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ESD.71 Engineering Systems Analysis for Design

Application Portfolio

An Assessment of Unmanned Aircraft Systems for Flight in the National Airspace System

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Executive Summary

This application portfolio addresses the development of real options for acquiring an unmanned aircraft system (UAS) that will be capable of achieving Federal Aviation Administration (FAA) approval to operate in the National Airspace System (NAS). The primary source of uncertainty modeled in this assessment is the fraction of manned aircraft missions the UAS will be capable of replacing. This translates into the relative revenue stream the UAS will be capable of generating as a fraction of replaced manned mission costs.

After a general overview is provided describing the situation associated with flying UAS in the NAS, the major alternatives for how a solution could be pursued are described in three major design categories: 1) A “Top-Down” systems engineering approach, 2) An “Empirical” approach, and 3) A “Flexible” approach. Each of these are described in further detail to more fully characterize their strengths and weaknesses.

Following the development of the major design options available, a more detailed treatment of the uncertainties on the project is presented, and a notional decision tree is described out to the second stage of outcomes and decisions. Each option is evaluated through the end of the second stage of the decision tree and an expected value is calculated for each option.

Uncertainty is then introduced into the picture by modeling the manned aircraft costs (recall, this forms the basis for the UAS revenue stream) as a probability density function that can be described using a binomial lattice with a specified annual drift and volatility. The uncertainty in the manned aircraft costs are modeled out across a 50-year time horizon to capture the full impact of the variability over the expected lifetime of the UAS. The portfolio concludes by assessing the relative value that is brought to the table by having the flexibility to cease operations at any point where the cost of flying the UAS will be greater than simply stopping operations.

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Background and Options Development

The system that will be analyzed for the application portfolio will be an analysis of three alternatives for integrating unmanned aircraft systems (UAS) into the national airspace system (NAS). UAS platforms face substantial restrictions in their operational use in the NAS because these platforms have no physical mechanism to comply with CFR Part 91 requiring pilots to "see-and-avoid" other air traffic. With the removal of the pilot from the airborne portion of the UAS system, the human eyeball is no longer capable of meeting the intent of the regulation. In addition, there are substantial technological issues with communication reliability links, procedural problems that need to be addressed, and regulatory guidance that needs to be developed in order to realize a fully capable and integrated platform.

The system boundary for this analysis will be the UAS platform and its interface with the NAS. It is this interface condition that poses the major challenge to successful integration between these two systems. There are fundamentally three different approaches to attempting to develop and identify the critical points of intersection on this interface. The first approach employs a systems engineering, top-down driven architecture that attempts to bound the requirements space, functionally decompose the problem, allocate functionality to specific subcomponents of the two systems, and then synthesize an interface form that will provide the required functionality. This will be called the "Top Down" approach. The second approach employs an "Empirical" method. In this instance, a UAS platform is outfitted with what the developer believes to be the critical performance enablers for routine flight in the NAS, and then submits the platform for operational approval to the FAA. Once feedback from the FAA is received, the developer modifies the design to meet FAA concerns, and tries again. In this way, the critical points of intersection between the UAS and the NAS will eventually be discovered through a trial-and-error process. The third approach, which will be called the "Flexible" plan, is a hybrid between the previous two in that it focuses on getting an operational platform fielded as quickly as possible to engage the FAA on a concrete basis, but it does so with the long-term system development requirements in perspective (unlike the short-term focused Empirical approach). For additional detail on each of these options, see the "Major Options and Decision Tree Analysis" section.

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The UAS platform consists of the air vehicle, the data links, the control station, and the pilot operating the platform. The NAS consists of all the infrastructure, operational procedures, air traffic control systems, command and control, surveillance, and regulatory requirements that provide for the safe passage of people and assets through the national airspace.

The principle design point for the purpose of the analysis will be the cost of manned aircraft operations as a basis of the UAS revenue stream associated with pursuing the Top-Down approach vs. the Empirical approach vs. the Flexible approach. Each venue has their advocates and relative strengths and weaknesses. The question that is of primary interest to the Air Force in this inquiry is the cross-over point at which one approach becomes more costly than another versus the near-term benefits that can be achieved through some partial expansion of operations relatively quickly.

The modeling approach that will be employed in this analysis will be to cast the three approaches into purely monetary terms and then evaluate the relative merits of each track by examining the financial merits over time. This will include an intensive look at the potential variation in the costs for all three options, the phasing of the costs, and the benefit that may result from partial (but not all) integration of UAS flights using each approach. The model will also account for the impact that various discount rates may have on the overall analysis. Excel will be used to accomplish this modeling effort.

The immediate benefits of this system are to provide enhanced flight safety to both the UAS operation and other aircraft that may be operating in close proximity to the UAS (See Figure 1). Specifically, the DOD has growing requirements to train and operate these assets in airspace that lies outside of DOD restricted airspace, and without routine and integrated access to the NAS, the limitations imposed by the FAA on UAS operations outside of restricted airspace are severe. A successful system may also have beneficial impact on the safety of manned aviation as well as lessons from collision avoidance and command and control are applied to other aviation arenas.

The primary contextual factors impacting the integration of UAS platforms into the NAS are regulatory in nature. In other words, the design of the UAS system should be sufficiently robust to allow the system to meet the equivalent manned regulations. Unfortunately, there is no manned aviation baseline against with the FAA is willing to benchmark the UAS effort. The consequence of this decision has left the UAS community largely at a standstill when it comes to

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designing and building an objective system with the appropriate performance characteristics needed for flight in the NAS. It is the intent of this exercise to provide some insight into the potential financial ramifications of various UAS design approaches and to help evaluate real options for proceeding forward with this system.

