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ENGINEERING SYSTEMS ANALYSIS FOR DESIGN
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APPLICATION PORTFOLIO

A REAL OPTIONS APPROACH TO THE PURCHASE OF RAW MATERIALS IN ADVANCE FOR THE MANUFACTURE OF THE SPACE TRANSPORTATION SYSTEM'S EXTERNAL TANK

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EXECUTIVE SUMMARY

Real Options theory has been applied to the design and uncertainty surrounding the External Tank of the Space Shuttle or Space Transportation System. Using a cost model developed during the Spring of 2006, this analysis will apply Real Options to the problem.

First, conventional NPV analysis was conducted using baseline design specifications with a corresponding initial cost to produce one External Tank. This baseline design was evaluated using a decision tree about whether or not to pursue the new design. The decision was that in all cases, the older design would be best. However, upon reevaluating new assumptions about the data, a new decision tree suggested that waiting two years to make a final decision had value, even if it did suggest using the older tank design. Furthermore, NASA has already determined to proceed with the development of the new design, suggesting that the cost model does not take into account certain important considerations.

This analysis explores the idea that the decision remains open whether to pursue the new design option or to pursue the original tank design. Therefore, an analysis in the face of uncertainty was conducted to determine whether the optimal decision would be to purchase all of these new systems at once or to have the flexibility to make the decision to purchase each year. If the decision was made to purchase the tanks each year, a subsequent decision would then need to be made as to which design to pursue. Several candidate uncertainties were evaluated and the variable price of the raw materials for the External Tank was selected as the most representative and amenable to this modeling approach.

The modeling approach and analysis suggests that accounting for the uncertainties of the variability of the price of the manufacturing raw materials of the external tank, the best option is to maintain flexibility in the procurement decision each year for External Tanks – with some exceptions. However, it is the opinion of this author that the results are not as clear as could be and this result is due to the granularity and low fidelity of the model. Furthermore, given the extremely risk adverse nature of NASA and the desire to maintain ultimate flexibility (e.g. if perhaps a critical design flaw is discovered along the way), the cost of including the flexibility in the system at all times is worth paying. Furthermore, this analysis gives NASA decision-makers a much more realistic view of all of these costs over time and the use of this analysis will allow them to budget more realistically. Having a more realistic budget outlook will diminish the inherent turbulence in government development programs and avoid cost-cutting measures that may result in additional design changes and increased risks to the overall program.

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DESCRIPTION OF THE EXTERNAL TANK PROBLEM

The Space Transportation System (STS) External Fuel Tank design was chosen for real options analysis. The STS has been flown since 1980 and has a rich history to support this application portfolio. The model being used for this problem originally started from the same EXCEL model created by Prof Wilcox and Prof de Weck (previously used in another Real Options class application portfolio). However, the model has been substantially modified since then by Mark Baldesarra and Robb Wirthlin (Baldesarra and Wirthlin 2006). For instance, it has also been translated into a MATLAB model, which provides greater flexibility in dealing with multi-attribute and multi-objective questions. The EXCEL model uses the SOLVER routine to find optimal solutions given set constraints and variables.

The objective of the original model was to maximize the incremental change in payload mass by changing the properties of the External Tank, subject to the constraint that the stresses in each wall section must be under yield stress and the fundamental mode of vibration is sufficiently far from resonance.

New modifications to the model were done so as to make the model more realistic, especially given the new STS constraint requiring the orbiter to reach the International Space Station during all flights. The Shuttle is designed to launch a payload of up to 25,000 kg into orbit (NASA 2006), so the model was modified so that the External Tank would be optimized for a fixed payload mass. Again, this is a different objective from the original model regarding the STS External Tank design.

MODEL DETAILS

The External Tank is represented by three hollow sections: a thin-walled cylinder with a hemispheric end-cap welded to the bottom and a nose cone welded the top as shown in Figure 1. The fuel, comprised of LOX and LH2, is contained inside this structure, and the entire internal volume is available for holding fuel.

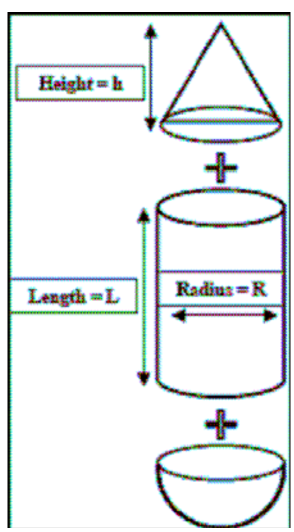

Figure 1: External Tank representation (Schuman 2002)

The cylinder, cone and hemisphere sections are welded from 4 pieces connected by seams that run the length of the sections. The radius of the cone and hemisphere are equal to the radius of the cylinder. The tank walls of the three sections have separate material thicknesses that are independent of each other.

ASSUMPTIONS

This representation is based on several simplifying assumptions. The actual ET contains several cryogenic tanks that hold LOX and LH2 and large amounts of internal and external piping to deliver the propellant to the Space Shuttle Main Engines (SSMEs). Furthermore, the ET has structural connections that support the Solid Rocket Boosters (SRBs) which are mounted on the sides of the tank through the initial part of launch sequence (Sigur 2005).

Although the representation of the External Tank in the model is an approximation and neglects important properties of the tank, for the purposes of mass and cost optimization we feel it is sufficient to capture the main effects of changing geometry and wall thicknesses.

KEY VARIABLES

There are six design variables of two types, tank dimensions and wall thicknesses, which characterize the properties of the External Tank. They are the overall tank length, the radius of the cylindrical section, the wall thicknesses in each of the three sections, and the height to radius ratio for the nose cone.

