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14. ABSTRACT

Uncertainty can significantly affect a system's cost. Any estimate/prediction of a system's cost is accompanied by a range of other potential costs. It is not overly pessimistic to assign at most a 30 percent confidence level to a complex system's cost estimate to account for significant technical and program uncertainties, and the estimation uncertainty itself. A decision-maker must understand the uncertainties and their potential impact while weighing these uncertainties against their cost and his resource constraints.

Decision analysis provides a structured approach analyzing and selecting a course of action to achieve an objective where the choices and outcomes are characterized by uncertainty as well as the value tradeoffs. For difficult decisions with careful analysis and hard choices, it is human nature to still wonder if you made the right decision. Regret analysis, a subset of decision analysis, is a basic operations research technique used to determine how much may be lost if a different decision were chosen. Regret occurs when the selected alternative is not the most preferred outcome (e.g. the least expensive). This paper illustrates an application of Regret Analysis via a case study using HQ Air Force Space Command's recent Operationally Responsive Spacelift Analysis of Alternatives.

15. SUBJECT TERMS

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AoA Case Study: A Variation of Regret Analysis

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Uncertainty can significantly affect a system's cost. Any estimate/prediction of a system's cost is accompanied by a range of other potential costs. It is not overly pessimistic to assign at most a 30 percent confidence level to a complex system's cost estimate to account for significant technical and program uncertainties, and the estimation uncertainty itself. A decision-maker must understand the uncertainties and their potential impact while weighing these uncertainties against their cost and his resource constraints.

Decision analysis provides a structured approach for analyzing and selecting a course of action to achieve an objective where the choices and outcomes are characterized by uncertainty as well as the value tradeoffs. For difficult decisions with careful analysis and hard choices, it is human nature to still wonder if you made the right decision. Regret analysis, a subset of decision analysis, is a basic operations research technique used to determine how much may be lost if a different decision were chosen. Regret occurs when the selected alternative is not the most preferred outcome (e.g. the least expensive). This paper illustrates an application of Regret Analysis via a case study using Head Quarters Air Force Space Command's recent Operationally Responsive Spacelift Analysis of Alternatives.

Introduction

This paper defines the difference between "risk" and "regret". It describes a variation of regret analysis for the purposes of a case study, and highlights the different analysis outcomes between the two types of regret analysis accomplished in the case study.

To illustrate this difference, this paper will explore the Head Quarters Air Force Space Command (HQ AFSPC) Operationally Responsive Spacelift (ORS) Analysis of Alternatives (AoA) as a case study. The purpose of the ORS AoA was to determine the most responsive means to launch, maneuver, service, and retrieve space payloads to enhance military effectiveness. The ORS AoA was designed to provide United States Air Force and Department of Defense with critical information about the military effectiveness and cost for making acquisition decisions concerning ORS. The main questions for the ORS AoA to answer are:

- What are the benefits of acquiring ORS?
- Is ORS the best way to achieve these benefits?

- Is ORS affordable?
- If so, what is the best approach to develop ORS?

Decision-makers involved with ORS range from the HQ AFSPC Commander - responsible for the development, acquisition and operation of the Air Force's space and missile systems, to the acting Secretary and Under Secretary of the Air Force, Washington D.C. and Department of Defense Executive Agent for Space. These decisions-makers are faced with a choice among a wide variety of launch vehicles (LVs) offering a range of performance and cost. The ORS AoA identified a launch vehicle architecture that on the basis of cost and risk appears most worthy to pursue.

Risk vs Regret Defined

Formally speaking, **risk** is the probability an unfavorable event occurs. **Risk** can be defined as the chance of potential harm that may arise from some present or future action. It is often defined as the probability of an undesirable event. Probabilities and value assessments of the consequences/impacts of events are combined into an expected outcome.

Risk is also defined as an adverse event or outcome, foreseen or not, that impacts an organization, operation, process, or project in a negative way. Although risk has no one definition, some theorists, notably Ron Dembo, have defined general methods to assess risk as an expected after-the-fact level of **regret**.

Webster's Revised Unabridged Dictionary (1913) defines **regret** as "To experience regret on account of; to lose or miss with a sense of regret; to feel sorrow or dissatisfaction on account of (the happening or the loss of something); as, to regret an error; to regret lost opportunities or friends." In game theory, the key idea is to minimize regret - the feeling one gets after making a bad decision and wishing the decision could be changed after the game is finished. The end product of this line of reasoning is that one would make decisions in such a way as to *minimize the maximum expected loss* to himself or herself.

