An Engineering Systems Analysis of Crewed Lunar Exploration Habitation Alternatives

Prepared by:
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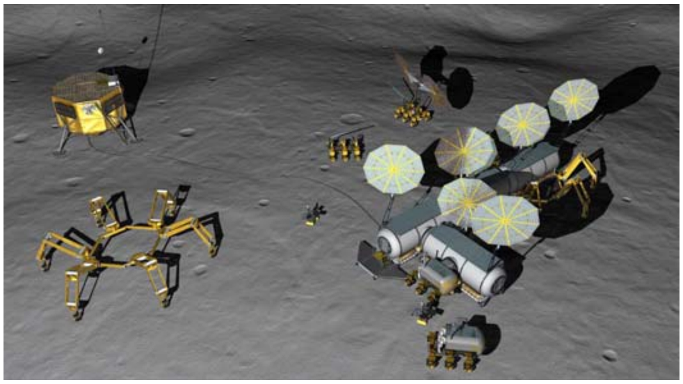

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An Engineering Systems Analysis of Crewed Lunar Exploration Habitation Alternatives

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This paper discusses various design alternative for developing and deploying lunar exploration habitats to support extended crewed missions to the Moon. The main "fixed" alternative studied includes developing a set of six interdependent habitats that, when assembled together, can support 180-day missions, but cannot support any missions until all elements are delivered to the lunar surface. The "flexible" alternative involves developing a set of six independent habitats that can also support 180-day missions when fully assembled, but can also support shorter missions dependent on the number of habitats delivered. The downside to this alternative is that the habitats would be more complex and therefore more expensive. To test which alternative is better in the face of an uncertain future, a decision analysis and a lattice valuation were performed. The decision analysis shows that the flexible alternative provides a higher expected amount of crew days when investigating the effects of uncertain project lifetime and uncertain flight rates. However, based on a benefit-cost ratio, the fixed alternative is preferable because of the lower development costs. Focusing on the fixed alternative, the lattice valuation shows the benefits of being able to cancel the program early because of the uncertain monetary value of a year of lunar surface exploration. With or without this flexibility, the development of habitats to allow extended lunar exploration appears to have a positive ENPV.

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I. Introduction and motivation

IN response to President G.W. Bush's Vision for Space Exploration, NASA is planning on returning humans to the lunar surface by 2020. In contrast to the "flags-and-footprints" missions of the Apollo program, this new endeavor, entitled Constellation, focuses on having humans live and work on the lunar surface for extended periods. This objective requires several complex systems to operate together including the lunar transportation system and the lunar surface system. One of the key components of the lunar surface system is the lunar outpost, which is made up of a collection of habitation modules. Because these modules are critical for supporting the astronauts during their extended missions on the surface of the Moon, it is important to ensure that the best configuration and implementation plan is chosen for the habitation modules.

Current architectures are based around the assumption that lunar crews will operate on mission rotations of approximately 180 days. In order to ensure enough habitable volume and due to the mass constraints of the lunar transportation system, an outpost that supports 180-day missions will require that several habitation modules operate together. While there are several various designs proposed, this paper will assume that each habitation module can provide enough habitable volume and equipment to support a crew for 30-days. Based on this assumption, six habitation modules will have to be delivered to the lunar surface to support 180-day missions.

While there are many factors that lead into the final design of the habitation modules, this paper will focus on one factor of particular importance: the interdependence between the habitation modules. One possible design, referred to as the fixed design in this paper, is to develop a system of habitation modules that have the subsystems and the required functionality distributed between the different modules. In this case, the six habitation modules, when assembled, will be able support a crew for 180-days, but they will not be able to support any crew before all the modules have been delivered to the lunar surface. The advantage of this is that the complexity, and therefore the cost, of each module is assumed to be decreased due to the distribution of its internal functions. The disadvantage of this is that all six habitation modules have to be launched and delivered to the lunar surface before any crews can be sent to explore the Moon. While it would be possible to send crewed sortie missions (i.e. missions of only a few days) to the lunar surface before the habitation cluster is ready, this option is not addressed in this paper.

The second possible alternative for designing the habitation modules is to make each module completely independent, known in this paper as the flexible design. This would mean that the complete subsystems have to be completely contained in each module, which would lead to higher complexity and higher costs. The advantage of this system is that crews could be sent to the lunar surface before all six habitation modules are delivered. The duration for these early crewed missions would be dependent on the number of habitation modules previously delivered as shown in

Table 1. To capture the costs of each alternative, NASA's JSC cost models were used to estimate the overall development and production cost of each module [NASA, 2008]. The difference between the two alternatives was captured by the assumption that the interdependent habitat modules were of "average" difficulty to develop, while the independent modules were of "high" difficulty. The cost model was able to use this information to provide the estimates shown in Table 2.

Table 1. Maximum crew duration as a function of the number of habitation modules for the two alternatives.

Number of modules	1	2	3	4	5	6
Fixed design – Maximum mission duration	0 days	0 days	0 days	0 days	0 days	180 days
Flexible design – Maximum mission duration	30 days	60 days	90 days	120 days	150 days	180 days

Table 2. Cost estimates for the two habitation module alternatives.

Type of habitation module	**Interdependent**	**Independent**
Overall cost [FY04 Million $]	$1,955	$3,040

The remainder of this paper focuses on the several methods of analysis for determining which alternative is the better choice when faced with the uncertainties in the system. A decision analysis is performed to determine which alternative produces more value, in terms of the number of cumulative crewed days on the lunar surface, for different possible futures based on the uncertainty related to the lifetime and flight rate for the project. A lattice analysis is then applied to the fixed alternative to show the benefits of having the ability of cancelling the project when faced with a varying economic return based on the annual return of value of having lunar astronauts explore the surface of the Moon.

II. Understanding the effects of uncertain project lifetimes and flight rates

Human spaceflight endeavors are heavily influenced by each new American presidential administration. As a newly inaugurated president takes office, they can place their mark on an exploration architecture by either maintaining the proposed flight rate, decreasing the flight rate, or terminating the program completely. As a starting point, it can be assumed that the crewed lunar exploration campaign will be operated for eight years (the maximum time in office for a president) starting in 2020. Based on current NASA architecture studies, it is also possible to assume that the baseline flight rate for the lunar exploration architecture will be two flights per year [Culbert 2008], comprising of a combination of cargo flights (delivering habitation modules) or crewed flights. This section will show how decision analysis can be used to determine which design alternative is preferred based on these sources of uncertainty.

The first part of determining the effects of the uncertainty is to quantify the uncertainty. To simplify the system, it will be assumed that the lunar exploration architecture has two four-year phases corresponding with the presidential election cycle (the first starting in 2020 and the second starting in 2024) and that at the beginning of each four-year cycle, the president can set the flight rate to two flights per year, one flight per year, or cancel the program for the following term. As previously stated, current estimates set this rate at two flights per year, but as history with the Space Shuttle has shown, these advertised flight rates are hardly ever met [Owens 2006]. Therefore, it is safe to assume that there is approximately a probability of 1/6th that the flight rate will equal the planned two flights per year. On the other hand, historical data has also shown that a significant amount of NASA programs are either cancelled or delayed for numerous reasons [Owens 2006]. Therefore, it is assumed that the chance of cancelling or delaying the program (by setting the flight rate to zero for four years) is approximately 1/3rd. Based on these assumptions, there is a 50% chance that the flight rate for any four-year period will be one flight per year, making this the most likely option. These probabilities are shown in Table 3.