The model considers the cost of the tank material to be fixed. This, however, should be considered as variable during this analysis. Furthermore, the costs of the LOX and LH2 were never considered in the model. These costs could also be used in this analysis but will be ignored as being outside of the scope of this effort. Finally, in the multi-objective analysis model, the material cost is directly related to the tank mass but the seam cost is inversely proportional to the thickness (as it is more difficult and costly to connect thinner sections). Thus, there is a non-linear scaling function that scales the seam cost up as mass decreases. A comparison of the manufacturing cost components shows that the seam cost is generally much higher than raw material costs. Therefore the manufacturing cost objective as a whole increases as the mass decreases, so these two objectives are mutually opposing. This trade between mass and manufacturing cost implied that a Pareto front of non-dominated solutions could be generated to represent this trade-off.

Further analysis of the model found that there are designs that are better than the baseline External Tank, which was used as a guide. The remaining issue is which point on the Pareto Front would be selected as the "optimum" design. The resulting Pareto Front represents a continuum of "optimum" choices for different relative importance of the design variables, *so the final selection would be a more qualitative sense of which objective is more important.* This is where a Real Options analysis could provide the most insight. What is most important? Obtaining the lowest cost (in manufacturing) or maximizing payload (kg to orbit)?

This analysis would like to provide insight into the trade space of External Tank design and options decisions based on the degree to which the new constraints (e.g. must fly to and remain in the higher International Space Station orbit) has impacted the "business case" of using the STS.

DEFINING THE SALIENT UNCERTAINTIES

Following a high-level review of the literature, the top three uncertainties for this Application Portfolio are:

1) Uncertainty in the ability to support launch requirements for ISS module delivery and re-supply (number of launches per year) – given 3 orbiters
2) Uncertainty of integration time to shuttle – potential impact to launch schedule
3) Uncertainties of costs of manufacturing materials of External Tank

Each of these three uncertainties will be discussed in more detail below. Since most of these uncertainties relate more to the Shuttle and the overall system, there may be concern that they do not relate. However, these uncertainties will still play a role in the External Tank acquisition and development. For instance, should all of the External Tanks be bought in a single buy in advance (but what about storage costs, etc), or should they be procured "just in time"? Is there a minimum buy "lot" to obtain "preferred pricing" or will NASA pay exorbitant fees for the flexibility demanded by the system? Will ISS module designers demand every possible bit of available payload mass or does NASA require less flexibility (and more safety margin) in the amount of payload possibilities (demanding max payload may push the limits of the system to unacceptable risk levels) since the Columbia accident?

UNCERTAINTY #1

Regarding the uncertainty in the ability to support launch requirements for ISS module delivery and re-supply, the following sampling of relevant data will help establish the concerns.
1) Historically proven variability above and beyond "normal" variability
   i) Problems with Shuttle: Examples here in the past include leaks in the 1989-1990 time-frame, electrical wiring problems in the late 1990's, and most recently post-Columbia rudder-speed brake anomalies.
   ii) Unforeseen problems with ISS components
2) Political considerations forcing reviews, studies and often re-designs of either hardware/software, processes or organizations

There are data available to assist in understanding this uncertainty. For instance, the following table illustrates the planned launch schedule as available in 2005.

Year (CY)	2005				2006				2007				2008				2009				2010			
Quarter	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Discovery		114			116		118	122		125		127		129	131			134						
Atlantis			121	115		117		120	124							132		135		137		139		141
Endeavour							119		123			126	128		130		133			136	138		140	

Table 1: Space Shuttle Manifest (STS-Missions by Orbiter) (Cates and Mollaghasemi 2005)

However, the schedule below is the latest from NASA, updated September 28, 2006, and is the current launch schedule for only those missions in terms of supporting the ISS (NASA 2006). Notice the disparity that already exists in less than 1 year from the "plan" above and the "current plan" below. Of course, there still exists a potential for other "science-only" related missions to be added to the NASA launch schedule (as depicted by the out of date table above). However, these may have already been entirely scrubbed to meet the US obligations to the ISS. The turn-around time is on the order of several months for each vehicle. The schedule shows an admission of uncertainty with NASA using the term "no earlier than" in its dates and variability of several months from published schedules (see example above, for example).

NET Dec 7, 2006 12A.1 Discovery STS-116
NET Feb. 22, 2007 13A Atlantis STS-117
NET June 11, 2007 13A.1 Endeavour STS-118
NET Aug. 9, 2007 10A Atlantis STS-120

NET Oct. 2007 1E U.S. Orbiter STS-122
NET Dec. 2007 1J/A U.S. Orbiter
NET Feb. 2008 1J U.S. Orbiter
NET June 2008 15A U.S. Orbiter STS-119
NET Aug. 2008 ULF2 U.S. Orbiter
NET Oct. 2008 2J/A U.S. Orbiter
NET Jan. 2009 17A U.S. Orbiter
NET April 2009 ULF3 U.S. Orbiter
NET July 2009 19A U.S. Orbiter
NET Oct. 2009 *ULF4 U.S. Orbiter
NET Jan. 2010 20A U.S. Orbiter
NET July 2010 *ULF5 U.S. Orbiter

UNCERTAINTY #2

Regarding the uncertainty of integration time to shuttle and its potential impact to launch schedule, the following information is relevant.

1) Mission complexity introducing extreme unexpected delays into Shuttle processing flows (e.g. STS-41, Planetary Mission).
2) Increased engineering conservatism
3) New hire additions to the work-force, lack of corporate memory
4) An aging fleet
5) An aging infrastructure
6) Political considerations forcing reviews, studies and often re-designs of either hardware/software, processes or organizations

This uncertainty is really a set of multiple uncertainties that are difficult to pinpoint root causes but the results are apparent in history as well as simulation. The following graph (Figure 2) is an historical example of shuttle processing times, followed by simulation results (Figure 3) that attempt to quantify the impact of representative potential issues, as listed above.