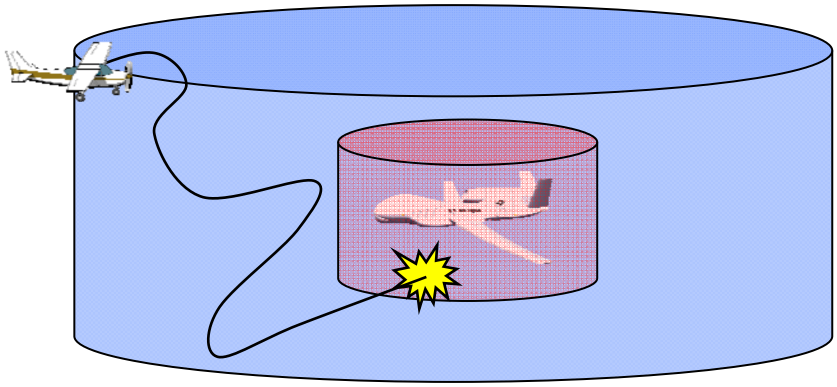

Figure 1. Graphical Depiction of Possible Mid-Air Collision Geometry[1].

Uncertainty Development in the Model

The development of uncertainty in the model will be confined to the simplest of measures to demonstrate the principle and structure of the evaluation. The addition of other sources of uncertainty could be added to the analysis as more detail and design specifics are enumerated for future work. For the scope of the portfolio analysis, the only major uncertainty that will be developed will be the projection of future manned platform costs, which in turn can be thought of as the "revenue" basis for the unmanned platforms. On the surface, this distinction may appear to be somewhat confusing, and it is worth clarifying at this juncture to avoid confusion later on.

The primary uses of unmanned aircraft are in missions or roles that replace current manned missions that are either extremely dangerous, monotonous, or that would be more effectively executed if the platform could stay on station longer. Under this context, the cost of manned operations for those missions provides the comparative costs against which an unmanned version of the mission could be compared. The cost of these manned missions, however, is not known in any deterministic sense, although they are often forecasted and

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budgeted in that manner. The composite cost of the manned missions are an aggregate of fuel costs, infrastructure costs, training costs, aircraft maintenance costs, etc. that are correlated to other variables that are exogenous to the system under investigation. For this analysis, only the aggregated cost for the manned mission will be modeled. Further, the costs for the manned missions will be assumed to be path independent and monotonically rising over the time at a rate slightly higher than inflation. This will allow a manned operations cost to be modeled over time using a binomial lattice approach that provides a reasonable estimate of the cost distribution with time.

Since the manned aircraft mission operating costs are being used as the comparative basis for evaluating the unmanned mission options, these costs then translate into the equivalent unmanned aircraft “revenue” stream for the purposes of evaluating the options. This is a convenient way to frame the problem because regardless of which option is exercised (Top-Down, Empirical, or Flexible), they will all be baselined against the same relative revenue stream. The result will be a relatively straight forward method for comparing the expected value of each option as the manned cost uncertainty unfolds over time.

The other major source of uncertainty that is modeled in this application portfolio, and that is fundamentally coupled with the option that is exercised, is the probability that the FAA will in fact approve the operation for flight in the national airspace system. This aspect of the regulator’s impact on the situation has been simplified to single deterministic probabilities in various chance nodes in a decision tree, and for this analysis, they will be considered to be exogenous inputs into the system. Because this uncertainty is discontinuous, the impact of this variable on the outcome will be modeled through a decision tree analysis.

Despite the simplifications, the model can provide excellent insight into the sensitivity and range of values over which a specific option’s expected value will come out ahead of the others. This in itself can be of significant value since the question in these situations is tied less to getting a single, specific cost figure for the plan but more generally to which option will provide the greatest degree of robustness over a broad range of possible outcomes.

The actual input deck that was used for initial calculations is provided in Table 1. Note that in each instance, the uncertainty modeled in this initial set of calculations is set to zero. These assumptions will be updated as the evaluation progresses, but for now, consider all of the

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variables to be deterministically set at the beginning of the evaluation with no uncertainty developed over time.

Air Force Variables

Discount Rate

Discount Rate:	7%				
Flex Plan (F)	7%	per year	Discount Rate Uncertainty factor	0%	of estimate
Top Down Plan (T)	7%	per year	Discount Rate Uncertainty factor	0%	of estimate
Empirical Plan (E)	7%	per year	Discount Rate Uncertainty factor	0%	of estimate

Expected Benefit for Doing NAS Operations = Cost of Current Ops * Percent Missions Replaced * Operational Life

Cost of Current Ops (manned)	523	milion dollars/year	Cost of Ops Uncertainty factor	0%	of estimate
Definition of Approvals (% missions UAS can accomplish)					
Limited Ops (LO)	10	percent	Percent Missions Replaced Uncertainty factor	0%	of estimate for Limited Ops
Expanded Ops (EO)	25	percent	Percent Missions Replaced Uncertainty factor	0%	of estimate for Expanded Ops
Restricted Routine (RR)	50	percent	Percent Missions Replaced Uncertainty factor	0%	of estimate for Restricted Routine Ops
Expanded Routine (ER)	75	percent	Percent Missions Replaced Uncertainty factor	0%	of estimate for Expanded Routine Ops
Fully Integrated (FI)	100	percent	Percent Missions Replaced Uncertainty factor	0%	of estimate for Fully Integrated Ops
Ops Life of NAS Capability			Life Expectancy Uncertainty factor	0%	of estimate
Flex Plan	10	years			
Top Down	10	years			
Empirical	10	years			

Expected Costs for Enabling NAS Operations = Variable Costs + Capital Expenditures