Table 3. Probability of flight rates for four-year periods.

Number of flights/year	0	1	2
Probability	33.3%	50.0%	16.7%

It is important to determine how this uncertainty impacts the choice between utilizing interdependent or independent habitation modules. During this analysis, the focus will be on the profits or value derived from the system independent from the cost of the alternatives. The proximate metric used to capture profits for the system will be “cumulative crewed surface days on the lunar surface”. As stated in the previous section, the fixed (interdependent) alternative requires that six habitation modules be delivered on the first six flights of the campaign and the remaining flights of the campaign are 180-day crewed flights. The flexible (independent) alternative allows a reduced number of habitation modules to be sent before sending crew. To simplify the problem, it will be assumed that for each four-year term a set of habitats are sent before any crewed flights are sent and then only crewed flights are sent for the remainder of the four or eight flights during that term (depending on the flight rate). The number of habitation modules sent each stage is a decision that is performed based on the information available and the expected value for each option. To determine this, as well as whether or not the fixed or flexible alternative provides more expected crew-days, a decision analysis was performed.

The decision analysis for this problem will be broken down into three sections. The first section, which is assumed to take place before 2020, involves the early decision by NASA whether to develop the fixed (interdependent) alternative or the flexible (independent) alternative for producing habitation modules. This decision will be followed by the policy choice, considered a chance probability from NASA’s viewpoint, of whether the architecture will proceed as proposed (two flights per year), be reduced (one flight per year), or be cancelled for the duration of the four-year presidential term. At this point, it is assumed that NASA will have to make a one-time decision on how many cargo flights and crewed flights they will launch during the four-year period. For the fixed option, this is set by the directive that all habitation elements must be delivered first, but for the flexible alternative, the decision will be based on maximizing the profit. Near the end of the first four-year term, the second chance point will occur as the new or returning administration sets the future of the program. After this choice has been announced, NASA will decide how many habitation elements to deliver versus how many crew flights to send. The entire decision analysis is shown in Figure 1 and shown in expanded views in the appendix.

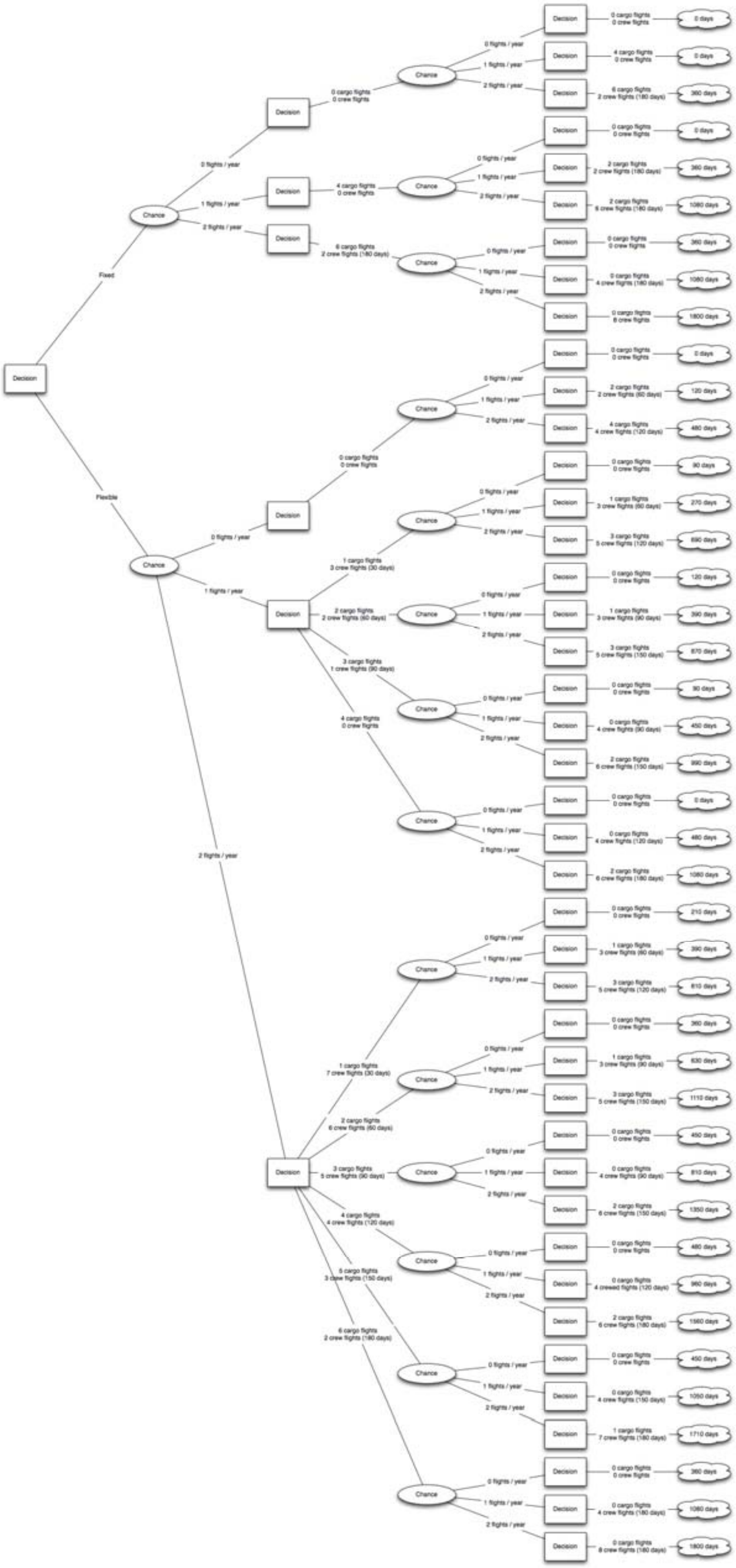


Figure 1. Complete view of the decision analysis problem for the habitation module development alternatives.

The decision of deployment for the final four years for the flexible alternative will be based on maximizing the number of days on the surface for the architecture. Because this is the final decision, it is possible to prune away all the non-optimal branches from the design space to leave only one possible choice for each decision. However, the decisions for the deployment options of the first four-year term are based on the expected values of each chance and the decision made during the second four-year term. Therefore, it is necessary to “fold back” these future chances and decisions to assist in pruning the decision analysis tree. Through calculations using Microsoft Excel, it is possible to determine the expected values of the first term decisions and prune the space as shown in the Table 4. In the table starting on the left, the first decision between fixed and flexible is shown in the first two columns. This is followed to the right by the three chance possibilities (for the flight rate) and by the decision for how many habitation modules and crewed flights are sent during the four-year period. “H-#” represents the number of habitation modules sent and “Cr-#” represents the number of crewed flights sent to the lunar surface. The decisions which turn out to be less than optimal after folding back the expected values (shown in the right-hand column) are crossed out in dashed red lines. This table is best read in conjunction with the tree shown in Figure 1.