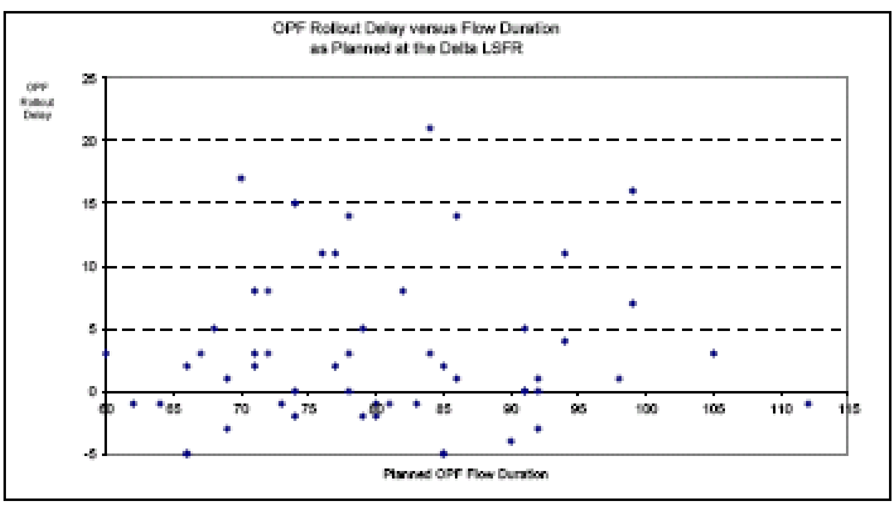

Figure 2: Variability (days) vs. STS Flow Number Designation, in Planned vs. Actual Orbiter Processing Time, Analysis Courtesy of Grant Cates, NASA Kennedy Space Center, Shuttle Processing Directorate (Zapata 2004)

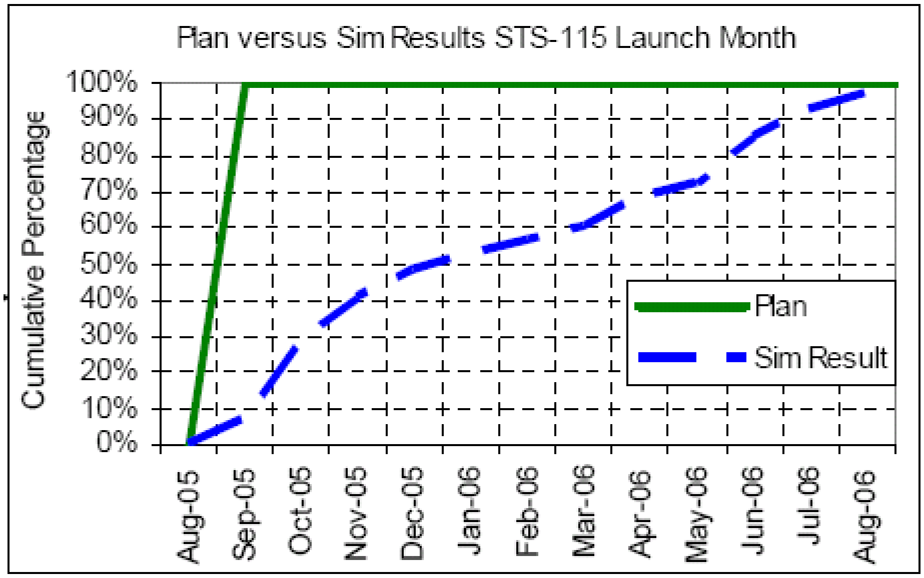

Figure 3: Planned completion versus simulated completion of pre-launch preparations. (Cates and Mollaghasemi 2005)

UNCERTAINTY #3

Regarding the uncertainties of costs of the manufacturing materials of External Tank, the following pieces of information are very important.

1) Costs of Aluminum
2) Costs of Lithium

Finally, information about the costs of the raw materials for the External Tank is shown below. The data clearly shows variability in the prices of the raw materials. Furthermore, the price of Aluminum will be used as a surrogate for the price of the Aluminum Lithium alloy for reasons outlined below.

The metal used in the External Tank is an Aluminum/Lithium Alloy, AL-Li 2195, "composed of 1 percent lithium, 4 percent copper, 0.4 percent silver, and 0.4 percent magnesium, with the remainder aluminum" (NASA 2005). "The 2195 aluminum-lithium alloy is 30 percent stronger and 5 percent less dense than the original 2219 alloy used. It can be welded and withstands fractures to a temperature of minus 423 degrees—the temperature at which the liquid hydrogen propellant is stored on board" (NASA 2005). The alloy properties are the result of the manufacturing process and the amounts of Lithium. The different manufacturing processes and Lithium raw material costs are where significant prices differences will occur in the alloy. According to one industry source, the actual cost of the alloy is approximately 2x to 3x of standard aluminum (Wikipedia 2006).

Figure 4: Price Chart of 5-year Aluminum (Kitco.com 2006)

Insights into Lithium: There is evidence of a growing market trend: Prices of lithium carbonate rose by 20% in 2005 and growth of up to 25% is forecast by Roskill Consulting Group for 2006, bringing prices back to the peak levels seen prior to SQM's entry into the market in 1996 (Wikipedia 2006). New capacity due on-stream in Chile, Argentina and China is forecast to alleviate the upward pressure on prices after 2007 (Wikipedia 2006).

a. Consumption of lithium increased by 4-5% per year between 2002 and 2005, driven by demand in lithium secondary batteries. Batteries accounted for 20% of total consumption in 2005, a rise from under 10% in 2000 (Wikipedia 2006).
b. Continued expansion in the portable electronic products market and commercialization of hybrid electric vehicles using lithium batteries suggest growth of up to 10% per year in lithium carbonate consumption in this market through 2010 (Wikipedia 2006).
c. Between 2002 and 2005, lithium minerals production rose by 7% per year to reach 18,800 tons Li. Chile and Australia account for over 60% of total output. FMC Lithium of the USA, Chemetall of Germany and SQM of Chile continue to dominate production of downstream lithium chemicals (Wikipedia 2006).
d. China may emerge as a significant producer of brine-based lithium carbonate towards the end of this decade. Potential capacity of up to 45,000 tons per year could come on-stream if projects in Qinghai province and Tibet proceed (Wikipedia 2006).

