under-estimated. A risk-free discount rate of 5% is assumed. Fig. 4 shows the distribution of volatilities. Fig. 5 shows the distribution of functional testing during, modeled as a lognormal distribution about the value from the planned schedule (Fig. 2).

The study approach considers the pseudo break-even scenario for the decision-making regarding MSS development for MSL. The expectation value of this development is $345,510 which is the difference between the NPV of future cash flows and the NPV of the costs at each stage of development. This is the best-case expectation value, with 100% probability of success along each development branch. The underlying cost figures were elicited during the MSS TIMA study and are point estimates rather than probabilistic distributions [9].

The final option in the compound series is the rollout, where the price of the option is the NPV of future cash flows plus the risk-adjusted strike price (i.e. discounted from the time the option is acquired until it is exercised). For example: the strike price is $100,000 (e.g. 4 MSS at $25,000 per unit); the NPV of future cash flows is $1,129,830 (e.g. proxy from savings of four commercially available units of $300,000 each.); the price of each predecessor compound option is the option value of its successor.

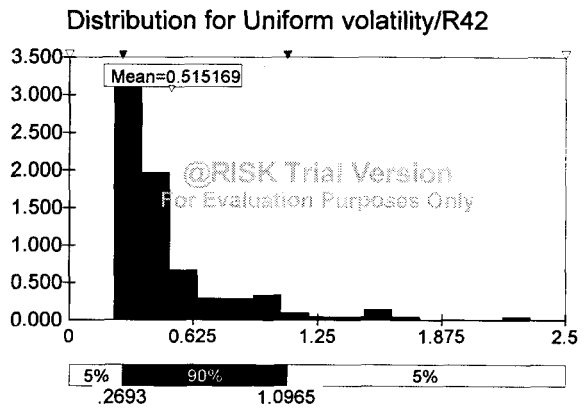


Fig. 4. A Monte Carlo simulation with 149 iterations yields the above distribution of volatilities.

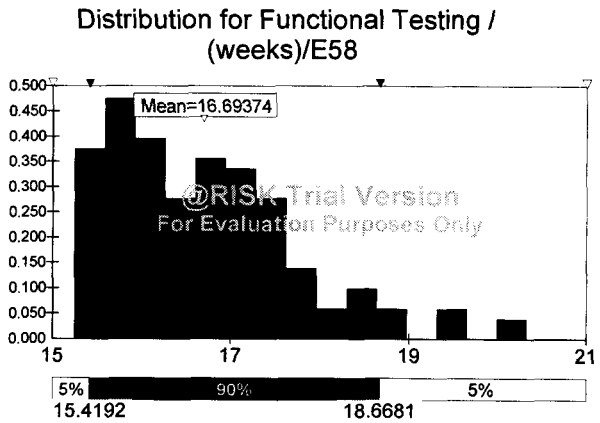


Fig. 5. A Monte Carlo simulation with 149 iterations yields the above yields the following distribution of work element durations for "functional testing," TIMA-estimated at 16 weeks.

The investment itself is valuated by determining the option value of the first option in the compound series minus the NPV of the initial investment. The first option in the compound series is valued at $418,300. The NPV of the initial investments is $72,800. The difference is $345,510 and precisely the same as the expectation value yielded by DTA. *Real options are equated to decision trees under zero volatility!* This is not dependent on likelihoods of success at the various branches, provided NPV costs are aggregated up to the first non-zero-valued option.

4. Discussion of Results

The results presented in this paper must be viewed as preliminary and as part of an ongoing case study analysis. Fig. 6 shows the resultant distribution of project values based on discounted cash flow, where the MSS development parameters are represented as probabilistic distribution functions as described in the previous section. Fig. 7 shows the project value based on real options valuation. The difference between the two approaches is indicated in Fig. 8.