It can be seen from this table that for the possible futures of having one or two flights per year in the first four-year term, there are two possible decisions that provide the same amount of expected return. The first flexible alternative (Flex 1) would be to choose to deliver the minimum amount of modules required to maximized expected value. (e.g. during the first four years, deliver 3, instead of 4 habitation elements, if there is only one flight per year or deliver 5, instead of 6 habitation elements, if there are two flights per year). The second flexible alternative (Flex 2) would be to do the opposite and deliver the maximum number of habitation elements to achieve the highest expected value. The differences in these alternatives and their comparison to the fixed option can be illustrated by a VARG analysis as shown in Figure 2.

Table 4. Microsoft Excel table of the habitation module decision analysis problem.

Dec EV		1st 4-Years			Dec EV		2nd 4-Years				EV
			# / yr	Prob				# / yr	Prob	Dec#3	
					Dec. #2			0	0.333	H-0 Cr-0	0
			0	0.333	H-0 Cr-0	60	C	1	0.500	H-4 Cr-0	0
								2	0.167	H-6 Cr-2	360
								0	0.333	H-0 Cr-0	0
	Fixed (EV=360)	C	1	0.500	H-4 Cr-0	360	C	1	0.500	H-2 Cr-2	360
								2	0.167	H-2 Cr-6	1080
								0	0.333	H-0 Cr-0	360
			2	0.167	H-6 Cr-2	960	C	1	0.500	H-0 Cr-4	1080
								2	0.167	H-0 Cr-8	1800
Dec#1											
								0	0.333	H-0 Cr-0	0
			0	0.333	H-0 Cr-0	140	C	1	0.500	H-2 Cr-2	120
								2	0.167	H-4 Cr-4	480
								~~0~~	~~0.333~~	~~H-0 Cr-0~~	~~90~~
					~~H-1 Cr-3~~	~~280~~	~~C~~	~~1~~	~~0.500~~	~~H-1 C-3~~	~~270~~
								~~2~~	~~0.167~~	~~H-3 Cr-5~~	~~690~~
								~~0~~	~~0.333~~	~~H-0 Cr-0~~	~~120~~
					~~H-2 Cr-2~~	~~380~~	~~C~~	~~1~~	~~0.500~~	~~H-1 C-3~~	~~390~~
			1	0.5				~~2~~	~~0.167~~	~~H-3 Cr-5~~	~~870~~
								0	0.333	H-0 Cr-0	90
					H-3 Cr-1	420	C	1	0.500	H-0 Cr-4	450
								2	0.167	H-2 Cr-6	990
								0	0.333	H-0 Cr-0	0
					H-4 Cr-0	420	C	1	0.500	H-0 Cr-4	480
								2	0.167	H-2 Cr-6	1080
	Flexible (EV=417)	C						~~0~~	~~0.333~~	~~H-0 Cr-0~~	~~210~~
					~~H-1 Cr-7~~	~~400~~	~~C~~	~~1~~	~~0.500~~	~~H-1 C-3~~	~~390~~
								~~2~~	~~0.167~~	~~H-3 Cr-5~~	~~810~~
								~~0~~	~~0.333~~	~~H-0 Cr-0~~	~~360~~
					~~H-2 Cr-6~~	~~620~~	~~C~~	~~1~~	~~0.500~~	~~H-1 C-3~~	~~630~~
								~~2~~	~~0.167~~	~~H-3 Cr-5~~	~~1110~~
								~~0~~	~~0.333~~	~~H-0 Cr-0~~	~~450~~
			2	0.1667	~~H-3 Cr-5~~	~~780~~	~~C~~	~~1~~	~~0.500~~	~~H-0 Cr-4~~	~~810~~
								~~2~~	~~0.167~~	~~H-2 Cr-6~~	~~1350~~
								~~0~~	~~0.333~~	~~H-0 Cr-0~~	~~480~~
					~~H-4 Cr-4~~	~~900~~	~~C~~	~~1~~	~~0.500~~	~~H-0 Cr-4~~	~~960~~
								~~2~~	~~0.167~~	~~H-2 Cr-6~~	~~1560~~
								0	0.333	H-0 Cr-0	450
					H-5 Cr-3	960	C	1	0.500	H-0 Cr-4	1050
								2	0.167	H-1 Cr-7	710
								0	0.333	H-0 Cr-0	360
					H-6 Cr-2	960	C	1	0.500	H-0 Cr-4	1080
								2	0.167	H-0 Cr-8	1800

