A Real Options Framework for Space Mission Design

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Abstract—a real options framework for use in space mission design is presented. Such a framework has potential application in architecting flexibility in certain mission designs with the objective of maximizing mission *utility*. It integrates economic principles of cost, return, risk, flexibility, and other concepts from Black-Scholes option pricing theory and the multiplicative binomial process. Options pricing theory provides an objective method for valuing flexibility in making future investment decisions based on new information becoming available; such flexibility may have great value in certain risky ventures. This flexibility in the future may or may not exist without additional investment. The development of investment strategies to create flexibility must include answering the question "how much can be invested to create the desired flexibility?" The answer must include *a priori* estimation of the value that the flexibility provides; in this application the real options framework becomes a powerful tool. The utility of this tool will be demonstrated through conceptual examples; these examples will also illustrate some limitations of the method. This work is by no means a comprehensive study. At best it attempts to demonstrate that there are techniques and ways of thinking – *frameworks* – that offer benefits for the complex process of mission design for an uncertain and often risky future.

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1. INTRODUCTION

From an economic viewpoint a space mission may be characterized by its investment (cost), expected return (value), risk (systematic volatility in returns and time to return due to nature), and flexibility (risk management). Figure 1 is a conceptual depiction of an investment process.

From the time an investment begins until the final return is realized flexibility might exist, perhaps even architected in such a way that future decisions may be made to maximize expected return or minimize expected losses. The primary purpose of this work is to provide insight into how to value and architect flexibility within the real options framework through application to high-level space mission design examples.

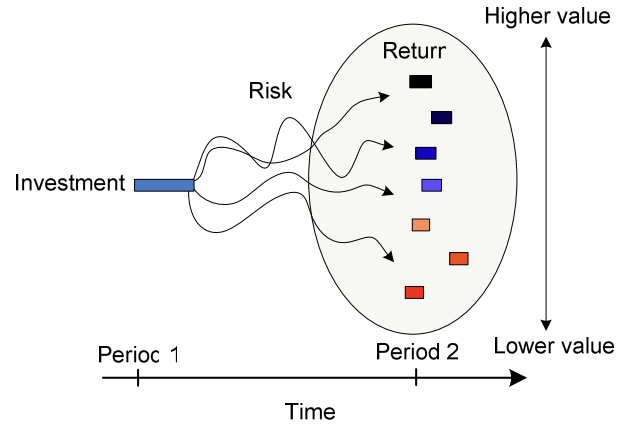

Figure 1: Investment, Return, Risk.

Application of real options analysis typically requires that assumptions be made about one or more of the four economic elements. Important past work, especially as related to NASA, includes [1], where the authors examine the use of real options valuation in the context of prioritizing advanced technologies for NASA funding and offer a set of computational procedures that quantifies the option value of each technology.

Development and practical use of a real options framework for analyzing most real-world investment problems – especially something as complex as a space mission, given the current state-of-knowledge –requires professional judgment that synthesizes knowledge from multiple disciplines. The assessment of the authors is that the most valuable aspect of a real options framework is not just its mathematical utility for analyzing a specific problem, but the often unique intuition and perspectives that it facilitates when making complex investment decisions for an uncertain future. As always, the reader must judge the accuracy of this assessment. The four primary economic elements of the framework are as follows.

Cost – At first glance cost appears to be one of the more straightforward variables to define. However, when cost analysis also incorporates all opportunity costs the problem becomes significantly more complex; opportunity cost will not be considered in this work.

Value – The United States and several other nations around the world have determined that many space-based science missions have a positive Net Present Value (NPV). In other words, the value of the science knowledge obtained from these missions is worth more than the use of resources (cost) in obtaining that science when the return of knowledge and cost are normalized to the present (compared in today's Dollars for instance).

Quantifying the value of new scientific knowledge is difficult and is one of the challenges in applying resource investment analysis methods and tools in the design of space missions. Nevertheless, the US National Aeronautics and Space Administration (NASA) and other public and private agencies make investment decisions based on competing science objectives; for example choosing between either new science knowledge about Jupiter, or Saturn. The true value of new knowledge is often represented by proxies or combinations of proxies including priority of science objectives as determined by the science community, the number of new Ph.D.'s that will result from a mission, the number of journal and other publications that result from a mission, number of bits of new science data received, and others. This approach is useful when the proxies for value are representative of true value and consistently applied so that relative comparisons between missions can be made. Defining a metric(s) for measuring value is critical in defining a real options framework.