In addition, regret associated with an outcome is classically defined as the utility of that outcome subtracted from the maximum utility of that state (condition) - in other words, the amount of additional satisfaction which one could have if they made a better choice. When the utility of an outcome is the maximum for that state (condition), the regret associated with that outcome equals zero. Regret measures the extent to which one would be unhappy to miss out on a positive outcome (or opportunity). It also expresses how much worse things are than they would have been had one chosen the other option within a certain state (condition).

A variation of regret analysis was applied in the case study described in this paper where alternatives offering the same utility at a defined level are compared and "regret" of an alternative is measured in terms of the difference in life cycle cost (LCC)—the lost opportunity for not selecting the least expensive alternative. The same alternatives are compared at three different defined utility levels with their relative cost and risk of achieving those levels not consistent across the levels.

A Real Example – ORS AoA Case Study

Introduction: The regret analysis case study is based on the ORS AoA. The Under Secretary of Defense for the Air Force (Space) commissioned HQ AFSPC Directorate of Requirements (AFSPC/DR) to deliver an AoA to determine the best means to responsively launch, maneuver, service and retrieve space payloads to enhance military effectiveness. The team took a capabilities-based approach rather than a traditional AoA approach of identifying the alternatives and then determining military utility. Typically an AoA defines and assesses a set of alternatives for cost and effectiveness, using defined measures (Measures of Effectiveness (MOEs)) for meeting mission needs. Effectiveness is determined through a utility analysis that relates measures of system performance (MOPs) to MOEs. By contrast, the ORS AoA began by establishing several levels (low, medium, and high) of mission utility and corresponding performance levels to which alternative designs were defined and subsequently costed. The advantage of this approach is that performance levels are *fixed* enabling the alternatives to be evaluated and compared strictly on the basis of cost and risk. The variation on regret analysis described in this paper was applied to enable this comparison.

Figure 1 represents the capabilities-based approach of the ORS AoA.

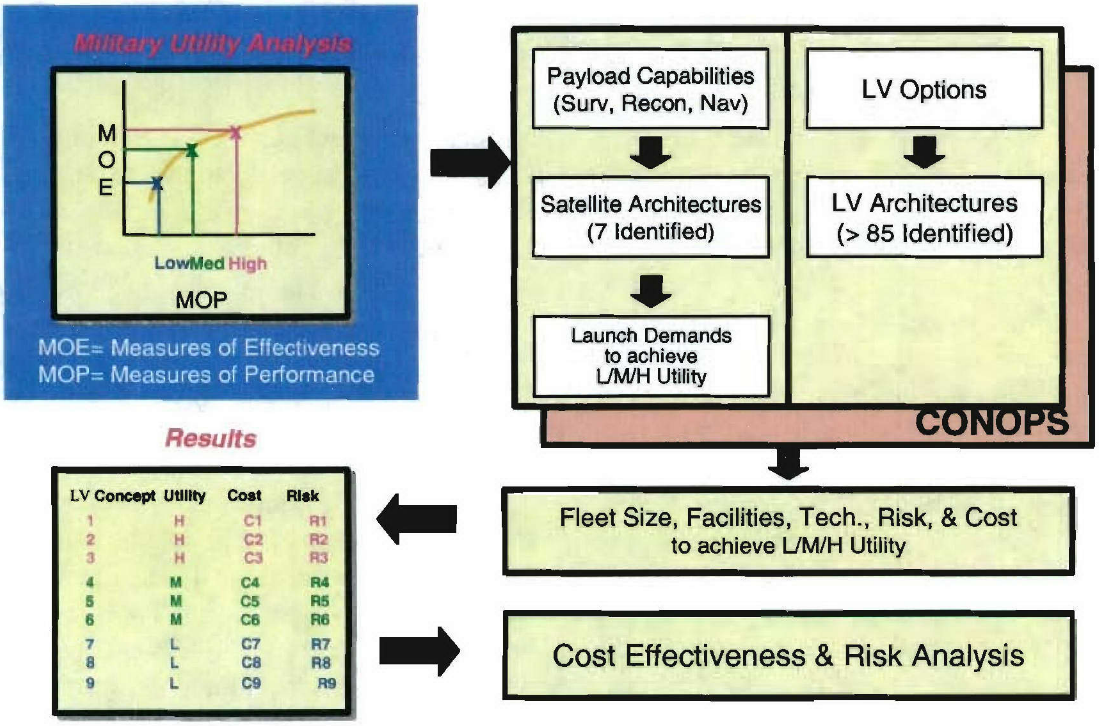

Figure 1. The ORS AoA Process.