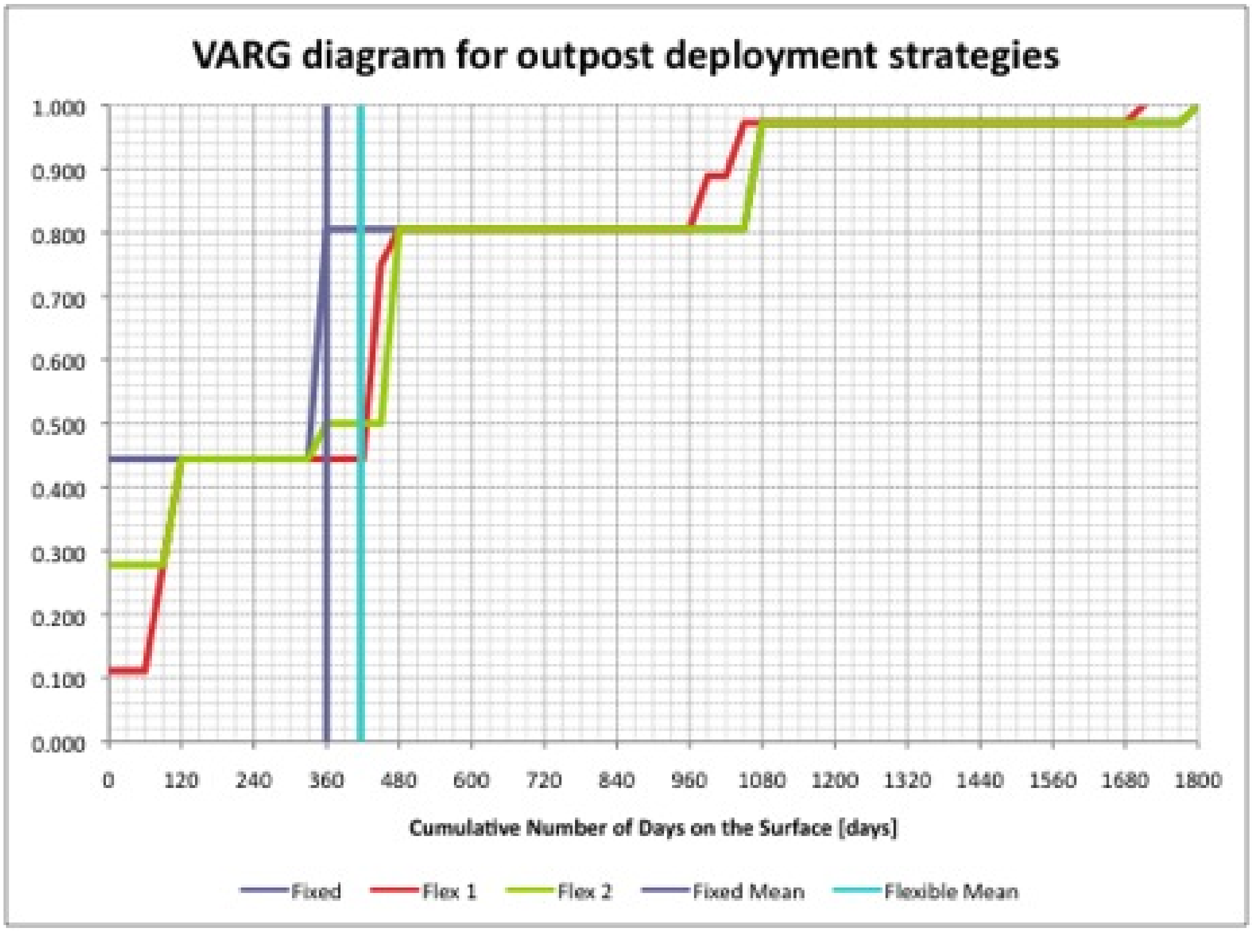


Figure 2. VARG diagram for habitation element deployment strategies.

It can be seen that for the shorter duration campaigns (caused either by early cancellation or reduced flight rate), the flexible alternatives are dominant compared to the fixed option showing that the flexibility reduced the risk side of campaign planning. For the longer campaigns, the flexible alternatives lose their dominance over the fixed alternative and end up providing the same or less crew days. (It should be noted that for campaigns longer than 480 days, the fixed and Flex 2 alternatives produce identical returns.) Through the VARG analysis, the difference between Flexible Alternative #1 and Flexible Alternative #2 can be seen: Flexible #1 provides a greater protection against the downside risk caused by political influences at the expense of reducing the gains. Flexible #2 does not provide as much protection against downside risk, but does not eliminate any of the gains from the fixed option.

To summarize, the decision and VARG analyses have shown that based on profit alone, the flexible alternative is preferred. In development of the decision analysis, it became apparent that some of the underlying assumptions, such as limiting the lifetime of the project to a maximum of eight years and limiting the maximum flight rate to the proposed two flights per year, have noticeable impacts on the system. If either of these assumptions were relaxed, the advantages of the flexible system, in terms of profits, would be reduced or eliminated entirely.

While this analysis provides useful insight into the choice of which development alternative to use, it is also be beneficial to examine the respective benefit-to-cost ratio. As noted in the introduction, the fixed habitation alternative has a lower cost of approximately $1,955 million US while the flexible habitation alternative has a higher cost of approximately $3,040 million US. When taken with the expected return information from the decision analysis, Table 5 shows that based on a benefit-cost ratio analysis, the fixed option is actually preferable and therefore, the fixed option will be examined further in the following section using a lattice analysis.

Table 5. Cost-Benefit Ratio for the habitation development options.

Habitation development option	Interdependent (fixed)	Independent (flexible)
Cost [USD, millions]	$1,955	$3,040
Expected return [cumulative crew-days]	360	416.7
Cost-Benefit Ratio [$ millions/crew-days]	5.43	7.30

III. Understanding uncertainty in monetary value of lunar exploration

When deciding which method of lunar habitation is optimal, one major uncertainty is the value, in monetary terms, of having the capability of having astronauts explore the lunar surface each year. While there are several different options for determining the amount of revenue produced from lunar exploration, the option used in this paper is that the baseline value of a year of lunar exploration (enabled by the fixed habitation alternative) is equal to the estimated annual value of the Apollo program and that this baseline varies based on the public interest in NASA as a whole. Also, as a proximate metric for public interest, this paper will use the variations in NASA budget as a measure of public interest under the assumption that as public interest increases, so would the budget, and vice-versa.

To determine the baseline value, it is first necessary to determine the annual estimated return from Apollo. A November 1971 study of NASA released by the Midwest Research Institute of Kansas City, Missouri ("Technological Progress and Commercialization of Communications Satellites." In: "Economic Impact of Stimulated Technological Activity") concluded that “the $25 billion in 1958 dollars spent on civilian space R & D during the 1958-1969 period has returned $52 billion through 1971” [MRI 1971]. Based on this study, the annual monetary return can be assumed to be approximately $4 billion each year. This will be the starting point for the assumed value of future lunar exploration enabled by the habitation elements.

To determine the variation of the value of lunar exploration, this paper will use NASA’s budget variation as a metric. Figure 3 shows the NASA budget in constant 2007 dollars for the years of 1975 until 2008 [www.wikipedia.org 2008].

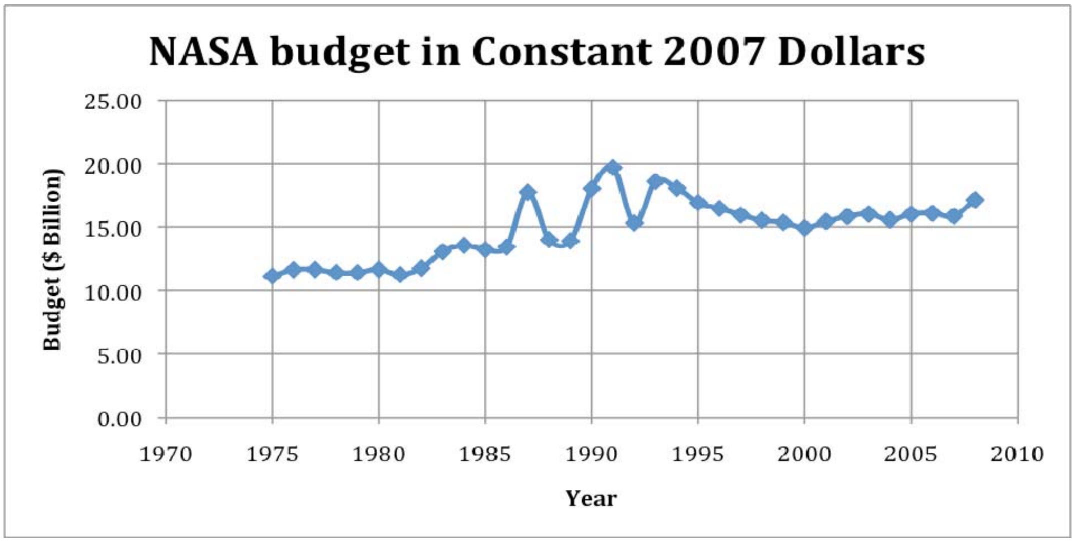


Figure 3. A plot of NASA's budget from 1975 - 2008.