Risk – The volatility in the expected (science) return of a mission can also be very difficult to characterize. In equity market models it is typically assumed that the return of an investment is determined by a stochastic process known as the *Wiener* process. Depending on the physical system this may or may not be an accurate model from which to estimate volatility. In addition, even if a given model is accurate the parameters of the model (e.g. component stochastic processes) are usually not known or possible to determine precisely; *this is particularly true if the project is the first of its kind*. At times the project's return is dictated by an identical or even similar underlying stochastic process as that of an adequate sample of previous investment projects. In such cases, regression and other statistical techniques may be applied to estimate the volatility and other parameters of the future project. Several simplifying assumptions about the nature of volatility will be made in the real options framework used in the examples in Sections 3 and 5.

Flexibility – Real options analysis provides an objective method for valuing future flexibility in making or changing investment decisions contingent upon future information becoming available; such flexibility may have great value in certain investments with high volatility in returns (so-called risky investments) and none in others. This future flexibility may or may not exist without additional investment. Significantly, flexibility may require addition investment and strategic thinking and planning on the part of mission (investment) designers. The real options framework provides a particular vantage point from which to view flexibility in a space mission; especially the value of flexibility which is a critical consideration when *architecting flexibility*. The next section presents a brief overview of the tool used to create flexibility, namely, options.

2. OPTIONS IN BRIEF

The subjects of Black-Scholes option pricing and theory of options in the role of risk reduction/management are both mature and complex; entire books are dedicated to subsets of these subjects. The intent of this section is to provide an intuitive example of a real option, and most importantly provide references for further study.

The quantitative origins of real options derive from the seminal work of Black Scholes [3] and Merton [4] in pricing financial options. To motivate and illustrate certain concepts underlying option theory an example is presented.

Suppose company *S* makes satellite buses that require titanium to produce, and that the price movement of titanium over the coming year is determined by some well-modeled stochastic process. The company may choose to buy an option to purchase a unit of titanium one year from now at a predetermined price – say 10% above today's price – in order to protect itself from large price increases that are possible. Suppose the cost of the option is a relatively small percent of today's cost of a unit of titanium; for example 5%. Now suppose that of all of the possible futures (price outcomes in one year), the one that occurs is one where the price of titanium does not increase at all; the option would expire unexercised (the titanium would be purchased for today's price). Now suppose that in another future the price of titanium increases by 50%; the option would be exercised and the titanium would be purchased for only a 10% premium over today's price. Company *S* could choose to purchase the flexibility (real option) to protect itself from risk – a significant increase in price in the uncertain future (similarly, the company selling titanium sells options in order to obtain resources today, also protecting itself from risk – a significant decease in the price of titanium in the future). Black-Scholes or binomial option pricing theory

may be used to answer the question, "what is the value of the option?"

There can be – and typically are – a large number of economic differences between a traded security on a public free-market stock-exchange and a real asset such as titanium or a space mission. Besides the obvious differences already discussed, there are fundamental differences that can exist in the underlying economic models (i.e. completeness of the market) that describes the economic system in which the asset exists. These are well beyond the scope of this work; however [2] includes a comprehensive discussion and analysis of these issues.

The next section presents a brief overview of the discrete-time multiplicative binomial process that can be used to readily value (approximately) real options provided appropriate assumptions are made. This method is a critical component of the real options framework used in examples in Section 5.

3. MULTIPLICATIVE BINOMIAL PROCESS

The binomial approach developed first in [5] and expanded upon by multiple authors over the past twenty-five years enables a more simplified valuation of options in discrete-time. This approach is also analogous to the conventional probabilistic binomial decision-tree description of the future. An example is now developed to illustrate several properties of this process; several simplifications are made for the purpose of illustration. For a thorough description of this process and mathematical foundations refer to [2].

Suppose there is human precursor mission to Mars to search for resources that can be utilized by in-situ propellant production that would significantly reduce the cost of future human missions (for instance hydrogen that can be extracted from exploitable water). Suppose such exploitable resources are believed to exist with high probability (~1.0) based on current knowledge. Further suppose it is estimated that out of every 10 potential locations 8 contain exploitable water in high densities and 2 contain exploitable water in relatively low densities (relatively lower value). Finally there is no way to determine *a priori* the type of exploitable water (high or low density) without investing in a mission that physically verifies the existence of the exploitable resource. Such verification is assumed to be performed via a mobile robotic platform that can use exploitable water it finds as fuel, to further its search to some maximum lifetime (assumed to be 2 periods in extent).