Variable Cost					
Platform Ops Cost	0	million dollars/year	Life Expectancy Uncertainty factor	0%	of estimate
Flex Plan NAS Cost	0	million dollars/year	Life Expectancy Uncertainty factor	0%	of estimate
Top Down NAS Cost	0	million dollars/year	Life Expectancy Uncertainty factor	0%	of estimate
Empirical NAS Cost	0	million dollars/year	Life Expectancy Uncertainty factor	0%	of estimate

Capital expenditure

	Limited	Exp	Rest Rout	Exp Rout	Integrated	Total
Flex Plan	150	200	400	600	600	1950 Million dollars
Top Down Plan	N/A	N/A	1500	100	100	1700 Million dollars
Empirical Plan	80	300	600	600	700	2280 Million dollars

Design Cycle Time	5	years
Capital Expenditure Across Cycle Time	Linear	curve

Capital expenditure Uncertainties

	Limited	Exp	Rest Rout	Exp Rout	Integrated	
Flex Plan	0	0	0	0	0	percent
Top Down Plan	0	0	0	0	0	percent
Empirical Plan	0	0	0	0	0	percent

Expected NPV

Flex Plan	$ 128.58
Top Down Plan	$ (240.10)
Empirical Plan	$ 184.27

Current Assumptions:
No uncertainty is currently modeled.
Costs and benefits accrue per the time phasing associated with the decision tree to account fo the discount factor.
Rework to get limited ops approved after an initial disapproval is estimated at 25% of original cost and two years of time.
Rework to get expanded ops approved after an initial disapproval is estimated at 30% of original cost and 3 years of time.
Capital costs for Flex and Empirical Plans for Limited and Expanded Ops are equally distributed across 5 years worth of funding
Capital costs for the TD Plan to achieve Restricted Routine access are equally distributed across 10 years worth of funding

Table 1. Initial Assumptions and Values Modeled for Air Force Variables.

Major Options and Decision Tree Analysis

As previously introduced, the major system concepts that will be analyzed fall into three primary categories. The first system concept involves employing a classical system engineering approach to the problem of designing a UAS sense-and-avoid system that is technologically capable of complying with Federal Aviation Administration regulations for flying routinely in the national airspace system. In this first system concept, the "Top Down" system, substantial upfront time and cost are expended to investigate and lock down system performance requirements, develop the required technology needed to meet those standards, and then integrate the technology onto the platform to finally go out and fly the appropriate missions.

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Characteristics of this system concept are to make substantial initial capital investment in researching, developing, and integrating an end-to-end solution before attempting to build and fly any actual capability. In addition, this system concept is required to operate in a context of uncertainty with respect to the required sensor performance needed to achieve the desired level of access. For this analysis, however, the sensor performance will be treated deterministically.

The second system concept, the "Empirical" system, will be the opposite of the Top Down system. In this scenario, virtually no up-front analysis will be done to specify target values. Instead, the focus will be on building to the current state-of-the-engineering with available, readily at hand technologies, and then getting a product out the door to go fly it as quickly as possible.

Characteristics of this system concept are to make relatively small investments up front but on a relatively frequent basis as systems are designed, tested, and feedback is obtained from the Federal Aviation Administration on the effectiveness of the technology. The going in assumption is the initial product will not likely be good enough, but no forethought is made as to the possibilities for future capability beyond the current iteration, so it is a very short-term and does not address the switching costs associated with later developments[2].

The third system concept, the "Flexible" system, will proceed down a similar path as the Empirical approach, but instead of proceeding forward blindly, some time and resources will be spent up front to determine what the design "hot spots[3]" are to analyze optional performance that the system may need to provide in the future, and then designing the system with the appropriate "hooks" so future decisions requiring expanded capability can be implemented with relatively low integration costs.

The first two system concepts really represent two different types of fixed designs, but in different temporal domains. In the first case, the Top Down system configuration is set relatively early after a substantial amount of upfront design to drive down the uncertainty in the actual technology performance requirements and their ability to meet an as yet unspecified functionality constraint. The Empirical system builds a series of fixed systems, so you could argue that this does represent a flexible design. The problem with this view is that the current design is actually not architected with future requirements in mind, but is rather the product of what the existing state of technology is capable of producing for a narrowly defined set of performance parameters. As a result, this approach will field intermediate systems of varying

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performance capability that result in partial levels of access, but does not provide for a convenient methodology for integrating downstream changes in already fielded systems. The result is a very expensive retrofit requirement for later systems as the performance objective changes in the future. It also does not provide a convenient way to "switch" architectures in mid-stream to accommodate future requirements as the desired approvals for operation become more comprehensive.

The Flexible system concept attempts to remedy the ills of both extremes by taking the same evolutionary approach suggested by the Empirical system concept, but the potential for future changes in performance are included in the initial system architecture by employing a modular construct to rapidly and inexpensively integrate future upgrades to capability. The intent is to design for changeability by creating an architecture that has additional flexibility and agility built into the basic structure[4]. In this context, the additional upfront cost of this approach compared to the Empirical concept will be assessed against the later integration costs the latter incurs. The Flexible concept will also be looked at in contrast to the Top Down concept by comparing the difference in the upfront costs against the later integration costs.

The principle uncertainty that will be modeled in each system concept will be the probability of operational approval being granted for a given set of sensor and operational mission load. As previously mentioned, the current analysis for the decision tree development will treat each pair of approved/disapproved outcomes as a deterministic value. Note, however, that these are not the same deterministic values for each chance node. This is an important distinction because it does account for the general differences that are expected in the approval rates for each different option available. This plays out through the decision tree analysis as the expected values are calculated for each option path.