Using the best-fit spreadsheet developed for MIT’s ESD.71 course, it is possible to determine the annual rate of growth, v, and the volatility, σ. This analysis is shown in the following two figures and indicates that the budget, in billions, can be represented by the formula:

$$Budget = \$11.959 \cdot e^{0.0122 \cdot t}$$

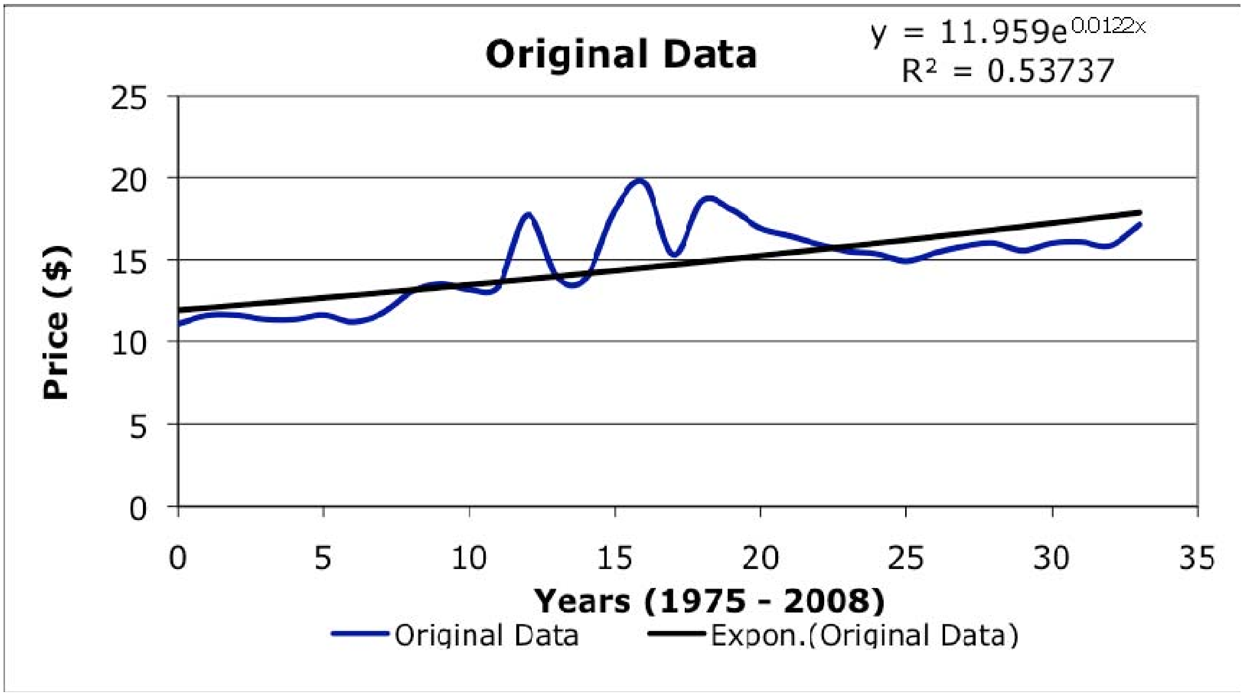


Figure 4. Best fit analysis of the NASA budget.

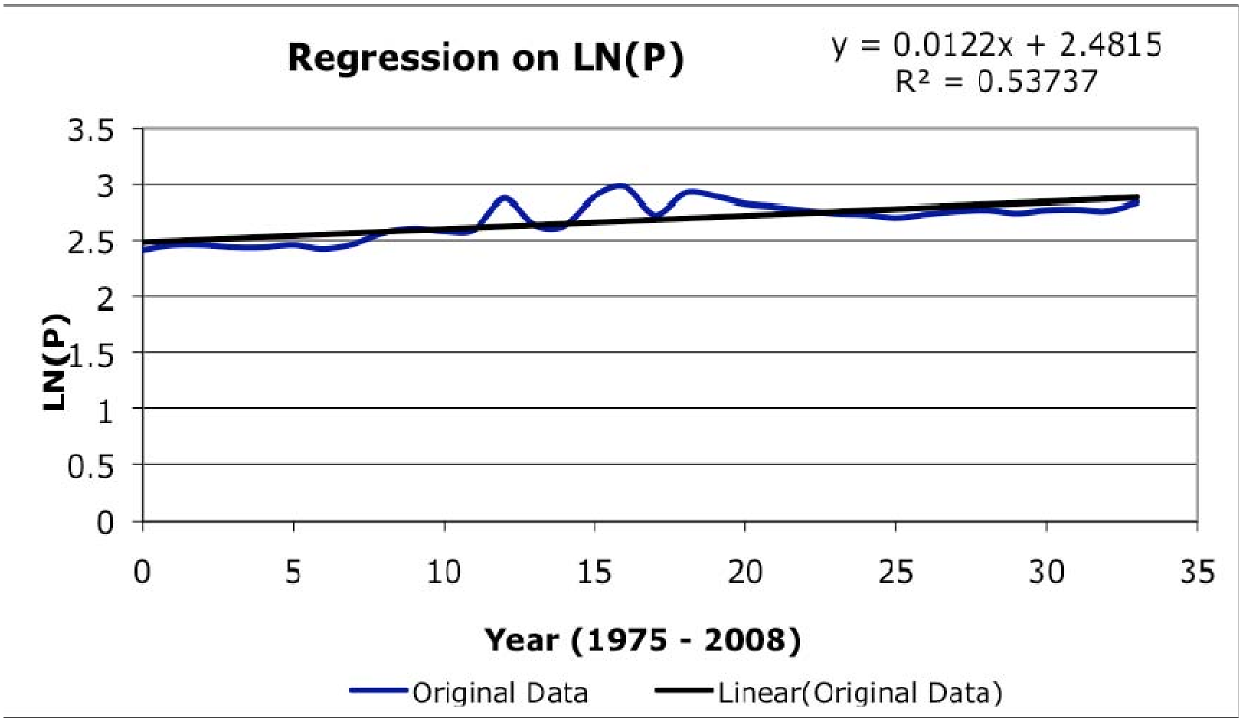


Figure 5. Regression analysis of the NASA budget.

Using the information provided by this analysis ($v = 1.22\%$ and $\sigma = 8.91\%$), it is possible to calculate the following values for p, d, and u to be used in a lattice analysis:

$p = 0.568$
$d = 0.915$
$u = 1.093$

Using the assumptions of two flights per year and a campaign start date of 2020, the first crewed lunar exploration will be in 2023 for the fixed option for the deployment of the habitation elements. As noted above, this analysis will set the initial value for annual lunar exploration at $4 billion USD per year in "year 0" or 2022. Using this as the starting value for the a lattice analysis, along with the values of p, d, and u shown above, it is possible to develop the data shown in Table 6 to show the possible states for the value of annual lunar exploration and the resepective probabilities for the years of 2023-2028 which is when the program is assumed to finish.

Table 6. Lattice for the estimated value of a year of lunar exploration (in million USD).