The ORS AoA entailed a complex series of analyses performed by several working groups. Detailed descriptions of each analysis are beyond the scope of this paper. The military utility analysis conducted by the ORS AoA Effectiveness Analysis Working Group encompassed a series of parametric experiments using the Lightning campaign model to establish the three levels of performance (low, medium, and high), and their associated utility.

Payload Analyses and Mission Task Analyses (Maintaining On-orbit capability in the presence of Red Offensive Counterspace (OCS), Blue Offensive Counterspace, Force Application) were used to define the low, medium, and high performance parameters. Table 1 provides a summary of the ORS AoA Effectiveness Analysis Working Group's definition of low, medium, and high performance used for defining and evaluating ORS alternatives.

Parameters/Utility Levels	**Low**	**Medium**	**High**
Red OCS	50% (reduction in Blue capability)	85% (reduction in Blue capability)	100% (reduction in Blue capability)
Blue Replenishment	50% (end result of 75% of original capability)	70% (end result of 75% of original capability)	85% of original capability
Blue OCS	None	Attacks Red NAV at 50% on day 2	Attacks Red ISR at 100% on day 0 and NAV 75% on day 0
# of Common Aero Vehicles (CAVs)	50 in 20 days	500 in 10 days	2000 in 20 days

Table 1: Overall Utility Settings for Low, Medium, and High

(Note: The start of a Major Theater War is Day 0. D-0 represents Day 0, D-2 represents Day 0 minus 2 days)

To develop alternatives for the ORS AoA, the Integrated Concepts Working Group (ICWG) first defined specific payload (e.g., satellite/constellation, weapon system) parameters and required deployment timeframes to meet mission needs. The ICWG established launch schedules using that data and then defined "launch vehicle architectures" (LVAs) to meet the demands of the launch schedules. LVs were grouped into LVAs so that each LVA had sufficient capacity to launch all space assets being defined. An LVA can have one, two, or three launch vehicles in its architecture. The ICWG then costed each of the LVAs for each performance level, reflecting the different mix and quantity of launch vehicles needed within the architecture to achieve the specific performance level. With each LVA having the same performance capability at a given performance level, only cost and risk differentiated them.

The results of the Military Utility Analysis and Alternative Development Phases of the ORS AoA resulted in a large number of alternatives to meet three different performance levels, yielding over 85 LVAs. For detailed analysis the ICWG reduced the set to 15, spanning the four types of vehicles: 3 Expendables, 8 Reusables, 3 Hybrids, and 1 Hypersonic. Table 2 shows the set of 15 architectures which meet the required performance levels. (Note: This paper will not discuss the details of the LVs in Table 2 but rather show the reader the four LVA groups and the LVs which make up the specific LVAs.)

LVA #	Configuration		
	Vehicle A	Vehicle B	Vehicle C
Exp LVAs			
4	Sol 25 k	Exp-Generic EELV 45 k	
11	RPRP 25 k	Exp-Generic EELV 45 k	
12	RPRP 45 k		
Reuseable LVAs			
30	RPOpt 15 k	RPOpt Growth to Trimese	
36	RPLHOpt 5 k	RPLHOpt Growth to 45 k	
39	RPLHOpt 25 k	Exp-Generic EELV 45 k	
41	RPLHOpt 45 k		
46	LH Bimese 15 k	LHBi Growth to 45 k	
47	LH Bimese 15 k	LHBi Growth to Trimese	
48	LH Bimese 25 k	Exp-Generic EELV 45 k	
51	LH Bimese 45 k		
Hypersonic LVAs			
64	RBCC 25 k	Exp-Generic EELV 45 k	
Hybrid LVAs			
67	RLV/ELV-Solid RD180	Exp-Generic EELV 25 k	Exp-Generic EELV 45 k
70	RLV/ELV 12.7k	Hybrid 2 RLVs/ELV 45k	
71	RLV/ELV 19.5k	Hybrid Growth to Trimese	

Table 2: Final ORS AoA Launch Vehicle Architectures

In addition, seven different Space Architectures (SAs) were developed within which the candidate LVAs operate to deliver weapons on target and provide capabilities to the warfighter (e.g. Intelligence, Surveillance and Reconnaissance (ISR) and Navigation (NAV) satellites operational in space). Table 3 shows the SAs and their definitions.