The next two graphs are limited in usefulness as the data is 10 years old, except to show that prices historically are variable over time. This is particularly true for Lithium as its use worldwide has increased significantly due to advances in battery technologies.

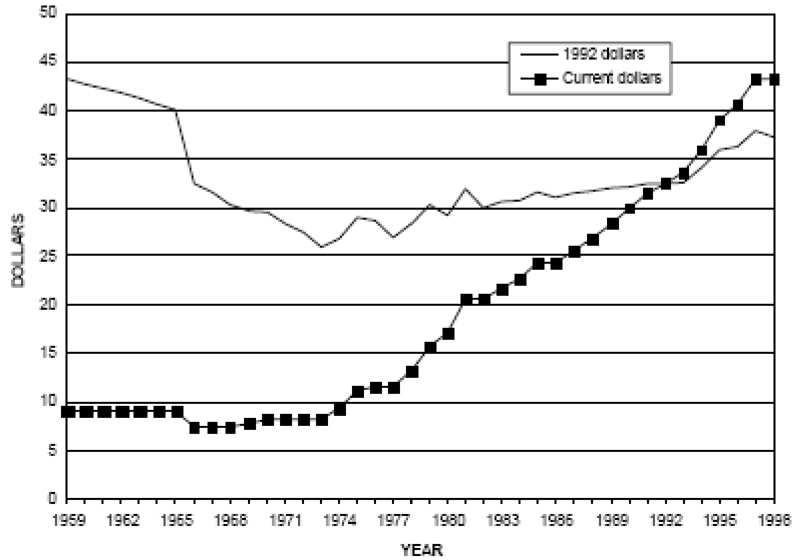

Figure 5: Year-end Average Lithium Price (Dollars per pound) (USGS 2006)

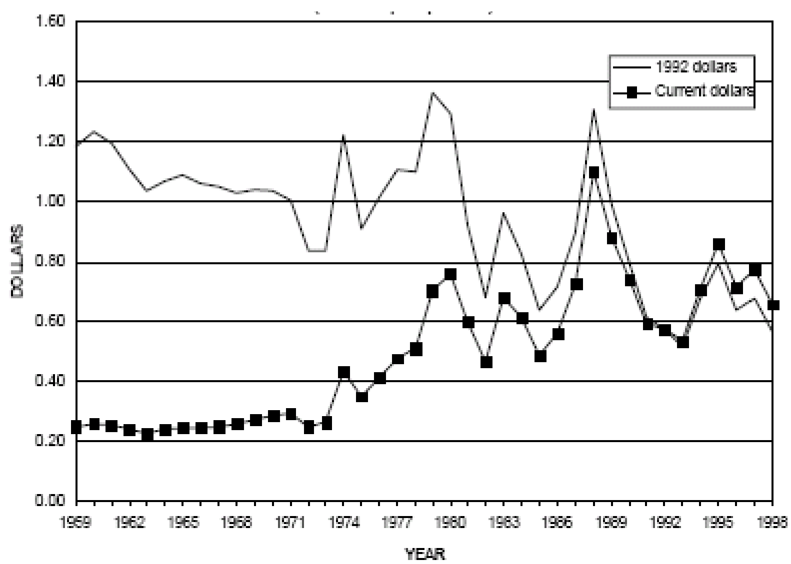

Figure 6: Annual Average Primary Aluminum Price (Dollars per pound) (USGS 2006)

DEFINE THE MEASURES FOR THIS APPLICATION.

Based on the data above, there are several measures that could be used to quantify the degree of uncertainty that could be encountered in the STS and External Tank. These are listed in order of the uncertainties named above.

1) Range of possible outcomes around a standard deviation (based on historical data). See (Zapata 2004).
2) Range of possible outcomes (based on simulation data). See (Cates and Mollaghasemi 2005).
3) Expected values of base metal prices (fit-curve data) See (Wikipedia 2006).

SIMPLIFYING THE UNCERTAINTIES

There are significant amounts of potential variability/risk/etc in the Space Shuttle system. A higher degree of attention must be paid to these factors and their potential impact to the overall system. *The flexibility in the design parameters of the External Tank may be key* to meeting the potential variability in the remaining life of the US Space Transportation System (aka the Space Shuttle).

For purposes of this analysis, the uncertainties regarding the prices of the metals used to manufacture the External Tank will be used as the subject of real options analysis. The other two options are more about uncertainties posed ON the system. The variability of the raw material price is variability IN the system.

DEFINING SYSTEM DESIGNS TO BE ANALYZED

The External Tank system design to be analyzed through the application of real options will be the decision required by NASA to determine if they should buy the new design or remain with the old design and can revisit this decision over time based upon the current market price of the External Tank.

Key Assumptions: NASA is constrained by its budget (having enough to pay the bills) each year and its schedule (it must complete the ISS construction per international agreements).

INITIAL DECISION ANALYSIS

The External Tank dilemma for NASA can have two different approaches: First would be the original tank design or a newer tank design. The design will remain unchanged for the duration of the remaining space shuttle program. The production costs will be fixed at the outset of the production. In this case, the fixed launch schedule is 5 launches per year for 4 years. This equates to 20 more launches until the retirement of the Space Shuttle. We will assume that the cost of long term storage for the tanks until they are needed is included in the base price and does not amount to anything substantive. This option allows these to be purchased all at once and stored until needed.

The base case would be to purchase the Aluminum Tank (original) design or the Aluminum-Lithium (new) tank design for the remainder of the space shuttle program. NASA would not be able to adapt to how the market evolved regarding the costs of these materials. Note: The new design is appealing to NASA because of other properties such as reduced weight but costs more to produce than the original tank. We will assume NASA is using the original tank design for the base case to avoid the extra costs that will be incurred if buying the newer tank design.

TWO-STAGE DECISION ANALYSIS OF ALTERNATIVE DESIGNS

A more flexible and two-stage approach would be to use the original design or the new design for just a two-year period and then reviewing its position recognizing how the market may have evolved over time.