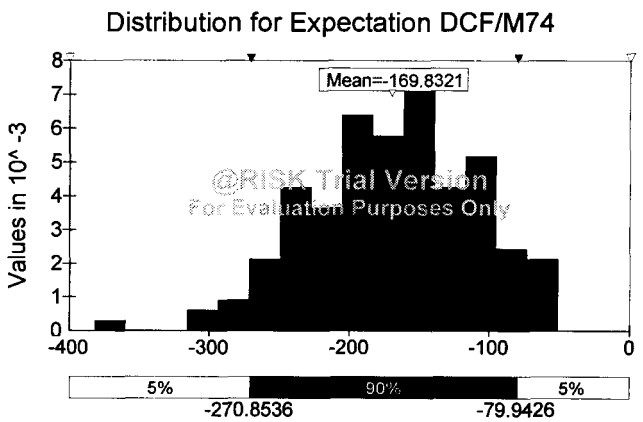


Fig. 6. A Monte Carlo simulation with 149 iterations yields the following distribution of the DTA expectation net present value of this MSS development and test effort

DCF and option values are expectedly dominated by assumptions of uncertainty. Nonetheless, the latter preliminarily yields an overall value distribution that can exceed DCF by up to $40,000 in some scenarios, though typically is below $10,000 with a mean of $6,200 for this relatively small technology development effort. This strategic value compared to the DCF economic value is sometimes known as the real options kicker. These figures represent the results of only one Monte Carlo analysis. Given the underlying probabilistically captured uncertainties, it would be of interest to understand which combination of parametric factors lead to real option kickers at the high end of the outcome distribution in Fig. 8. Further runs would be used to assess sensitivities to underlying assumptions and functional forms of PDFs.

Each option in the compound series is "in the money," – the situation in which an option's strike price is below the current market price of the underlier (for a call option) and thus has intrinsic value. Therefore, in this particular case study, the value of acquiring the next option exceeds that of abandonment. The greatest sensitivity to being in the money arises from the inferred volatility for the particularly development which, depending on how comprehensive a measure of volatility can be defined, drives the downstream value of the option. For example, in some sample scenarios, a volatility of 200% would bring an option out of the money, in which case abandonment of the project at that stage is the best solution. In this concept study, a lognormal volality PDF was used for each development step. Unlike financial or other types of real options where market data can be used to determine appropriate volatility values over a period of time, herein this measure of uncertainly is one that warrants further discussion (see Section 5) in terms of complexity of technology development steps.

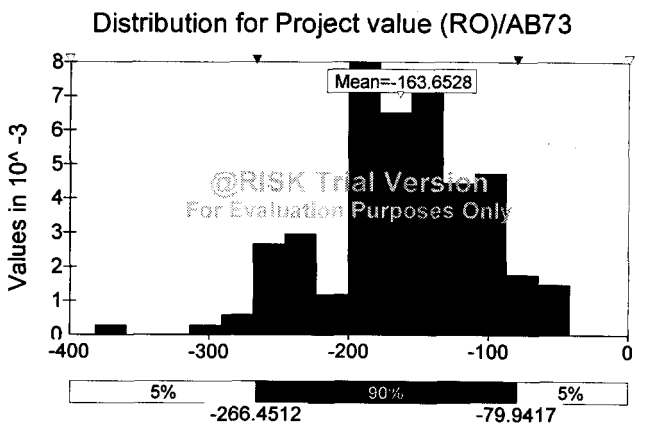


Fig. 7. A Monte Carlo simulation with 149 iterations yields the following distribution of the project value based on real options

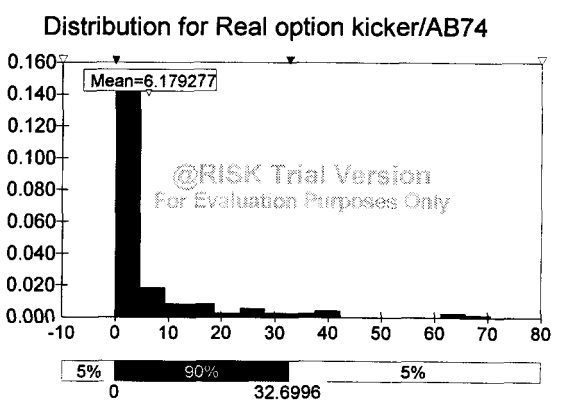


Fig. 8. A Monte Carlo simulation with 149 iterations yields the above distribution of strategic value attributed to the real options approach.