There are also inherent uncertainties associated with the cost for sensor development and the fraction of actual missions the unmanned aircraft will be able to replace (Reference back to Table 1). These uncertainties could be further decomposed into their respective components. Again, for the purposes of the application portfolio, these uncertainties will not be modeled explicitly.

The decision tree used for this initial analysis of the three options is provided below in Figure 2. Note that the current decision tree analysis allows for a fully automated assessment of the discount rate, the cost of current operations, the percentage of current operations that can be

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replace for any given type of approval, and the capital costs associated with the pursuit of any given plan and an associated approval level. The model currently does not provide for statistical variation across any of these variables, nor does it automate the introduction of a number of other variables that will likely be important for future analysis. These additional variables are considered beyond the scope of the application portfolio exercise, and they will remain "hard wired" for the purposes of this analysis.

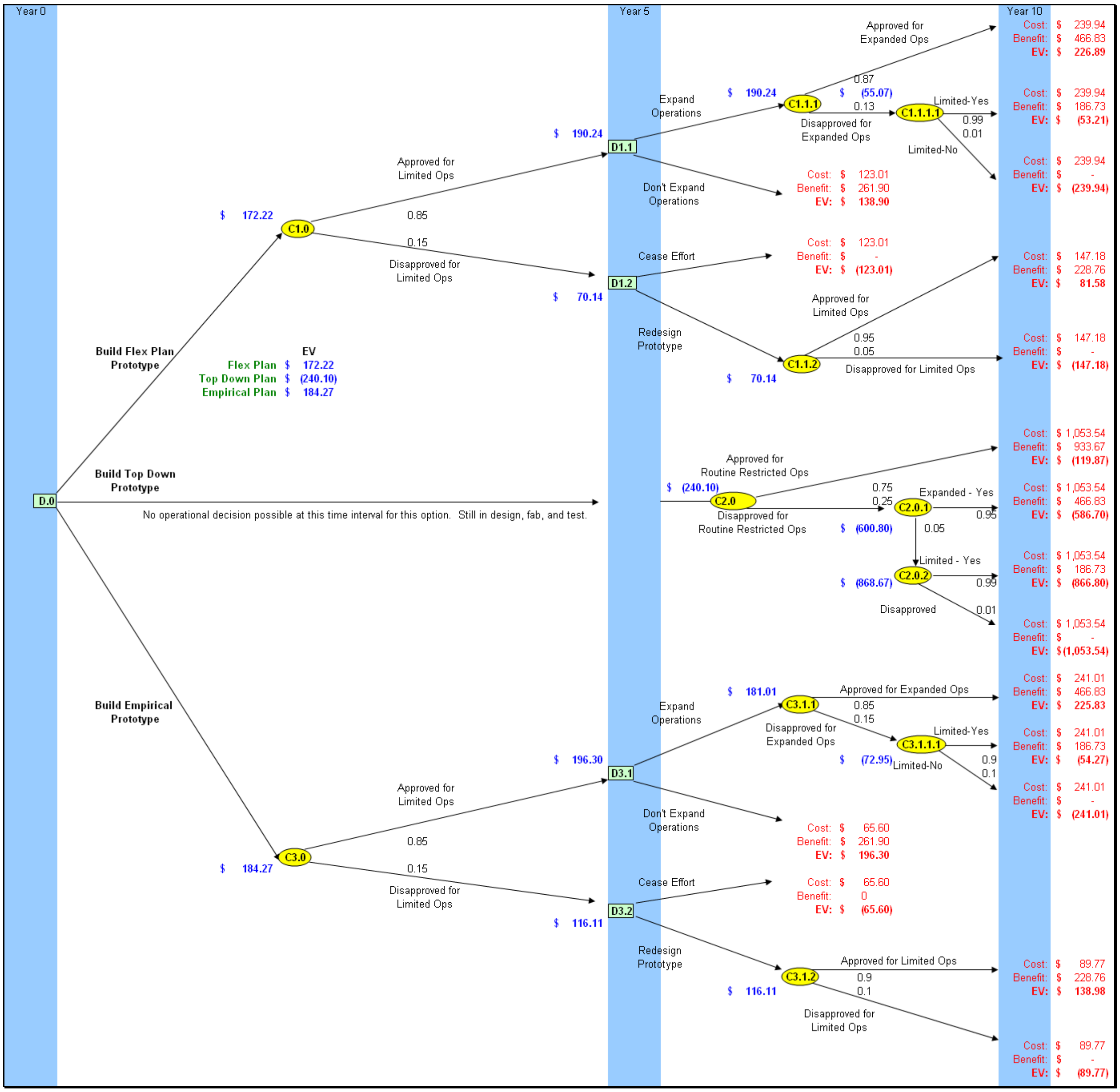

Figure 2. Decision Tree Analysis of Three Options.

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The result of these initial calculations provides the Net Present Value (NPV) for each of the options out through Year 10 of the evaluation as depicted in Table 2.

	Expected NPV	
Flex Plan	$	172.22
Top Down Plan	$	(240.10)
Empirical Plan	$	184.27

Table 2. Net Present Value of Options using Decision Tree Analysis ($ in millions).

Several additional details are worth noting with respect to the decision tree analysis that was performed for the results depicted in Table 2. First, the "benefits" associated with each decision tree branch are calculated based on the following formula. Each year is baselined against the manned operating costs of $523M/yr. This represents the maximum possible revenue the unmanned mission could replace. This total available pool of money is then multiplied by the fraction of missions the unmanned aircraft has been approved to replace. For the purposes of this assessment, these were broken down into five distinct categories: limited operations (10% of manned missions or $52.3M/yr in revenue), expanded operations (25% of manned missions or $131M/yr in revenue), restricted routine operations (50% of manned missions or $262M/yr in revenue), expanded routine operations (75% of manned missions or $392M/yr in revenue), and fully integrated operations (100% of manned missions or $523M/yr in revenue).