We can now illustrate how this flexible approach could be done. Stage 1 would be defined as NASA buying the original design or the new design. Stage 2 would then be the reaction to the uncontrollable but observable market evolution after two years where NASA could take an option.

They could continue with the original choice or change its choice of tank design based on the price of the materials.

The outcome of the market can be of three types:

- If the prices of Aluminum go down, it means it is cheaper to construct the original design. It also means that the newer design would be cheaper to build too, but not as much as the original design and NASA would have to decide if the other benefits (more payload to orbit within same original cost) were worth the extra amount paid.
- If the prices of Aluminum increase, both designs would cost more. NASA would need to decide if the extra cost was worth it.
- If the prices of Aluminum remain the same, NASA can still choose either alternative.

This gives us, with a 3-level approach (high, low, forecast), a design space for each of the scenarios.

The complete options tree is illustrated by the following graphic.

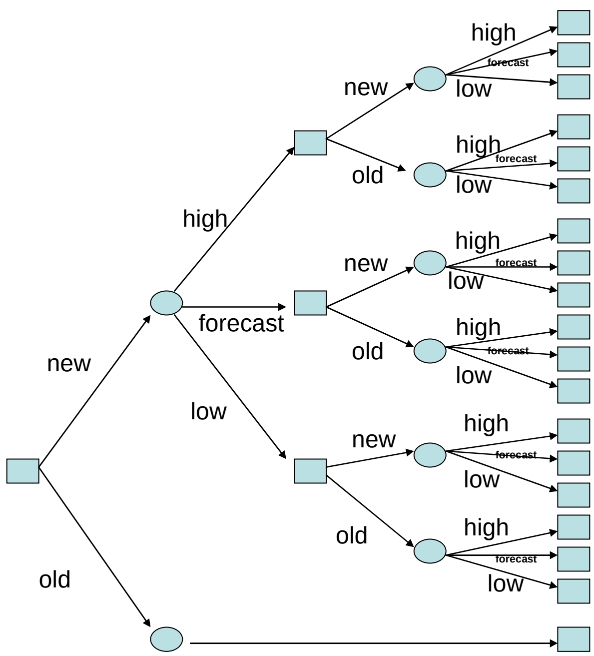

Figure 7: Options Tree

This decision tree can possibly be simplified by taking out the irrelevant branches (the ones that worsen the situation). However, due to the unusual characteristics of the External Tank and its design, all of the branches will be carried forward and evaluated.

From the initial data collection, we learn that the price of Aluminum in the past 5 years has been increasing about 12% per year, but with some variability and uncertainty. Therefore we will assume that the probability of prices going up will be 0.50, the probability of prices staying the same is 0.35, and the probability of prices going down is 0.15. We will use the unit cost of the External Tank as the measure of Expected Value. Scaling these by the total number of tanks purchased is not necessarily helpful. Our objective will be to minimize the cost needed to be paid, or to take the lowest values on the decision tree. The expected value of this decision tree can be found by filling in the values for each possible outcome, and then calculating with the probabilities.

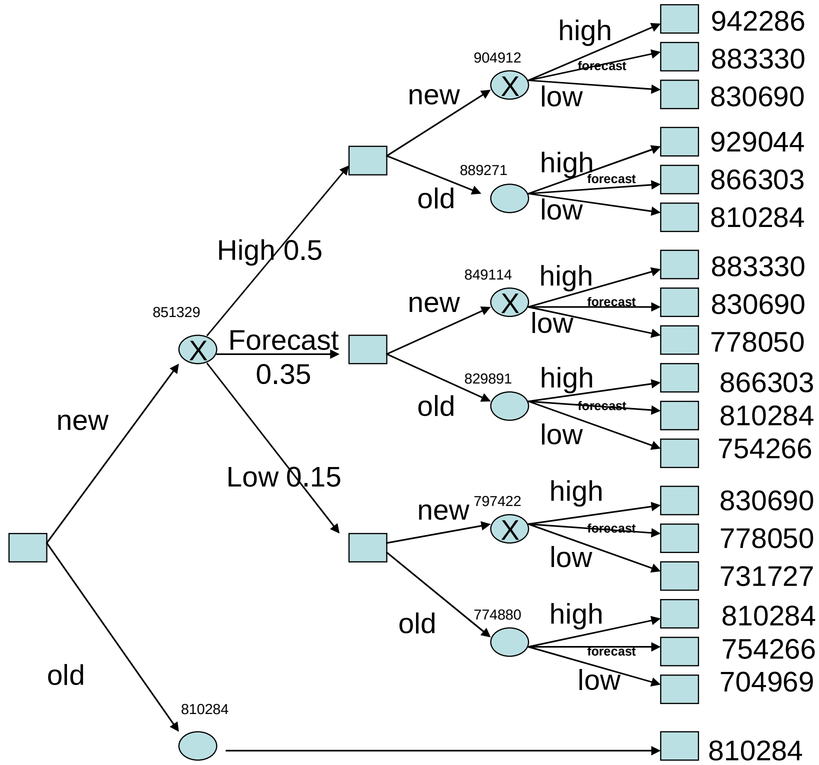

Figure 8: Decision Tree

The decision tree shows that the best decision is to stick with the original design from the outset. As the escalating factor for the price of Aluminum is 12% a year, it is not a surprising outcome to purchase all of the External Tanks in advance. However, the new design has several benefits, such as a reduced weight, which means being able to put more material into orbit. In this case, the outcome of the decision tree would probably be overruled by NASA administrators because the relatively cheap costs of putting additional mass into orbit using the new External Tank design is a very cheap $19/kg in a worst case, highest cost scenario – a cost that Congress or the other International partners are likely willing to pay, given current cost per kg ratios for other launch vehicles. This outcome probably reflects upon the coarse granularity of the model and suggests that there are other factors, perhaps more important, in this design.