	2022	2023	2024	2025	2026	2027	2028
Monetary Return [$M]	4000	4373	4780	5226	5713	6245	6827
		3659	4000	4373	4780	5226	5713
			3347	3659	4000	4373	4780
				3062	3347	3659	4000
					2801	3062	3347
						2562	2801
							2344
Probabilities	1.00	0.57	0.32	0.184	0.104	0.059	0.034
		0.43	0.49	0.418	0.317	0.225	0.154
			0.19	0.318	0.361	0.342	0.292
				0.080	0.183	0.260	0.295
					0.035	0.099	0.168
						0.015	0.051
							0.006

The information in the lattice for the value of a year of lunar exploration shown above can be combined with the development and operations costs to determine an expected Net Present Value or ENPV. As noted earlier, the development and production costs for the fixed habiation modules is approximately $1,955 million USD. The other cost that is required for this analysis is the cost of launching the habitats and the crews each year. Based on current estimates of the cost of launching, it can be assumed that the annual cost of launching the habitats (i.e. launching two habitats) is $1,000 million USD. This means that to launch all six habitation modules over three years, it would cost approximately $3,000 million USD. When added to the cost of development of the habitats, this leads to an capital expenditure of $4,955 million USD in year 0 (2022). For simplification, these expenses are being counted in a single year, instead of spread over the previous decade which would be the case in reality.

The final cost is that of launching the crew each year. Because the current launch architecture requires that two separate launches into LEO per crew are required and because of the higher complexity involved in human-rated launch systems, it can be assumed that the launch cost is approximately 3x that of launching habitats. This equates to a launch cost of $3,000 million USD each year. To determine the ENPV, this amount will be subtracted from the expected value of exploring the lunar surface during the years of 2023 to 2028. Because NASA is a governmental agency, a relatively low discount rate of 10% will be used to calculate the ENPV. This information is shown in Table 7 and can be used to determine that the ENPV of the lunar exploration system is $333 million USD.

Table 7. Lattice valuation for uncertain value of annual lunar exploration.

	2022	2023	2024	2025	2026	2027	2028
Cash Flow [$M]	4,955	1,373	1,780	2,226	2,713	3,245	3,827
		659	1,000	1,373	1,780	2,226	2,713
			347	659	1,000	1,373	1,780
				62	347	659	1,000
					199	62	347
						438	199
							656
PV Cash Flow [$M]	4,955	1,248	1,471	1,672	1,853	2,015	2,160
		599	826	1,031	1,216	1,382	1,531
			287	495	683	852	1,005
				46	237	409	564
					136	38	196
						272	112
							371
Probability	4,955	780	575	409	283	193	129
Weighted		284	491	574	565	501	417
Cash Flow [$M]			65	209	361	470	519
				5	63	171	295
					7	6	58
						7	10
							4
	0	1	2	3	4	5	6
E [Cash Flow]	4,955	1,065	1,131	1,197	1,265	1,334	1,405
PV(E[Cash Flow])	4,955	968	934	900	864	829	793
ENPV over 6 years	**333**						

As can be seen from the table above, it is possible that the act of exploration the lunar surface actual costs NASA more money than it produces if public interest reaches relatively low levels. This lattice valuation can also be used to show the benefits of deciding to cancel the lunar exploration campaign at any given time based on the expected net present value of possible futures from that point in time. This calculation is completed by folding back the costs or gains of each year, starting in 2028, into the previous year to determine the net present value at that time. If this shows that the ENPV is negative, at any given time, then the lunar exploration campaign can be stopped. As this is rolled back to year 0, it can be seen to increase the ENPV of the system to $338 million USD. In other words, the capability to cancel the program at any given time is worth $5 million USD to NASA. Table 8 shows the dynamic programming approach for finding this new ENPV. This analysis shows the benefit of flexibility (in terms of the ability to cancel early) also applies to the interdependent (fixed) alternative for deploying lunar habitaiton elements. The final section of the table shows when the lunar exploration campaign should be cancelled based on the expected value of lunar exploration. Figure 6 shows the VARG analysis for these two alternatives and highlights that having the ability to shut down the program can reduce the downside losses.

Table 8. Dynamic programming of the income lattice for crewed lunar exploration.

	2022	2023	2024	2025	2026	2027	2028
ENPV (Cash Flow) [$M]	333	7,346	8,017	8,172	7,659	6,287	3,827
NO FLEXIBILITY		3,801	4,666	5,131	5,069	4,326	2,713
Dynamic programming			1,863	2,586	2,902	2,685	1,780
approach				457	1,089	1,312	1,000
(check next year)					428	163	347
						798	199
							656
ENPV(Cash Flow) [$M]	338	7,346	8,017	8,172	7,659	6,287	3,827
WITH SHUTDOWN OPTION		3,815	4,666	5,131	5,069	4,326	2,713
Dynamic programming			1,898	2,586	2,902	2,685	1,780
approach				546	1,089	1,312	1,000
(check next year)					199	163	347
						438	199
							656

	2022	2023	2024	2025	2026	2027	2028
Shut Down?	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
WITH SHUTDOWN OPTION		**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
Dynamic programming			**NO**	**NO**	**NO**	**NO**	**NO**
approach				**NO**	**NO**	**NO**	**NO**
(check next year)					YES	**NO**	**NO**
						YES	YES
							YES

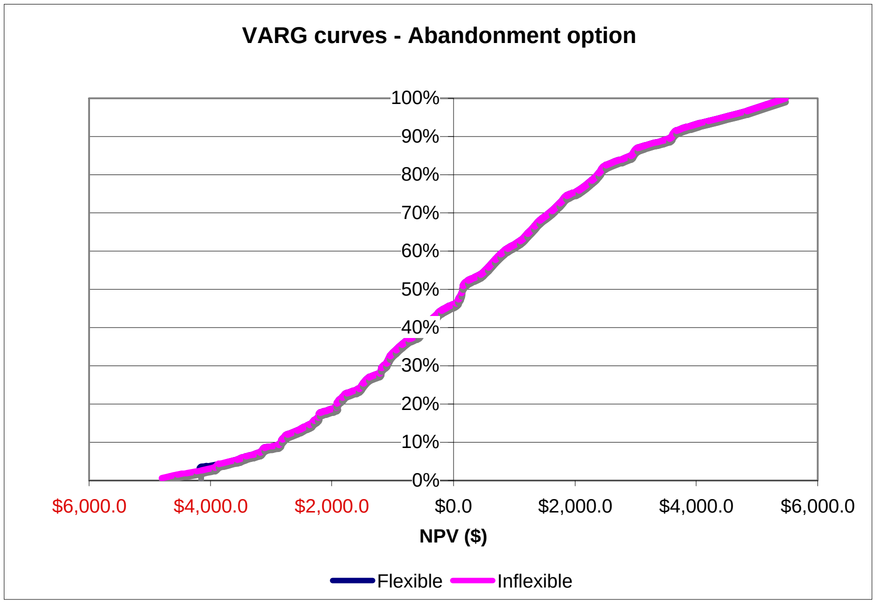


Figure 6. VARG analysis of flexibility (shut down option) for the interdependent habitation modules.

IV. Summary and conclusions

This paper has discussed various options for developing and deploying lunar exploration habitats to support extended crewed missions to the Moon. The main “fixed” alternative studied include developing a set of six interdependent habitats that, when assembled together, can support 180-day missions, but cannot support any missions until all elements are delivered to the lunar surface. The “flexible” alternative involved developing a set of six independent habitats that can also support 180-day missions when fully assembled, but can also support shorter missions dependent on the number of habitats delivered. The downside to this alternative is that the habitats would be more complex and therefore more expensive. To test which alternative is better in the face of an uncertain future, a decision analysis and a lattice valuation were performed on the options.