The expected costs for each year are calculated by adding the non-recurring engineering costs associated with the development of the unmanned aircraft and the recurring operating costs associated with actually flying and maintaining the unmanned aircraft. The nonrecurring engineering costs are generally captured across the timeframes in which they are expended. For this analysis, the design cycle was fixed at five year intervals for all three options, but the costs associated with each plan were distributed linearly across all five years. Also, given the large amount of work required in the upfront stage for the Top Down plan, no operational capability is provided until after the first two design cycles, or Year 10. For the initial analysis reported above, no recurring operating costs were modeled. This was done simply to facilitate an initial comparison across plans without the additional variability in the operating costs to muddy the

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waters. If all the plans are assumed to have similar operating costs, estimated at approximately $500M/yr, then the resulting NPV calculation provides the values reported in Table 3.

	Expected NPV
Flex Plan	$ (1,654.88)
Top Down Plan	$ (2,025.10)
Empirical Plan	$ (1,350.65)

Table 3. Decision Tree NPV Results with Recurring Costs ($ in millions).

Note that this valuation does not change the rank ordering of the options out through Year 10. This makes intuitive sense since the same recurring operating costs were used for all three options. While differences in unmanned operating costs between options are not modeled further for this analysis, the analysis framework is sufficiently robust to explore this aspect of the options space should there be a desire to extend the analysis at some point in the future.

Finally, recall that the decision tree analysis addresses the specific uncertainties associated with the approval or disapproval of a given operation by the FAA. While these probabilities are handled in deterministic fashion with the current decision tree, the effect of varying the chance outcomes can be computed and displayed with relative ease by building data tables with varying probabilities for each outcome. In this way, the impact of changing the probability of mission approvals can be assessed across a wide range of values.

Uncertainty Development

Building on the decision tree analysis, the next step is to incorporate the uncertainty associated with the cost of manned operations the unmanned aircraft system is replacing. **A**ctual historical trend data was not available to calibrate the binomial lattice factors for the upside probability, the upside factor, or the downside factor. Expert judgment was used to estimate the probable drift in the cost of manned operations and the volatility in the cost in any given period. For this particular case, the annual growth in manned costs was assumed to be an average of 5%, and the volatility in the costs was estimated to be 20% per year. This resulted in an upside probability, p, of 0.873; an upside factor of 1.40; and a downside factor of 0.715. Recall, each

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UAS iteration is on a five-year cycle time, so the time used in calculating the above values was set to 5 years.

An initial starting value of $523 million was used as an estimate for current annual manned operations costs. The probability at 5 year increments was calculated using a binomial lattice that estimated the subsequent manned operation costs given the above parameters. The progression of the probability distribution function with respect to the manned operations costs is given in Figure 3 below.

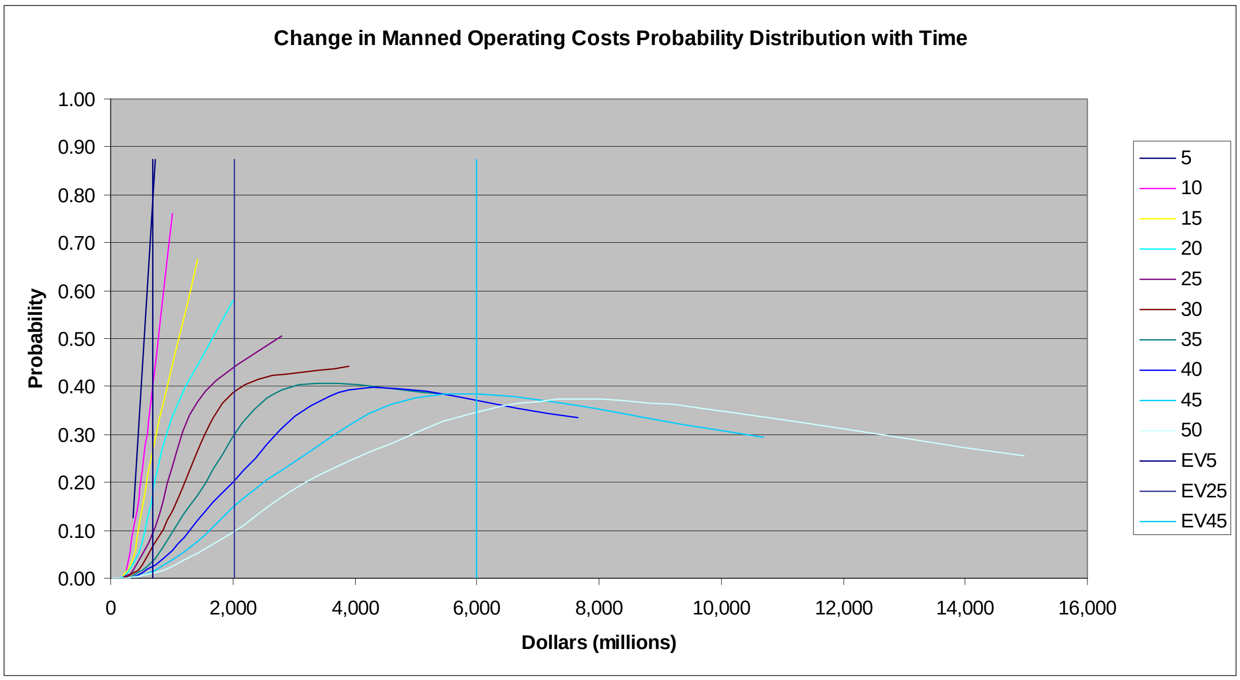

Figure 3. Probability Distribution of Manned Operating Costs over Time.