Sensitivity analysis of the price variation of Aluminum shows that price trends for the past 5 years are not the best to use to predict future values. In an analysis of all historical prices since the late 1880s, the price of Aluminum has actually been decreasing by about 0.5% per year (CRU Strategies 2006). With this new information, the probabilities of how the price will move over time change. I estimate there is a 20% chance the price will increase, a 50% chance that the price will remain relatively the same, and a 30% chance that the price will go down. Therefore, a new decision tree analysis is appropriate using the new rate of price change. The associated decision tree is placed below.

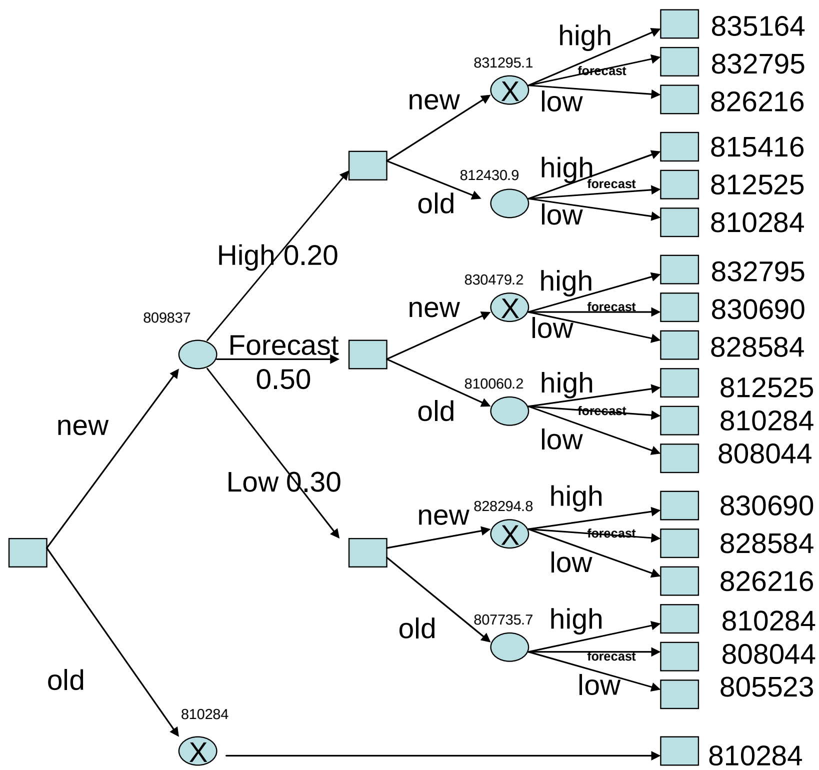

Figure 9: Revised Decision Tree

The analysis of the new information shows that NASA should not purchase all of the external tanks at once, but should delay the decision – however, the old External Tank design should be preferred. Again, given the high cost of putting material into orbit, NASA will probably ignore the results of this analysis and choose the new design, although it is more expensive than the old tank. The most important reason to choose the new design is that the new External Tank design is about 2100kg lighter. This translates to a direct payload gain of 2100 kg of material and as stated above, the relative cost of sending this extra material into orbit makes this option very attractive and relatively inexpensive.

LATTICE ANALYSIS OF EVOLUTION OF A MAJOR UNCERTAINTY

Given the results of the previous decision analysis, a more refined and substantive analysis is warranted. A proven tool and one that can more accurately model uncertainty is a lattice analysis.

Perhaps the largest uncertainty regarding the Space Shuttle External Tank is the cost of the material, the Aluminum-Lithium Alloy. As noted earlier, the cost of the Alloy is 2x – 3x the cost of Aluminum. To reflect the additional safety issues relating to manned human spaceflight, the assumed cost of the material will be 6x the normal cost of aluminum.

On November 3, 2006, the aluminum market price was $1.2610/lb. Therefore, the assumed cost of AL-2195 (aluminum-lithium alloy) will be $7.566/lb.

The standard deviation of the variable price of Aluminum is $0.088 per lb (CRU Strategies 2006).

Therefore, the standard deviation of Aluminum is = 0.088/1.2610 = 0.07

Variation of Aluminum prices over time is projected to be – 0.5% (CRU Strategies 2006). This is different than the assumed variability shown in the original decision analysis. The difference is accounted for by looking over the entire historical period for which data is available and not just the previous 5 years.

Therefore, the following information can be calculated.

u = e exp (.07) = 1.07
d = e exp (-.07) = .93
p = 0.5 + 0.5(-.005/.07) = .464

OUTCOME LATTICE

7.57	8.10	8.66	9.27	9.92	10.61
	7.04	7.53	8.06	8.62	9.22
		6.54	7.00	7.49	8.02
			6.09	6.51	6.97
				5.66	6.06
					5.26

Table 2: Outcome Lattice of Aluminum Prices ($/lb)

PROBABILITY LATTICE

1.00	0.46	0.22	0.10	0.05	0.02
	0.54	0.50	0.35	0.21	0.12
		0.29	0.40	0.37	0.29
			0.15	0.29	0.33
				0.08	0.19
					0.04

Table 3: Probability Lattice of Aluminum Prices ($/lb)