The decision analysis showed that the flexible option provides a higher expected amount of crew days when investigating the effects of uncertain project lifetime and uncertain flight rates. However, based on a benefit-cost ratio, the fixed option is preferable because of the lower development costs. A summary of these various methods for evaluating the design alternatives are shown in Table 9. Focusing on the fixed alternative, the lattice valuation showed the benefits of being able to cancel the program early because of the uncertain monetary value of a year of lunar surface exploration is worth $5 million USD. With or without this flexibility, the development of habitats to allow extended lunar exploration appears to have a positive ENPV.

Table 9. Summary of evaluation methods for the design alternatives.

	Fixed	**Flexible**	**Preferred?**
Min Return [days]	0	0	Either
Max Return [days]	1800	1800	Either
Expected Return [days]	360	416.7	Flexible
Capital Expenditure [$]	$1,955M	$3,040M	Fixed
Cost-Benefit Ratio [$M/day]	5.43	7.4	Fixed
ENPV [$M]	333	n/a	n/a

Acknowledgments and future project suggestions

The author would like to acknowledge and thank Professor Richard de Neufville for his lessons taught in MIT’s ESD.71 course during the fall term of 2008. These lectures provided the theoretical knowledge for completing this paper. The author would also like to acknowledge Michel-Alexandre Cardin for his continuous and thorough guidance during the formulation of this project.

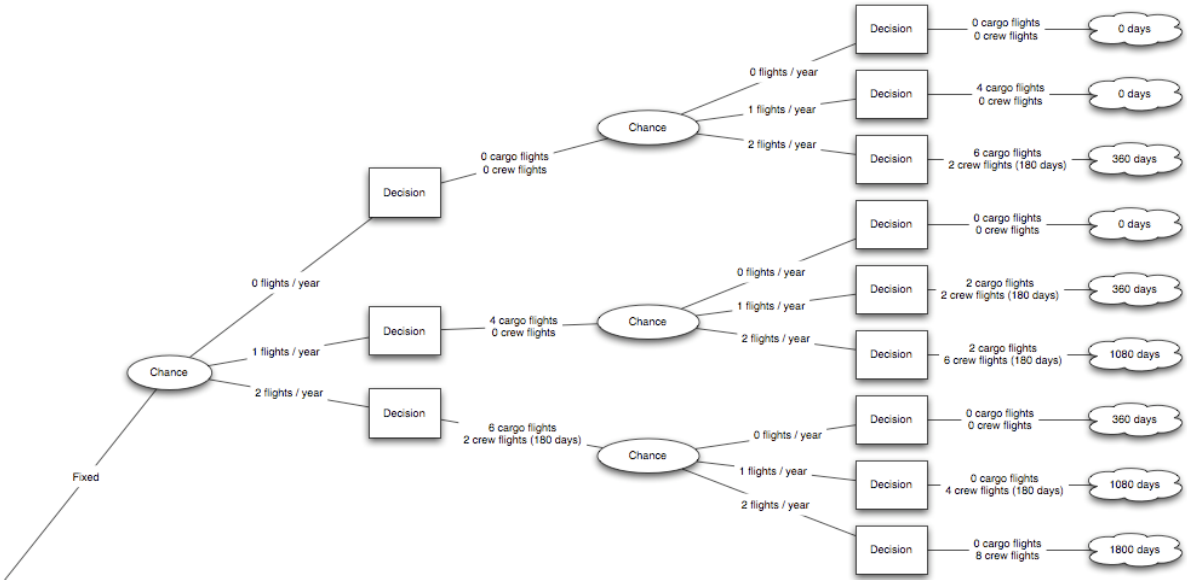
This paper was completed as an Application Portfolio for the ESD.71 course. This experience has allowed the author to apply the analysis tools taught in ESD.71 to a real-world problem. One of the main lessons learned was in how to formulate a problem or describe a system in order to allow certain tools to be applied to it. Future participants in ESD.71 should be sure to understand the limitations and assumptions of the tools to be used early in the formulation portion of their Application Portfolio.

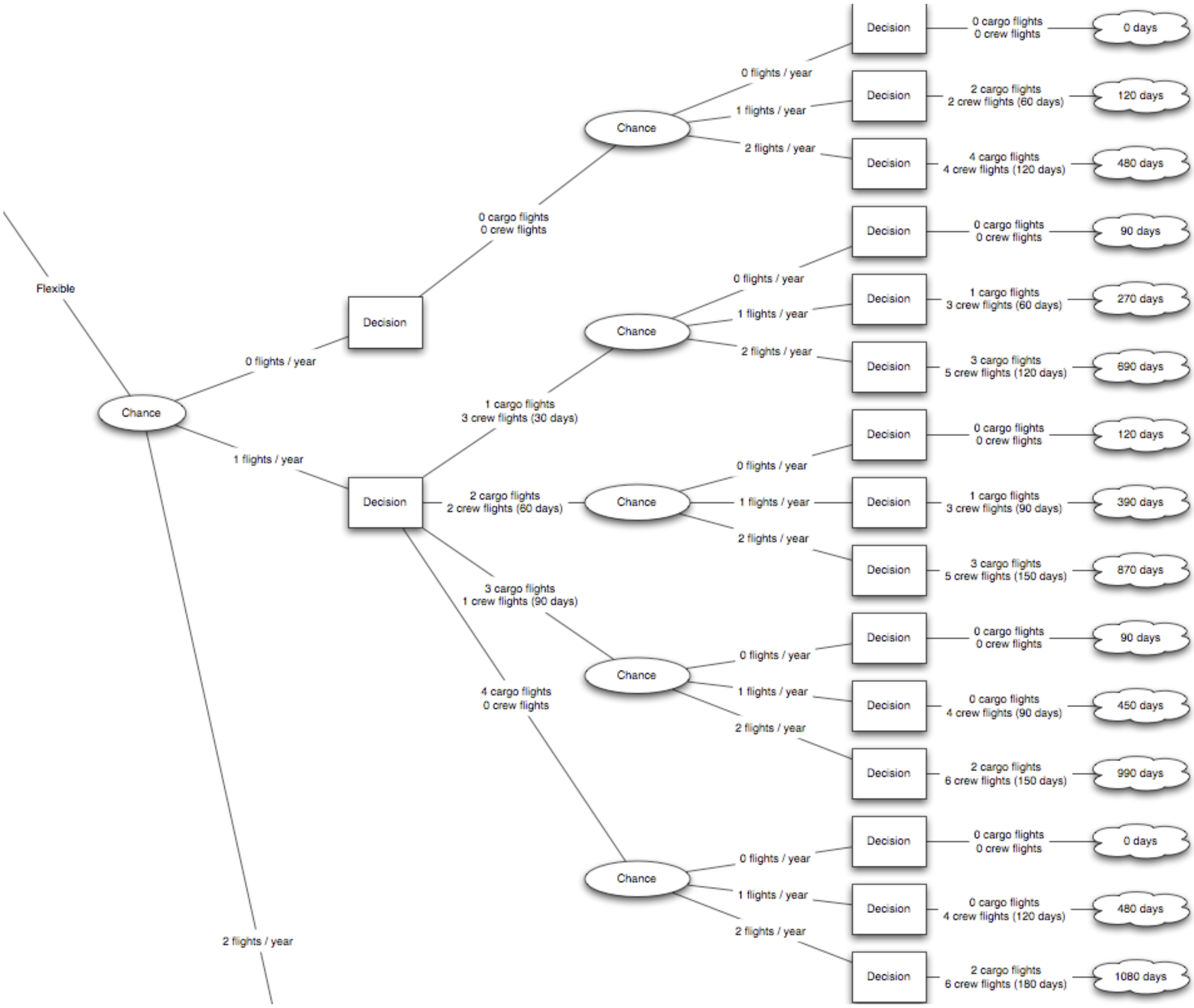
I think that the AP was an excellent tool overall. It was both interesting and instructional to attempt to apply the tools from class to a real world problem. That being said, one of the greatest challenges was fitting the project to the tools. This task, in itself, was an excellent assignment to increase the way we think about systems and visualize them, but in the end, I don't believe I was able to fit my specific project to the lattice analysis in particular.