In Figure 3, each curve represents the range of possible values the manned operating costs could have in that time frame. The time frame is represented by the number in front of the line color in the legend and should be read as the time from t = 0 on the program. Also plotted for a reference are the expected values of three of these time frames, denoted by "EV" and then a number specifying which time frame. The expected values are denoted for years 5, 25, and 45.

The expected values themselves can be plotted with respect to time to observe the overall trend associated with the distributions described in Figure 3. It is useful to consider the expected value with respect to the maximum and minimum vales the distribution in Figure 3 generated.

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This is depicted in Figure 4, and it provides a nice visualization of how the cost of manned operations is expected to change over time.

Note that none of these calculations have included the effect of the discount rate in their development. To include the effect of discount rate, the values at each time interval would need to be adjusted by dividing the calculated "Then Year" dollars by the discount rate at that time step. This would yield a "Current Year" dollar perspective on the anticipated costs of manned operations.

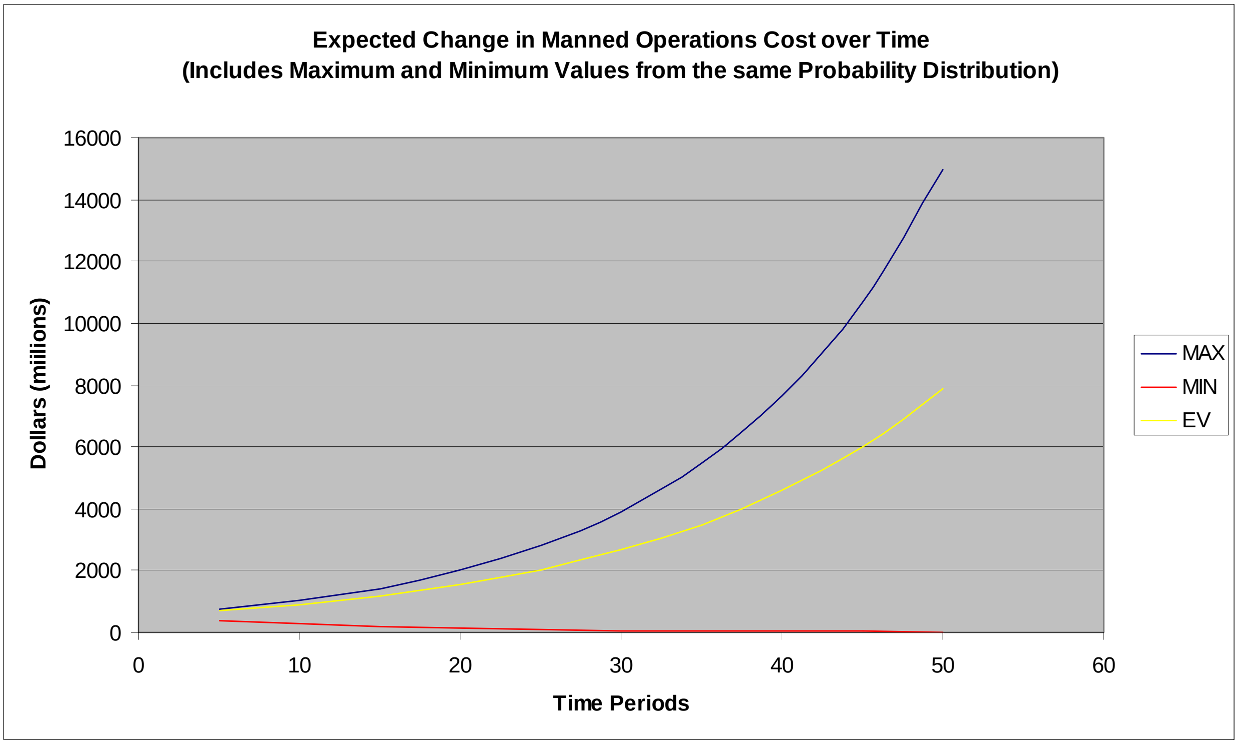

Figure 4. Expected Value over Time.

The binomial lattice used to generate these curves is provided in Table 4 and Table 5.

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	0	5	10	15	20	25	30	35	40	45	50
Operational Benefit Uncertainty (Captured as a function of manned aircraft annual costs)											
Ops Benefit:	2615.00	4089.72	6396.12	10003.20	15644.49	24467.17	38265.38	59845.08	93594.62	146377.14	228926.29
		1672.05	2615.00	4089.72	6396.12	10003.20	15644.49	24467.17	38265.38	59845.08	93594.62
			1069.12	1672.05	2615.00	4089.72	6396.12	10003.20	15644.49	24467.17	38265.38
				683.60	1069.12	1672.05	2615.00	4089.72	6396.12	10003.20	15644.49
					437.10	683.60	1069.12	1672.05	2615.00	4089.72	6396.12
						279.49	437.10	683.60	1069.12	1672.05	2615.00
							178.71	279.49	437.10	683.60	1069.12
								114.27	178.71	279.49	437.10
									73.06	114.27	178.71
										46.72	73.06
											29.87

Table 4. Upside and Downside Value Determinations at each Time Step (millions of $).