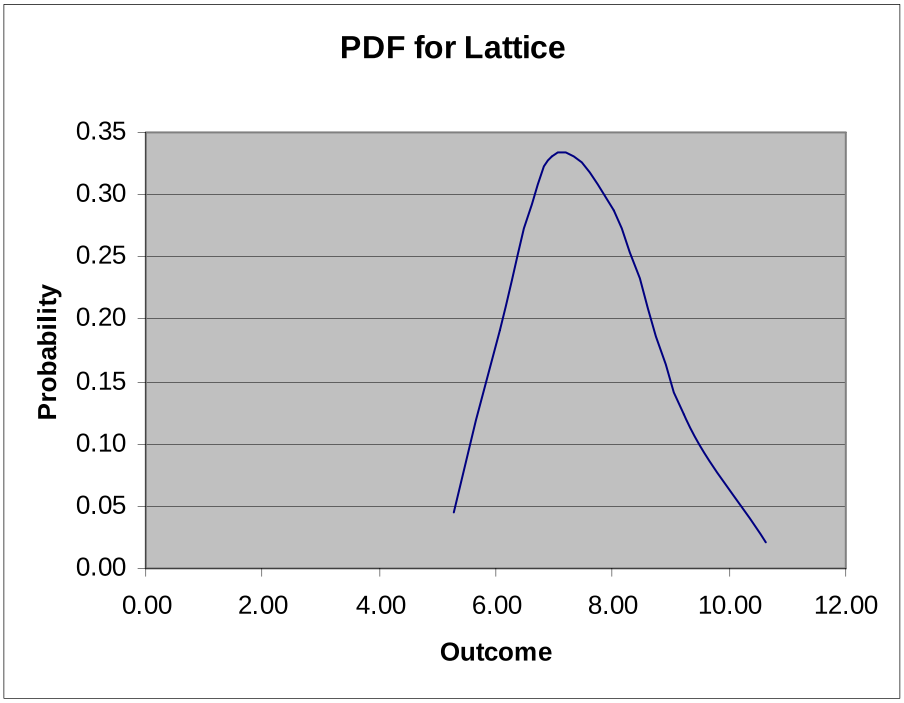

Figure 10: Probability Distribution Function for Lattice Outcomes

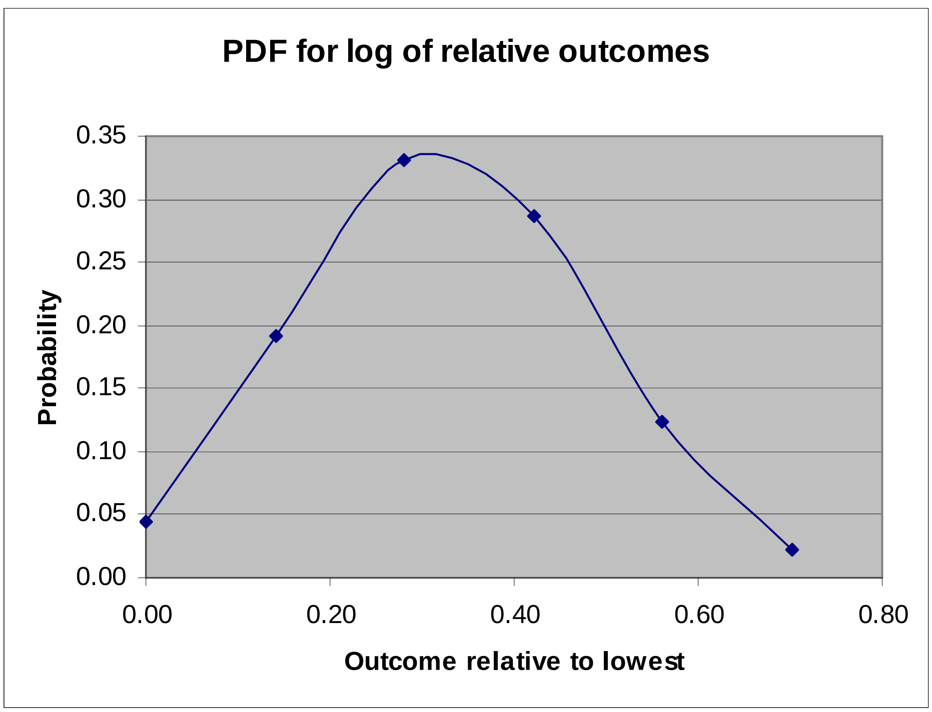

Figure 11: Probability Distribution Functions of

Model forecast = (forecast at time zero) a e exp (rt).
Model forecast = 1.2610 * 2.02 *e exp (step)

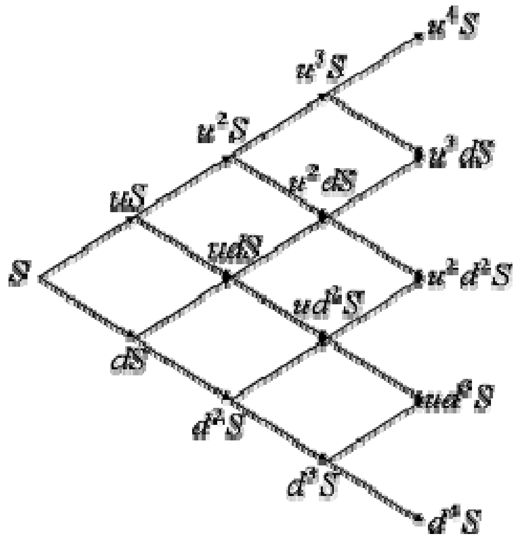

Figure 12: Outcome Lattice

This figure (Figure 10) is a representation of how the outcome lattice is calculated. It uses straightforward application of the values calculated above.

DECISION ANALYSIS USING LATTICE MODEL

Building upon the information gained in each step of the analysis and using the more sophisticated tools to more accurately reflect the prices and variability of Aluminum, a decision analysis to choose between the original design and the new External tank design can be done at regular intervals.

The following work assumes that the price of the Aluminum-Lithium Alloy directly reflects upon the ET tank costs (e.g. labor costs are held constant over time). The price of Aluminum was converted from dollars per pound to dollars per kilogram to be usable in the cost model, discussed earlier ((Baldesarra and Wirthlin 2006). Finally, a baseline purchase of 5 tanks per year is assumed.

First, a regular NPV analysis is conducted (labor costs are constant). The NPV of a 5-year contract is: $13.8 Million.