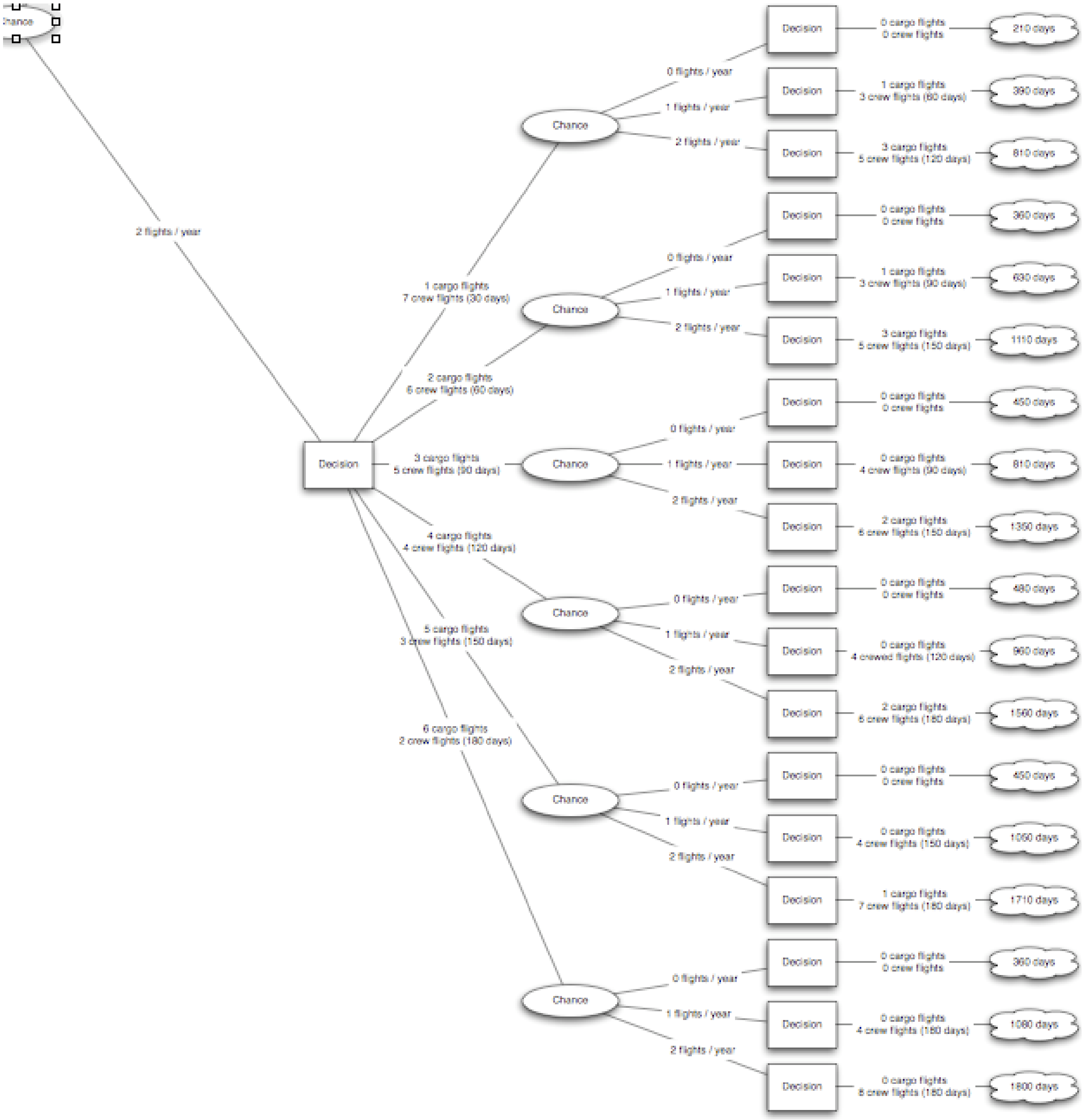
The concept of breaking up the AP into assignments and allowing us to receive feedback on each part was also quite beneficial. I know with my project, Michel's assistance was a big part of my learning and success. He tried his hardest to steer me in the right direction as he say that there would be difficulties with my project and the lattice analysis, but although he pointed this out and I had read ahead to try to understand the limitations of the lattice analysis, I was not able to fully grasp the issues with path independence and other factors until after the lectures.

Appendix

The following images are exploded views of the decision tree shown in Figure 1.




Flexible
Chance
0 flights / year
1 flights / year
2 flights / year
Decision
Decision
0 cargo flights
0 crew flights
1 cargo flights
3 crew flights (30 days)
2 cargo flights
2 crew flights (60 days)
3 cargo flights
1 crew flights (90 days)
4 cargo flights
0 crew flights
Chance
Chance
Chance
Chance
Chance
0 flights / year
1 flights / year
2 flights / year
Decision
0 cargo flights
0 crew flights
0 days
Decision
2 cargo flights
2 crew flights (60 days)
120 days
Decision
4 cargo flights
4 crew flights (120 days)
480 days
Decision
0 cargo flights
0 crew flights
90 days
Decision
1 cargo flights
3 crew flights (60 days)
270 days
Decision
3 cargo flights
5 crew flights (120 days)
690 days
Decision
0 cargo flights
0 crew flights
120 days
Decision
1 cargo flights
3 crew flights (90 days)
390 days
Decision
3 cargo flights
5 crew flights (150 days)
870 days
Decision
0 cargo flights
0 crew flights
90 days
Decision
0 cargo flights
4 crew flights (90 days)
450 days
Decision
2 cargo flights
6 crew flights (150 days)
990 days
Decision
0 cargo flights
0 crew flights
0 days
Decision
0 cargo flights
4 crew flights (120 days)
480 days
Decision
2 cargo flights
6 crew flights (180 days)
1080 days



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