	0	5	10	15	20	25	30	35	40	45	50
Probabilities:	1.00	0.75	0.56	0.422	0.316	0.237	0.178	0.133	0.100	0.075	0.056
		0.25	0.38	0.422	0.422	0.396	0.356	0.311	0.267	0.225	0.188
			0.06	0.141	0.211	0.264	0.297	0.311	0.311	0.300	0.282
				0.016	0.047	0.088	0.132	0.173	0.208	0.234	0.250
					0.004	0.015	0.033	0.058	0.087	0.117	0.146
						0.001	0.004	0.012	0.023	0.039	0.058
							0.000	0.001	0.004	0.009	0.016
								0.000	0.000	0.001	0.003
									0.000	0.000	0.000
										0.000	0.000
											0.000

Table 5. Upside & Downside Probabilities for Table 4 Values at each Time Step.

The conclusion of the cost uncertainty development in the model is that it is possible to model a wide range of uncertainty in the cost estimation. Quantifying the uncertainty in this manner provides a mechanism to deal with the unknowns in the future cost figures by addressing this uncertainty explicitly in the design of the options. As will be discussed in the next section, this will also lead to an ability to value the added flexibility a particular option brings to the design. This aspect will be developed as the final element in this analysis.

Flexible Option Valuation

Considering a single scenario from the decision tree developed previously, the NPV of the operation can be calculated given the conditions of that scenario. For the purposes of this

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analysis, the Flexible Development Plan will be used to assess the NPV of the operation assuming that each stage of development is successful and approved by the FAA for operations.

In addition, the recurring costs of operations for the unmanned aircraft will be assumed to be $100M/yr for each stage in which operations are conducted. With this as a backdrop, the expected NPV of the Flexible Plan can be calculated assuming that we operate across the entire 50 year time horizon regardless of what the cost of manned operations does in this same time frame. Table 6, Table 7, and Table 8 summarize these calculations.

Captial Costs:	150.00	200.00	400.00	600.00	600.00						
Recurring Costs:		500	500	500	500	500	500	500	500	500	500
Approval Status:		LO App	EO App	RR App	ER App	FI App					
% Mission Capable:	0.00	0.10	0.25	0.50	0.75	1.00	1.00	1.00	1.00	1.00	1.00
Net Revenue:	150	291	1,339	6,402	18,456	42,318	76,031	119,190	186,689	292,254	457,353
		533	15	1,967	6,895	17,006	30,789	48,434	76,031	119,190	186,689
			526	154	2,169	6,657	12,292	19,506	30,789	48,434	76,031
				587	236	2,426	4,730	7,679	12,292	19,506	30,789
					554	696	1,638	2,844	4,730	7,679	12,292
						11	374	867	1,638	2,844	4,730
							143	59	374	867	1,638
								271	143	59	374
									354	271	143
										407	354
											440

Table 6. Net Revenue Calculation Given Manned Operations Uncertainty.

	0	5	10	15	20	25	30	35	40	45	50
Probability	150	218	753	2,701	5,839	10,042	13,532	15,910	18,690	21,944	25,755
Weighted		133	6	830	2,909	6,726	10,960	15,085	20,298	26,848	35,044
Net Revenue			33	22	457	1,755	3,646	6,076	9,590	14,547	21,408
				9	11	213	624	1,329	2,552	4,557	7,706
					2	10	54	164	409	897	1,795
						0	2	10	38	111	276
							0	0	1	8	27
								0	0	0	1
									0	0	0
										0	0
											0

Table 7. Net Revenue (Table 6) * Probability of Occurance (Table 5).

	0	5	10	15	20	25	30	35	40	45	50
E [Revenues]	150	351	726	3,543	9,215	18,747	28,817	38,574	51,578	68,910	92,011
PV(E[Revenues])	150	251	369	1,284	2,381	3,454	3,786	3,613	3,444	3,281	3,124
NPV over 25 years	**7,088**	Current Year $$s over 25 years			**31,729**						
NPV over 50 years	24,336	Current Year $$s over 50 years			311,620						

Table 8. Expected and Net Present Values for Varying Manned Operation Costs.

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The results of including the uncertainty associated with the cost of manned operations, the addition of fixed operating annual operating costs, and the assumption that operations would be approved at each stage with a resulting fraction of manned operations replaced by unmanned missions results in an expected NPV of $28.1B. Notice the difference that a small discount rate of only 7% makes in the expected present value. Without the discount factor, the expected value would have been $368.5B. Also note that the discount rate is applied at five-year intervals as opposed to every year, so some error has been introduced as a result of this simplification.

The above analysis assumed that operations would occur regardless of the actual change in manned operating costs in any given year. This additional uncertainty factor can now be taken into consideration and a decision made not to operate at any point in which the costs of operating will exceed the benefits. This is done by comparing the Net Revenue at any given state in the binomial lattice with the fixed costs of the activity. If the cost of operating exceeds the fixed cost of the effort, then the operation is terminated at that point and not turned back on.

The cumulative effect of the ability to make a decision to not operate in a given time period can be assessed by looking ahead at each point in the binomial lattice to determine if the weighted average of the upside and downside states will be greater than or less than the fixed costs in that year. If they are greater, then the decision is made to shut down operations, and just the fixed cost for that year are included in the calculation of the NPV. If they are less, then the decision is made to continue operating and the calculation proceeds to the next time stage. Table 9 summarizes the calculations for the NPV given a decision can be made at each time stage based on the actual cost of manned operations that will be replaced.