Year	**0**	**1**	**2**	**3**	**4**	**5**
Capacity (kg of material needed)	25688	25688	25688	25688	25688	25688
Demand (kg of material needed)	25688	25688	25688	25688	25688	25688
Production (kg of material needed)	25688	25688	25688	25688	25688	25688
Unit Price (dollars)	16.67	16.59	16.50	16.42	16.34	16.25
Cost of material (dollars)	428218.96	426077.8652	423936.7704	421795.6756	419654.5808	417513.486
Labor costs (dollars)	343368	343368	343368	343368	343368	343368
Unit Cost (dollars)	3857934.8	3847229.326	3836523.852	3825818.378	3815112.904	3804407.43
Discount Factor @ 12.0%	1	0.892857143	0.797193878	0.711780248	0.635518078	0.567426856
Present Value (dollars)	3857934.8	3435026.2	3058453.3	2723142.0	2424573.2	2158722.9
NPV (dollars)	**13799917.6**					

Table 4: NPV analysis without uncertainty

Next a NPV analysis was done by incorporating the uncertainties spoken of above. What follows is the overall outcome lattice (Table 5) and the probability lattice (Table 6). Using the information from both of these tables, the expected value of the 5 year period can be calculated (Table 7).

OUTCOME LATTICE						
Year	**0**	**1**	**2**	**3**	**4**	**5**
	4153450.00	4132734.58	4112122.48	4091613.19	4071206.18	4050900.95
		4174269.25	4153450.00	4132734.58	4112122.48	4091613.19
			4195192.87	4174269.25	4153450.00	4132734.58
				4216221.36	4195192.87	4174269.25
					4237355.26	4216221.36
						4258595.09

Table 5: Outcome Lattice

PROBABILITY LATTICE					
1.000	0.464	0.216	0.100	0.046	0.022
	0.536	0.497	0.346	0.214	0.124
		0.287	0.400	0.371	0.287
			0.154	0.286	0.331
				0.082	0.191
					0.044

Table 6: Probability Lattice

	EXPECTED VALUE					
Year	**0**	**1**	**2**	**3**	**4**	**5**
E[Revenues]		4154985	4156521	4158058	4159595	4161132
PV(E[Revenues])		3709808.303	3313553.226	2959623.27	2643497.569	2361138.146
NPV =	14987621					

Table 7: Determining the Net Present Value of an Analysis with Uncertainty

The analysis shows that the probable cost over 5 years (due to accounting for uncertainty) will increase by about $1.1 Million. As NASA budgets are set years in advance, any shortfall would cause extreme difficulties. Therefore, the ability to know about this cost in advance is huge.

At this point, it is advisable to understand how important it is to have the option of whether or not to purchase the External Tanks each year versus a single purchase. The following table uses the lattice structure to analyze the value of having this option.

PRESENT EXPECTED VALUE WITH OPTION						
Year	**0**	**1**	**2**	**3**	**4**	**5**
PV Net Revenu	19141071	16696242	13995775	11010410	7707555	4050901
		16864042	14136435	11121067	7785018	4091613
			14278508	11232836	7863258	4132735
				11345727	7942285	4174269
					8022107	4216221
						4258595

Table 8: Net Present Value with the Option to Buy or Not Buy Each Year

In all cases, the Net Present Value of the Option is more than the single buy option.

Base Case	With option	Option Value
14987621	19141071	4153450

Table 9: Option Value

The value of this option is $4.1 Million dollars. This gives flexibility throughout the system.

0	**1**	**2**	**3**	**4**
TRUE	TRUE	TRUE	TRUE	TRUE
	TRUE	TRUE	TRUE	TRUE
		TRUE	TRUE	**FALSE**
			TRUE	**FALSE**
				FALSE

Table: 10: Decision Key

The strategy implied by the outcome would be to exercise the option every year to purchase the External Tanks needed for that year. Only when costs suggest that it is no longer cost effective to purchase the External Tanks each year, should an advance buy of External Tanks occur. This scenario occurs three times during year 4 and only after looking at the future state where the cost of materials has risen above the price that could have been used to make an initial bulk External Tank purchase. However, even in these 3 limited scenarios, given the Billions of dollars invested in the Space Shuttle and the International Space Station, it would in fact be prudent to purchase the option to buy or not buy each and every year.

At this point, a more detailed and sophisticated analysis would be required to inject the other modes of uncertainty into the system. Given the aggressive launch schedule and the uncertainty surrounding pre-launch processing time, it is not clear that 5 launches per year would be certain. Having the flexibility to buy or not each year would allow NASA flexibility and be able to be more confident in the budget request for the next 5 years of External Tank purchases. In other terms, having the flexibility of choosing to purchase all at once or waiting to purchase over time is worth roughly the cost of five additional External Tanks. This is very significant and would allow program management to budget accordingly, especially if others override recommendations and pursue a one-buy over multiple time periods option. If this case happened, the expected value with option would provide the decision-makers a realistic view of the funds required over time and a more realistic budget could be submitted for funding.

CONCLUSIONS

FLEXIBLE APPROACHES TO DESIGN AND VALUATION OF OPTIONS

In reflecting upon the analysis done for this problem and the overall options to go forward, the best places to use this method are in the early design stages of a project. It is very adept at running "what-if" scenarios as well as injecting a more realistic sense of probable outcomes given the amount of information known at that time. Taking this one step further allows for additional realism in projecting costs of manufacturing and development that are often so very wrong in forecasting.

Furthermore, an analysis such as this can also identify where within a system design flexibility is most useful. In this case, there is not as much flexibility in the External Tank design as originally postulated. But the value of this information can force other portions of the system design to be critically evaluated and possibly find additional options for adding flexibility.

Furthermore, after questioning the initial assumptions in the first decision tree led to a more robust answer. In this case, it is wise to question all assumptions and ensure that they are sound. The change in the initial assumptions underscored the value of having options and flexibility in a system.

PERSONAL LEARNING

I have found this exercise to be very enlightening. From an intuitive perspective, I have become skeptical of straightforward NPV analyses, but have never been able to articulate clearly my reservations. Now, I have a set of tools that will not only allow me to make some empirical judgments from existing data – not merely forecast data – that will be much more realistic in the predictive realm of possible outcomes. This is VERY powerful and will be a key to decisions made in the future.

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