Architecture		Descriptions
1	Strategic	Current way of doing business still exists in 2017
		Constellations consist of conventionally designed assets
		Make use of DV to avoid Red OCS
2	Responsive-1	Full responsive launch & s/c ops capability available
		Relatively capable system already deployed during peacetime
		One-to-one replacement for reconstitution
3	Responsive-2	Limited responsive launch & s/c ops capability available
		Gap-filler, band-aid launch on-need
		One-to-one replacement for reconstitution
4	Serviceable	On-orbit servicing capability available
		Maneuver capability enabled due to servicing
		Spacecraft have bigger tanks for maneuvering
		Responsive launch & s/c ops capability available
5	Recoverable	Use fly-back (recoverable) reusable spacecraft
		Responsive launch & s/c ops capability available
6	Retrievable	Use retrievable (by RLV) reusable spacecraft
		Responsive launch & s/c ops capability available
7	Storage-on-Orbit	Current way of doing business still exists in 2017
		Constellations consist of conventionally designed assets
		Use spares from orbit to replace assets disabled by Red OCS

Table 3: ORS AoA Space Architectures

Space Architecture 2 (Responsive-1) (SA 2) was selected as the 'reference architecture' for the detailed analysis for the ORS AoA since it appeared to be the most probable 'world state' for an operationally responsive spacelift system.

The ORS AoA Cost Effectiveness Working Group (CEWG) faced the issue of first determining the relationship between performance and cost; and second, determining how to evaluate the alternatives' performance, cost, and risk together. The ORS AoA cost uncertainty analysis addressed a number of technology and other areas of risk. Two areas of uncertainty, launch vehicle production cost and processing time, were addressed in cost assumptions and were significant analysis drivers which needed to be bounded as part of the regret analysis.

The ICWG made two significant assumptions concerning these areas of uncertainty for the cost analysis portion of the study. The first significant assumption was that a 50 percent reduction in launch vehicle production cost for the reusable portion of the launch vehicle was achievable (50 percent reduction from the full shuttle-like production cost). The second significant assumption was that a reduction in launch vehicle processing time was achievable (where the notional best case was approximately 1 to 2 days and the worst case was approximately 4 to 16 days, depending on the launch vehicle). The ICWG and CEWG bounded the trade space by defining high and low production costs, and faster and slower processing times. Figure 2 graphically and notionally displays the wide spread in production cost versus processing time represented in the analysis. Actual values of both axes are not provided due to the sensitivity of the data.

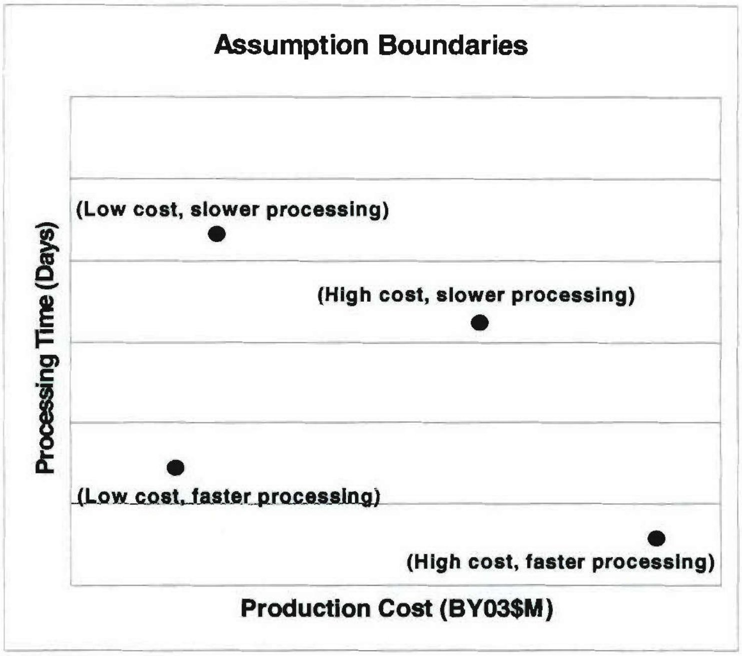

Figure 2. Trade Space Bounded by Launch Vehicle Production Costs and Processing Time Uncertainty.