This hypothetical mission to Mars is modeled with the two-period binomial (event) tree with three possible outcomes as described in Fig. 2. Here u (=4) is the multiplicative factor for an *up outcome* in the future (location of easily exploitable water in high water density regolith) and d (=0.25) the multiplicative down factor for a *down outcome* (location of exploitable water but in low water density regolith) in the future. The probability of an up or down movement is given by p and $1–p$, respectively.

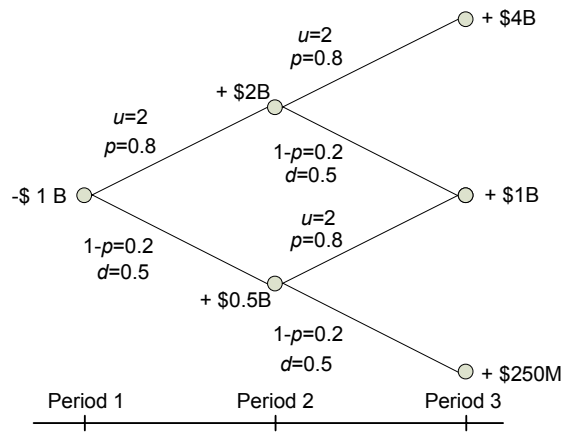

Figure 2: Two-period binomial tree model of mission.

In period one, $1 billion is invested to design, build, and launch a space mission that incorporates a robotic Martian lander that can locate, mine, and process in-situ resources on the surface of Mars for its own benefit. Note that the assumption here is that the actual knowledge of the location of water is very valuable in the context of future human mission to Mars. The mission is characterized in more detail by the following descriptions.

Up Outcome in Period 2:

The probability that a robotic vehicle will land on the surface of Mars and locate the high density exploitable resources is 0.8; the return on investment is estimated to be $2 billions, or 2 times the original investment. Furthermore, the hydrogen burning rover now has enough fuel to investigate others regions for exploitable water.

Up Outcome in Periods 2 and 3:

After an up outcome at Period 2, the mission can have another up outcome in Period 3 with probability 0.8; in this case the lander finds even more high-density exploitable resources using resources obtained from Period 2 (these may be in the form of information and actual processing of a percentage of the resources for continued operations). The volume (value) of the resources located in this period is estimated to be a factor of 2 greater than Period 2, for a total of 4 times the original investment.

Up Outcome in Period 2, Down Outcome in Period 3:

Alternatively, there is a 0.2 probability that in Period 3 the lander will only be able to locate exploitable resources in

relatively low densities such that the value is half that found in Period 2.

Down Outcome in Period 2:

There is a 0.2 probability of a down outcome in Period 2; in this case the robotic vehicle lands on Mars but locates relatively low density exploitable resources estimated to be $500 million, half the original investment.

Down Outcome in Period 2, Up Outcome in Period 3:

After a down outcome at Period 2, the lander can have an up outcome in Period 3 with probability 0.8 by finding high density water from mobile discovery using resources located in Period 2. The value of the water located from this discovery is estimated to be equal to the initial investment in Period 1, or twice that located in Period 2.

Down Outcome in Periods 2 and 3:

After a down outcome in Period 2, the lander can have another down outcome with probability of 0.2 by locating additional low density water. The value of the water location obtained is estimated to be half of that obtained in Period 2, or 1/4th the initial investment.

There is a critical question that should be answered in Period 1, before a resource (dollar) is ever invested in a mission illustrated with this simple model. Does this mission (investment) have expected positive net present value (NPV)[1] as estimated from the beginning of period 0? The expected (average) net present value is determined by weighting all outcomes in Periods 1 and 2 with the appropriate probabilities and subtracting the investment as follows:

$$(0.8\times 2+0.2\times 0.5+0.64\times 4+0.04\times 0.25+0.16\times 1$$
$$0.16\times 1)-1=\$3.59\text{ B}$$

Another important question is "what is the probability that the mission will have a negative net present value?" This and many other measures of risk might be important considerations in the development of such a mission. The probability of a negative net present value ($500M + $250M – $1B = –$250M) is $0.2\times 0.2=0.04$; this might or might not represent unacceptably high risk.

Figure 3 illustrates an alternative scenario with u=4, d=0.25 with all other parameters being identical to that of Fig. 2. The expected net present value given this model is given as:

$$(0.2\times 4+0.8\times 0.25+0.04\times 16+0.64\times 0.0625$$
$$+0.16\times 1+0.16\times 1)-1=\$1.0\text{ B}$$

The probability that the mission will have a negative net present value ($250M + $62.5M – $1B = –$687.5M) is $0.8\times 0.8=0.64$. So while the up-side potential of $16B is high here (with relatively low probability of 0.04), the probability (risk) of a negative return is very high.