The cost-benefit space generated by DDP (i.e. using simulated annealing or genetic algorithms) represents the complete set of all possible permutations of elicited risk-retirement-based development options. This cost-benefit space is measured only in economic terms, and does not include the strategic value of requirements attainment. Further, risk retirement or development activity costs currently are point estimates rather than probabilistic and thus fail to capture uncertainty. Uncertainties in benefit (i.e. percentage of requirements attained) also are not included. Further, while the PACTs can be phased in time, DDP does not discount costs (i.e. cash flows) – inflation rates should be included in long-term technology efforts like MSL, where the development horizon is several years out.

An intriguing consideration for future tool development would be to construct a probabilities cost-total value space where costs are appropriate probability distribution functions and total value is defined as:

Total Value = Economic Value (P(DCF)) + Strategic Value (Options)

where P(DCF) is the probability distribution of the DCF. The resultant Pareto front would have an uncertainty bound. For the sake of ersatz, imagine that Technology A, with its attendant PACTs and residual risk profile, may represent a lower cost-benefit ratio than Technology B. However, the strategic value of Technology B may be higher than that of Technology A. Furthermore, the PDF of the aggregated Technology A costs, for a particular (x,y) location on the Pareto space, may suggest less uncertainty than that for Technology B – in other words, the distributions about a central point may be quite different. The cost-benefit ratio thus is a ratio of corresponding PDFs obtained through Monte Carlo simulations. Optimization in this manner would encompass all elements of uncertainty, driven both by well-constrained parameters and others that are less so.

5. CONCLUSIONS

The case study herein presents a concept for demonstrating strategic valuation from a technology development workflow. The results are preliminary. The plan is to continue this case study with MSS TIMA towards reconstructing the cost-benefit space with strategic benefit and probabilistic cost distributions.- with probabilistic cost distributions for the option premium *and* strike prices. The novel approach presented not only captures the *economic value* of technology maturation investment decisions, from proof-of-concept to demonstration/validation but highlights unique risk or probability of success at each stage in addition to uncertainties in order to perform compound real options valuation.

Preliminary results suggest where financial modeling might improve current processes and tools for technology risk management, infusion planning, and new technology cost estimation and program-level portfolio management. Noting the perspectives of a task or project manager (i.e. value investor) and a technology program manager (i.e. growth investor), total valuation allows for strategic decision-making with economic R&D planning and execution. While this is not the first application of real options in the NASA technology domain, it is the first attempt to drive valuation with a workflow that represents an optimum point on the cost-benefit Pareto front of TIMA development alternatives – where benefit is the aggregated percentage of targeted mission requirements attainment (i.e. measure of risk level). The subject EM development is approximately $800,000 over two years. DCF and option values are expectedly dominated by assumptions of uncertainty; nonetheless, the latter preliminarily yields an overall value distribution that can exceed DCF by up to $40,000 in some cases, though typically is below $10,000 for this relatively small development effort. Furthermore, the short duration of this case study project decreases the potential of options valuation [see 2, 3].

Some provocative questions are raised by this study: What is the marginal strategic value achievable by changing the order of PACTs in a DDP analysis, hence re-architecting the workflow pseudo-decision tree? This would consider the time-value-of-money in the aggregation of PACTs for a given point in Pareto space. What is a proper and useful proxy to volatility? Volatility captures market influences over a given period of time. Here, volatility intends to encompass influences due to program management, human and organizational factors, specialized manufacturing and testing facilities availability and usage, competitive landscape, supplier/vendor relationships, mission readiness and other such factors beyond unique developmental risks. Perhaps a review of all PACTs from all TIMAs to date could be undertaken, developing a database, a taxonomy, classification and measure of applications domain complexity (e.g. by subsystem, by mission type, etc. Finally, are real options amenable to driving trade space exploration and design convergence?

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