The ideal ORS architecture should provide faster launch vehicle processing at a low launch vehicle production cost. If this is not achievable, a decision-maker must decide or settle for one of the other architectures, trading between cost and processing time. In today's funding-constrained environment, a low cost launch vehicle architecture may have a better chance of being chosen even if it is does not provide faster launch vehicle processing time. The life cycle cost estimate (LCCE) for the LVA will reflect the lower production costs offset by some degree by the increased operations costs cause by slower processing. This LCCE variability provides a dilemma for the decision-maker in deciding which conditions to trade off and for which conditions to settle.

Figures 3, 4 and 5 depict the LCCE variability for the least expensive LVA of each type (Expendable, Reusable, Hybrid, and Hypersonic), measured for the low, medium and high performance levels respectively. The cost and processing time variables have been combined into a "best case" (faster LV processing time and low production cost) and a "worst case" (slower processing time and high production cost) in deriving the LCCE of each LVA alternative. In each figure, the black segment of each bar represents the best case. The red portion represents the additional cost of the worst case (slower processing time and high production cost). Other combinations of the two variables create cases whose LCCE fall between that of the best and worst case. Due to the sensitive nature of the estimated costs, the y-axis does not have the actual scale. However, the chart depicts the relative LCCE differences among the alternatives.

Figure 3 illustrates that LVA #71 has the lowest LCCE for the low performance level for SA 2 and under the best case (faster LV processing time and lower production cost). Figures 4 and 5 show LVA #71 also has the lowest LCCE for medium and high performance levels respectively for SA 2 under the best case. It should be noted that both LVAs #67 and #71 are included in the hybrid category. Although LVA #71 appears to be the least expensive in the best case across low, medium and high performance levels, LVA #67 is a close second and has a lower LCCE in the worst case (slower LV processing time and high production cost) in that LVA category (hybrids).