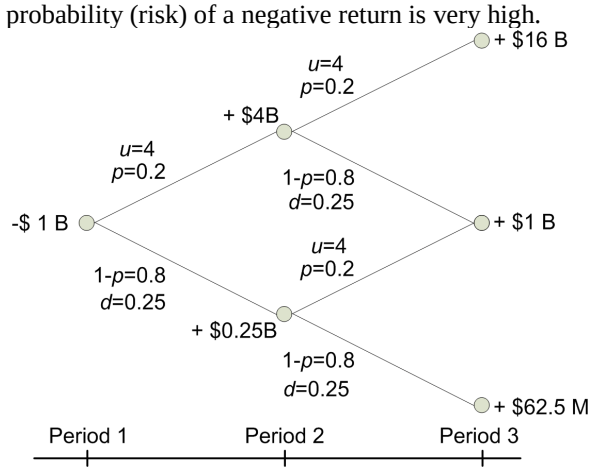

Figure 3: Alternative two-period binomial tree model.

The reader should observe several assumptions and characteristics about the two previous models:

1. Volatility in future return is a function of both the probability of an up or down outcome and the magnitude of that outcome (determined by u and d).
2. The probability of an up or down event can be designed or determined independently of estimates of u and d.
3. u and d are related by $u=\frac{1}{d}$. This may or may not be a requirement of the mode (it *is* a requirement to approximate the standard option pricing formula with discrete-time option pricing formula; refer to [2] for more details).
4. For the model presented it is assumed that all up and down outcomes are obtained from multiplying the value from the previous period by some factor (u or d).
5. There is one (bulk) investment in the initial time period 0.
6. The model is highly simplified and ignores the time-value of money, and only considers the most top-level mission parameters.

This is clearly a very contrived example; nevertheless the model will be expanded within the real options framework to demonstrate the utility of the framework in determining the value of flexibility, and to gain insight

[1] Note: in the highly simplified model of Fig. 1, the time value of money (or discount rate) is ignored. This factor often cannot be ignored in practice without significantly altering outcomes.

into how to architect such flexibility. Finally, the practical relationship between the multiplicative binomial process and the discrete-time option pricing will be demonstrated in part via examples in Section 5. For a detailed discussion and analysis of this relationship, and the relationship between discrete-time option pricing and the classic continuous-time Black-Scholes option pricing theory the reader is encouraged to refer to [2].

4. REAL OPTIONS FRAMEWORK

The real options framework is a set of assumptions, concepts, and methods that constitutes a way of viewing reality, especially the future and investment decisions creating flexibility in the future. Sections 2 and 3 provide a brief overview of certain underlying concepts and methods that are critical components of the framework. However, currently there is no concrete and comprehensive list of assumptions, concepts, and methods that can be simply stated to readily and comprehensively define this framework for broad application in mission design (or many other fields). As such, the application of the framework is currently both an art and a science. The examples of the next section seek to demonstrate that application of the framework benefits significantly from integrating the following perspectives.

a) When architecting an investment strategy not only should many resource investment decisions be viewed as real options, but such decisions may also contain a collection of possibly interrelated real options; some of which might create flexibility that has value, some of which might not.

b) The value of flexibility that real options create is contingent upon both the volatility of return and future information that will be used to decide whether or not to exercise a real option. When there is no potential for such information as viewed from the present, the real option cannot have value in the present.

c) The components of the framework – especially investment, return, expected net present value, options and their value, return-on-investment, formal definitions of risk assigning probabilities to outcomes, and the use of probabilistic binomial (trinomial etc.) event-tree models – must be combined in a way that helps the designer/analyst assess *utility*. This utility is not determined by a single number or a probability but by considering some combination of metrics that may be weighted by or compared within the constraints of budget profiles, political factors, and other real-world factors.

Applying these perspectives the space program of the United States – from the pre-Apollo era until the next human that sets foot on the Moon, then Mars and beyond – may be viewed as a complex of interrelated options creating choice and flexibility. Furthermore, space science missions by their very nature are designed and executed to acquire new information, and often have a large amount of uncertainty in expected return caused by nature (including human error). Given these characteristics of missions the application of a formal real options framework in their design would appear to hold tremendous potential value. Finally, the utility of a given mission and the quantitative metrics used to determine that utility should be defined as concisely as possible when applying a real options framework. Well recognized investment examples or strategies that exist within a real options framework include the following taken from [2]:

1. Option to defer
2. Time-to-build option
3. Option to alter
4. Option to expand
5. Option to abandon
6. Option to switch
7. Growth options
8. Multiple interacting options

Application of the framework is typically highly iterative and involves the following steps:

1. **Define Utility Metrics** to estimate utility *a priori*. Such metrics are user dependent. They may be a combination of expected return on investment and probability of a negative return on investment, but numerous other metrics are possible.