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	0	5	10	15	20	25	30	35	40	45	50
PV(Net Revenue)	180,943	228,300	287,872	360,514	445,212	536,260	620,554	683,995	709,389	656,447	457,353
WITH OPTIONS		90,179	114,756	144,818	179,962	217,738	252,412	278,574	289,198	267,811	186,689
(check next year)			43,979	56,633	71,517	87,513	101,900	112,822	117,406	108,921	76,031
				20,580	27,180	34,271	40,364	45,055	47,171	43,959	30,789
					9,057	12,505	15,206	17,349	18,455	17,401	12,292
						3,621	4,922	6,022	6,715	6,542	4,730
							776	1,401	1,916	2,103	1,638
								271	4	288	374
									354	271	143
										407	354
											440
Shut Down?	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	
WITH OPTIONS		NO	NO	NO	NO	NO	NO	NO	NO	NO	
(check next year)			NO	NO	NO	NO	NO	NO	NO	NO	
				NO	NO	NO	NO	NO	NO	NO	
					NO	NO	NO	NO	NO	NO	
						NO	NO	NO	NO	NO	
							NO	NO	NO	NO	
Value of option =	180,943							YES	NO	NO	
-	24,336								YES	YES	
	156,608									YES	

Table 9. Value of Option to Shut Down Operations.

From these calculations, the decision to shut down would be exercised if the cost of manned operations were ever in the states depicted at the bottom of the range for years 35, 40, and 45. The flexibility of being able to curtail operations in these situations results in a total NPV of the effort of $180.9B. This means the option to shut down operations is worth $156.6B over that of the value of the effort with no ability to shut down operations.

Conclusion and Final Thoughts

This analysis has provided insights on several key points in the design of systems in the face of uncertainty. The first observation is that there is a legitimate way of introducing uncertainty into the analytical methods used to evaluate and determine design options on an engineering system. The second observation is that there is value in attempting to explicitly call out this uncertainty because it can be turned to advantage if handled correctly. This insight is somewhat counterintuitive, and would generally result in a negative impact to the system if the means of dealing with the uncertainty was not explicitly included in the design options.

Another very important lesson is taken from the value that can be obtained from a general trend or overall choice standpoint even when the amount and quality of the data available to understand the uncertainty in the system is relatively lacking. In the case of the binomial lattice

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model, the historical data was not available, but the insights gained even making several gross assumptions allowed a substantial number of "what-if" scenarios to be considered from a parametric analysis standpoint. In this respect, the distinction between "choice" and "judgment" discussed as part of the ESD.71 curriculum makes an even more pronounced impact, especially if the objective is less to quantify a given point design and more to understand over what range of parameters a given design or option may provide robustness against a wider range of uncertainties while still delivering the highest value to the stakeholder community.

The other aspect the analysis helped drive home was the difference in the strength of various types of models. By working through the specifics of both a decision tree and a binomial lattice case, it became apparent just where each of these models would fit into the trade space of available tools for modeling and designing with uncertainty. Specifically, the decision tree handled discrete, discontinuous types of events very well. This corresponded with the type of uncertainty introduced by the decision of the FAA on the mission approval status. Conversely, for those uncertainties that tend to develop in a path independent way, such as the cost of operations, the binomial lattice provided a powerful mechanism to quickly and simply calibrate data and generate expected distributions of values.

In addition to these general conclusions, several specific observations can also be offered on the actual approach the Air Force should consider as they continue their dialogue with the FAA on flying unmanned aircraft in the national airspace system. First, the Air Force should pursue a more comprehensive analysis of the design variables by exploring the parametric space over which a given design approach returns the best value in comparison to the other options. In this manner, the robustness of a given design option can be assessed vice the determination of a specific point design.

Second, the Air Force needs to better quantify what the utility will be to the operation for those situations in which the FAA allows some expansion in the access, but does not grant fully integrated operations. Even with this relatively simple analysis, the impact of the utility of partial access and the associated probability of approval from the FAA appear to be dominant variables in determining the overall value of an option. These two variables in particular need a solid analytical basis on which to conduct the analysis, and a greater degree of fidelity is needed than the current analysis currently provides.

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Third, the sheer complexity of the undertaking, and the number of contributing variables, recommends itself to the Wang[5] approach of option identification in order to narrow the playing field of important variables to model in the analysis. In the current analysis, the only uncertainty that was developed was that associated with the cost of manned operations. In reality, the utility of partial access, the probability distribution around the FAA approval rate, the non-recurring engineering costs associated with putting the appropriate capability on the unmanned aircraft system, and the recurring cost of operations of the unmanned aircraft system are all likely to be significant contributors to the overall value of an option at any given point in time. Wang's approach provides a disciplined process for establishing these key variables and then developing the appropriate uncertainty bounds around them.

Fourth, the Air Force should engage in a detailed dialogue with the FAA with respect to how this approach to dealing with the above described uncertainties would impact the actual design and implementation of an unmanned aircraft system capable of flying in the national airspace system. It is likely that the application of these approaches to dealing with uncertainty in key variables has the potential to revolutionize the overall architecture of the solution currently being pursued by the Department of Defense. This shift in approaching the engineering design work from a classical systems engineering decomposition of static performance requirements to an assessment of the likely uncertainties and how to design against these uncertainties should be explored as soon as possible.

In the end, the take away from this experience is that uncertainty can and should be explicitly dealt with in engineering designs, regardless of how well the specifics can be quantified. Lack of detailed knowledge or insight should not be a roadblock to thoughtful and reasoned approaches to addressing the uncertainty in system design. In fact, this very uncertainty, if handled appropriately, provides a means of adding value to the system that would not otherwise be possible. The challenge that lies ahead is to continue to push the theoretical basis for combining the two types of models used in this analysis to take advantage of their relative strengths and broaden the base of relevant applications. As these tools become more flexible, their use will continue to grow, and the result should be an overall increase in the robustness and value engineering systems deliver to their stakeholders and society at large.

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[1] Figure taken from an MIT/LL briefing provided to the 303 AESW/XRX staff on 23 May 2007 providing background on the UAS collision avoidance problem.

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