2. **Design Base-Case** to model likely mission (investment) variations with binomial event trees: include in the models expected investments, estimates of uncertainties (probabilities), expected returns (multiplicative up and down factors).

3. **Architect Flexibility** by designing feasible options in the binomial event-tree model, thus creating scenarios modeled as binomial decision-tree models. In this context "feasible" means not only physically realizable, but also having the potential to hold value (*i.e.* is future information going to become available?)

4. **Conduct Real Options Analysis** to estimate the value the option creates for a given mission strategy. The utility of the option – that is, how the option affects the metrics defining utility – is estimated. Sensitivity analysis of the underlying assumptions and model parameters should be performed.

5. **Objective Comparisons** are performed between the base-case design and alternatives with flexibility/options, to determine which has the highest relative utility.
6. **Iterate** steps 3, 4, and 5. They may lead to new ideas and insights that inspire alternative options and decision-tree models.

Step two has already been accomplished in Figs. 2 and 3 for two different estimated states of nature (probabilities and multiplicative factors). The next section extends these base-case models with steps 1, 3, 4, and 5; step 3 will use the *option to abandon* from the list above.

5. FRAMEWORK APPLICATION EXAMPLE

Defining utility—it is assumed in this example that the investor finds high utility in minimizing the losses in worst-case scenarios while maximizing expected NPV.

It is desirable to reduce the probability of a net loss from the investment in the mission scenario of Fig. 2; recall the probability of a negative NPV is 0.04. There are a number of ways to reduce this probability; all involve investing resources to buy down uncertainty. In this example an option is created in Period 2 that will allow a percentage of the investment to be postponed until uncertainty is reduced; the result is a reduction in the probability of a negative return on investment as viewed from Period 1. This flexibility may be created as an option to abandon the investment that could be made in Period 2 (this problem could have also been formulated as an option to expand depending on the outcome at the end of Period 1).

Clearly the cost of such risk mitigating flexibility must be estimated a priori; more generally the relationship between the cost of flexibility and the amount of uncertainty (probability) reduced must be determined in order to architect the flexibility in a multi-mission design. In most of the variations below the total investment will be held constant. Typically investment, expected present value, or expected net present value can be held constant in the first step of analysis in order to compare the basic model to the one with option(s). Here the choice is somewhat arbitrary and is only meant to be the first step in an iterative analysis/synthesis process. This example will demonstrate – among other things – that the risk associated with the probability of a negative outcome inherent in scenario one (Fig. 2) cannot be mitigated by increasing flexibility with a real option (at least not with the option to abandon), while the risk in scenario two (Fig. 3) can be mitigated with an *option to abandon*.

Scenario One

In this scenario the mission represented by Fig. 2 is altered to become a two-phase mission scenario.

Determine the Period 1 investment – The goal here is to buy down uncertainty with as little investment as possible while keeping total investment constant. Suppose it is determined that for $500M a robotic rover can be landed on Mars with capability of locating and exploiting water but with much shorter lifetime and therefore more limited mobility capability; the rover can only last for one period.

Estimate the Period 2 investment – The goal in period two would ideally be to take maximum advantage of the information obtained in Period 1; however the total cost of the mission is to remain constant (which is typical of space missions). As in Period 1 a $500M robotic rover can be landed on Mars with capability of locating and exploiting water. However, there is an option to abandon or cancel the second mission (beginning of Period 2) depending on the outcome of the first mission (end of Period 1)

Determine expected NPVs as viewed from Period 2 – The expected mission NPVs are now calculated from the viewpoint of Period 2. In Period 2 there are two possible states, the expected NPV for each ignores the –$500M investment in Period 1 (in Period 2 this investment is a sunk cost and should not enter into the NPV calculation). So there is a positive NPV in either state as viewed from period two. This means that – assuming the underlying models are correct – regardless of the outcome in Period 1, the investment in Period 2 will result in a positive net present value (as viewed from Period 2). Note that there is still a 0.04 probability that the overall mission will have a negative NPV. The option to abandon in Period 2 can have no value because is would never be exercised from a purely economic perspective (again the sunk cost in Period 1 should not be considered in economic decisions occurring in the second period).

Now the question should be asked, what is the gain from splitting the original investment into a two period investment? The answer in this case is there would be a loss on average: the expected NPV of the mission depicted in Fig. 2 is **$3.59B** while that of Fig. 4 is **$2.105B**. Given the underlying assumptions of the model – namely multiplicative return on investment which is a function of time – this makes intuitive sense because the earlier the search capability is deployed the higher the expected return is in Period 3. In summary, in this scenario the flexibility (option to abandon) has no value and the investment (mission) scenario of Fig. 4 is an inferior investment to that of Fig. 2.

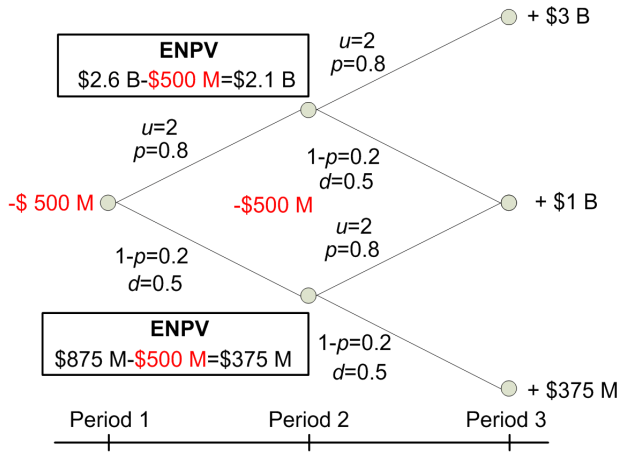

Figure 4: Scenario one with real option.

Scenario Two

In this scenario the mission represented by Fig. 3 is altered to become a two-phase mission scenario.

Determine the period one and two investments **–** These are identical at scenario one; $500M and $500M respectively.

Determine expected NPVs as viewed from period two **–** The expected NPVs of the mission (ENPVs) are again calculated from the viewpoint of period two and depicted in Fig. 5. Note that after a down outcome (at the end of period one) there is a negative expected NPV of –$175 M at the beginning of Period 2 assuming the second rover is deployed. In the event of an up outcome going into Period 2 the second rover would be deployed with expected NPV of $2.3B. The expected NPV for the scenario of Fig. 5 as calculated from (the beginning of) Period 1 is **$320 M**.

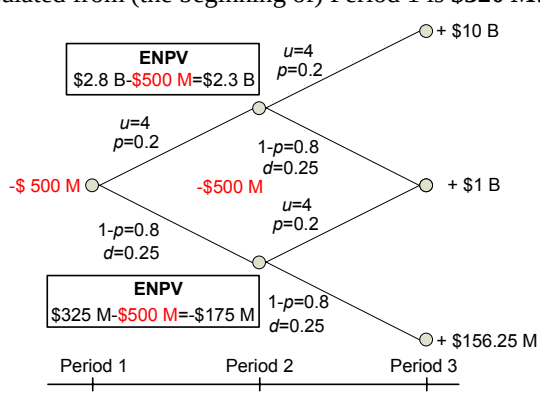

Figure 5: Scenario two with real option.

Valuation of the scenario with a real option—calculating the expected (total) net present value of scenario two from Period 1 is now accomplished using the binomial *decision-tree* model of Fig. 6. Here if a down outcome occurs in period two, there is no further investment and the expected NPV in period two is $0 (the option to abandon is exercised).

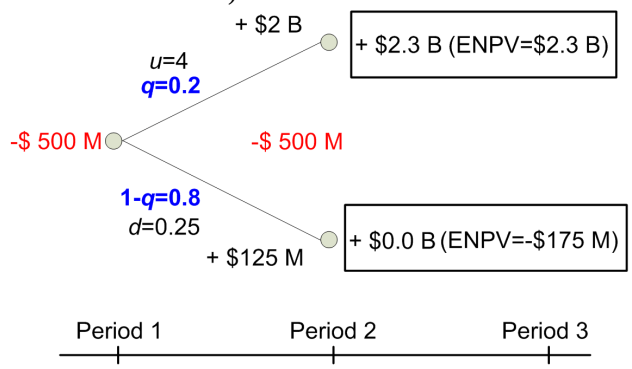

Figure 6: Scenario two with binomial decision tree and real option.

In the model of Fig. 6 q is the risk-free probability and is given by:

$$q = \frac{1-d}{u-d} = \frac{1-0.25}{4-0.25} = 0.2$$

While q=p in this scenario, this is generally not the case; q is referred to as the risk-neutral probability because q is the value p has if the investor is risk-neutral[2] [2]. In this scenario and that of Fig. 3 p was chosen such that risk matches the up and down multipliers of the original investment; these is no reason to believe this would be the case in a real space mission. The expected net present value of the scenario in Fig. 6 with real option is then:

$$(0.2\times 2 + 0.8\times 0.125) + (0.2\times 2.3 + 0.8\times 0) - 0.5 = \$460\text{ M}$$

Note that the $500M investment in Period 2 is subtracted in the calculation of the expected NPV of $2.3B. This valuation of $460M is significantly less than the $1B valuation of Fig. 3. The next questions to answer are "what is the value of the real option and how does it affect risk?"

Value of the Real Option (Flexibility)

Scenario of Fig. 6 versus scenario of Fig. 5 – The value of the option is the expected NPV using the binomial

[2] An unresolved issue here concerns whether NASA (as a government agency) should be risk-neutral altogether without regard to whether uncertainties can be hedged (with a traded twin security) or not. Following in the footsteps of [1] we also take the viewpoint that "the public goods aspect of NASA investments suggests that NASA should be risk-neutral in valuing its R&D projects, thus validating the use of a riskless discount rate".

decision-tree model with integrated real option minus the expected NPV using the conventional binomial event tree model and is given by:

$460 M – $320 M = $140 M.

Scenario of Fig. 6 versus scenario of Fig. 3 – The difference in the expected NPVs is $460M – $1B = –$540 M. Architecting the flexibility (option) – creating a two-phase approach or campaign as opposed to a single mission – has effectively lost an expected (not deterministic) $540M in return. However, it is important to use this number in conjunction with knowledge of how the flexibility has changed risk.

Consider that for the scenario modeled in Fig. 6 the probability of a negative outcome is **0.8**, and the loss associated with this outcome is $125M - $500M = **–$375 M**. While in the scenario modeled by Fig. 3 the probability of a negative outcome is **0.64** with a loss of $62.5M – $1B = –**$937.5M**. In the scenario with option to abandon the probability of a negative outcome is increased by **16%**, but the loss in that outcome is reduced by **$562.5M** (~56% of the original investment of $1B). The expected loss given the mission has only down outcomes – the mission experiences worst case conditions – or the two scenarios are as follows:

Scenario of Fig. 6 → 0.80 × – $375 M = –$300M

Scenario of Fig. 2 → 0.64 × – $937.5 M = –$600M

Even though the ***value*** of the option to abandon is now known (an expected –$540M) the ***utility*** of implementing a two-phase mission approach with option to abandon versus a single-phase mission is not straightforward to analyze. However, it should be clear that such utility is virtually impossible to characterize – at least quantitatively – without estimating the value of the option. At the "heart of the problem" of analyzing this utility – obviously a critical part of mission design – is the classic dilemma of choosing between increased return with relatively higher risk versus decreased return with relatively lower risk. As with most real-world economic problems there are no "absolute" correct answers, only "trade-offs."

Extensions

Table 1 indicates the option to abandon value with varying investment profiles in the two-period scenarios of Figs. 5 and 6. Table 2 indicates the worst-case outcomes for the single-period and two-period scenarios of Figs. 3 and 6, respectively.

Period 1 Investment	Period 2 Investment	ENPV with No option	ENPV with option	Value of real option
$500 M	$500 M	$320 M	$460 M	$140 M
$100 M	**$900 M**	**-$224 M**	**$188 M**	**$412 M**
$900 M	$100 M	$864 M	$864 M	$ 0
$500 M	$900 M	$176 M	$586 M	$332 M
$900 M	*$500 M*	*$720 M*	*$780 M*	*$60 M*

Table 1: Value of real option with different investment profiles

Period 1 Investment	Period 2 Investment	Loss with down outcome in Period 2 (Fig. 6)	Loss with down outcome in Period 3 (Fig. 3)
$500 M	$500 M	–$375 M	–$937.5 M
$100 M	**$900 M**	**–$75 M**	**–$937.5 M**
$900 M	$100 M	–$675 M	–$937.5 M
$500 M	$900 M	–$375 M	–$1.3124 B
$900 M	*$500 M*	*–$675 M*	*–$1.3125 B*

Table 2: Worst-case outcomes for the scenario with two-period investment and real option (Fig. 6) and single-period investment (Fig. 3), with probabilities of 0.8 and 0.64 respectively

Given the information in tables 1 and 2 the strategy to reduce risk is clear; the investment in Period 1 should be made as small as possible until uncertainty is bought down – observe the bold highlights (technology, design, and engineering would likely set the lower practical limit on cost of developing a mobile lander to accomplish the necessary functions). This is also what intuition would indicate – with the absolute lowest risk strategy being to invest $0 and doing nothing.

The strategy to maximize expected return, howbeit with significantly increased risk, is highlighted in italics with investment of $1.4B. The expected NPV for the scenarios of Figs. 3 and 6 are given as:

Scenario of Fig. 3 → $1.4 B ENPV

Scenario of Fig. 6 → $720 M ENPV

For the scenario of Fig. 3 the loss in a down outcome for this highest expected NPV case is –**$1.3125 B**, that is **~94%** of the original investment of $1.4 B, and this occurs with **64%** probability. For the scenario of Fig. 6 the loss in a down outcome is –**$675 M**, that is **~48%** of the original investment, and this occurs with **80%** probability. Note that in Table 2 the single period investment for the scenario of Fig. 3 is set equal to the sum of the period one and two investments for the scenario of Fig. 6.

What is the utility of one of the mission scenarios in Tables 1 or 2 over another? Clearly it is difficult to package the answer in an equation or formula. The investor's tolerance for risk plays an enormous part in answering this question and may or may not be a rational quantity from an economic perspective. As example consider how non-economic and non-technical political

events can collectively impact a space mission investor's tolerance for risk

Sensitivity Analysis

While sensitivity analysis of the parameters (probabilities, multiplicative factors, etc.) and underlying assumptions of the models of Figs. 2-6 was beyond the scope of this work, this is a critical component in applying a real options framework. There are many assumptions in modeling real-world investments (in this case space missions); it is important to understand the sensitivity to errors in these assumptions before results are applied to trade studies comparing one mission strategy against another and other mission analysis/synthesis activities.

7. CONCLUSION

The primary components of a real options framework were introduced and then applied to the analysis and synthesis of a hypothetical mission. The analysis and exampled ignored the cost of capital in an attempt to maximize clarity; in actual application the cost of capital often cannot be ignored without generating invalid and possibly misleading results.

Finally it is the opinion of this author that the real options framework is a powerful analysis/synthesis tool for space mission design. This tool incorporates insight for quantitatively valuing flexibility for managing and/or mitigating risk inherent in an uncertain future. The framework provides insights for making trade-offs and asking and answering important questions that are required when architecting flexibility for risk management, as abstractly portrayed in Fig. 7. This figure is consistent with the underlying philosophy that mission investment decisions should be valued and have their utility assessed as quantitatively as possible in the larger context of what follows them and what the long term objectives of the space program are. Finally, the formal application of the framework is in its infancy not only in certain areas within the space industry but numerous other investment endeavors as well—including numerous technology development programs.

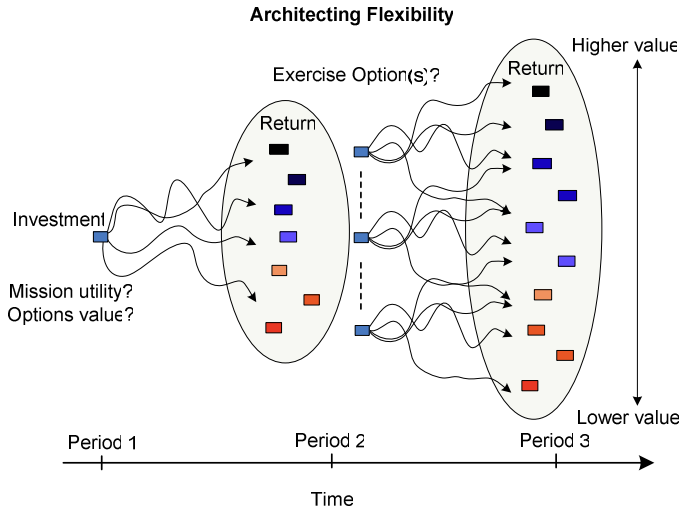

Figure 7: Architecture flexibility

REFERENCES

[1] R. Shishko, D.H. Ebbeler, and G. Fox, "NASA Technology Assessment Using Real Options Valuation," *Systems Engineering*, vol. 7, no. 1, 2004.

[2] L. Trigeorgis, *Real Options: Managerial Flexibility and Strategy in Resource Allocation*, The MIT Press, Cambridge, Mass., 2000

[3] F. Black, M. Scholes, "The pricing of options and corporate liabilities," *Journal of Political Economy*, vol. 8, pp. 637-659, May-June 1973.

[4] R.C. Merton, "Theory of rational option pricing," *Bell Journal of Economics and Management Science* vol. 4, no. 1, pp. 141-183.

[5] J. Hull, *Options, Futures, and other Derivatives*, Prentice Hall, Upper Saddle River, N.J., 2002.

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