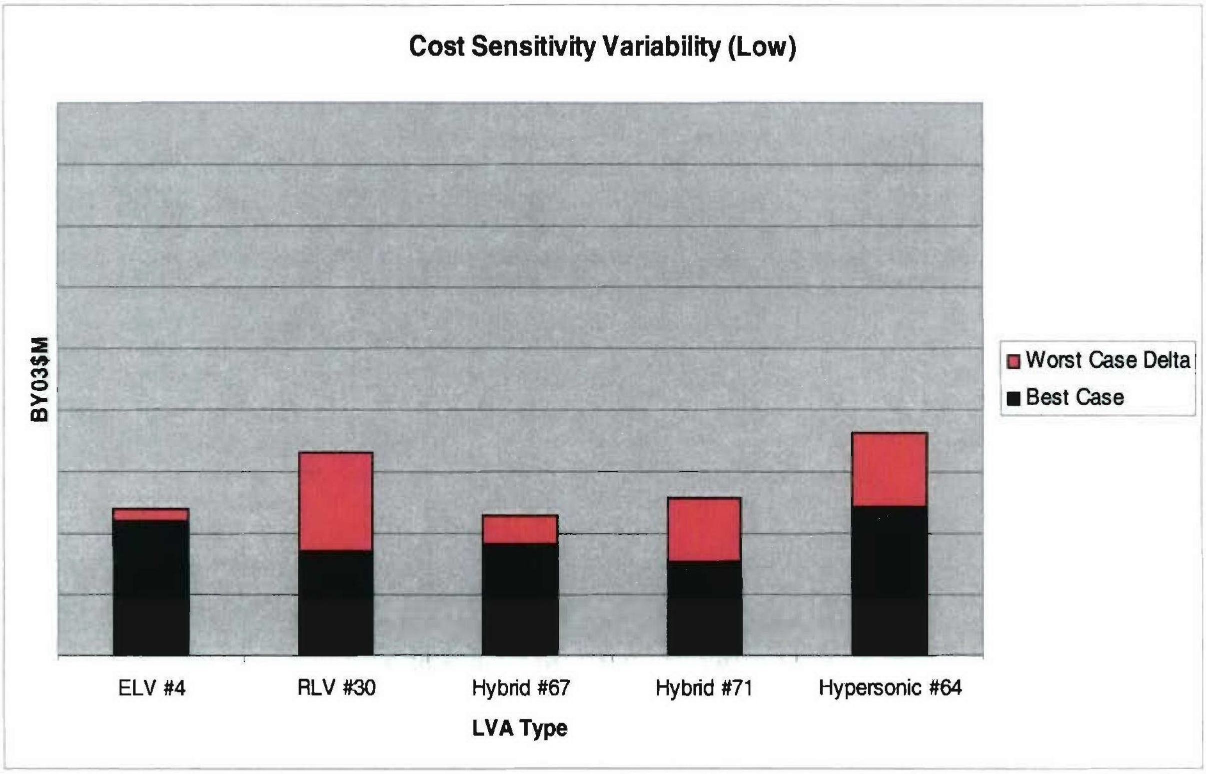

Figure 3. Best and Worst Case Conditions for Low Performance Level.

The figures show that there is significant variability in the cost across the least expensive architecture of each type of LVA. They also show that the cost variability among alternatives increases for the medium and high performance levels. This result was counter intuitive: the CEWG expected the variability to be consistent across performance levels. This finding led the CEWG to examine the sensitivity of the cost assumptions, and to determine if other LVA alternatives would potentially be cost effective.

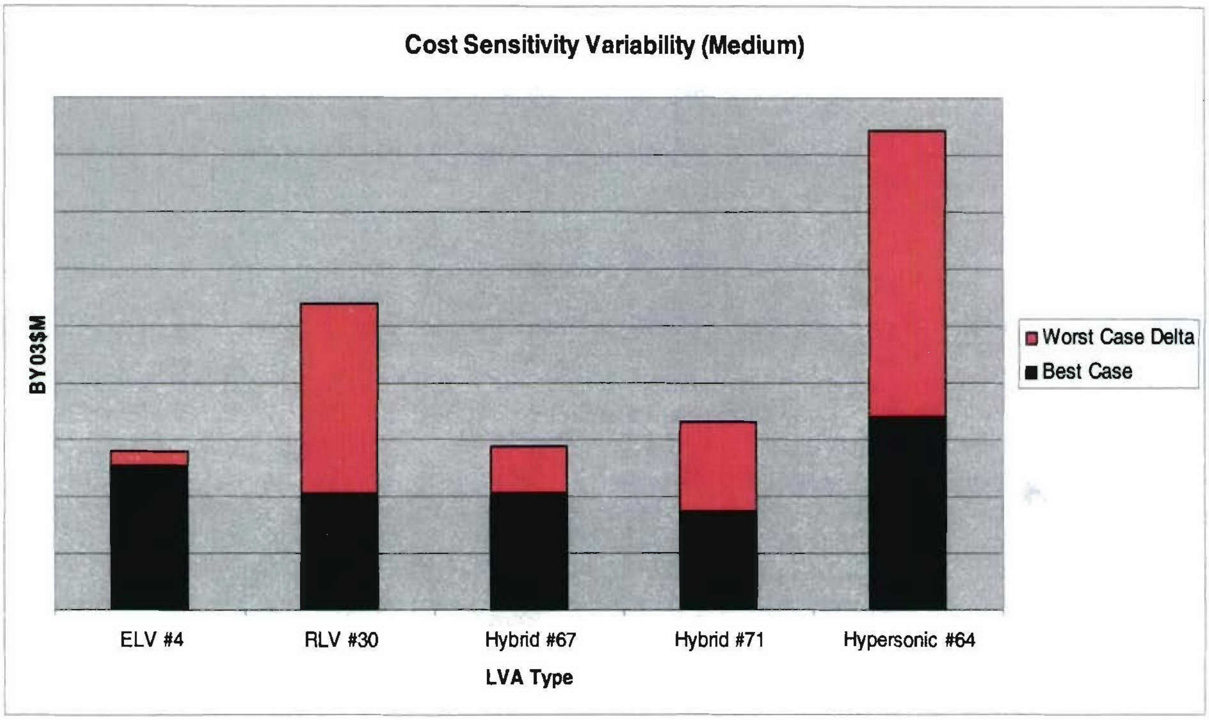

Figure 4. Best and Worst Case Conditions for Medium Performance Level.

Figures 3 through 5 graphically depict there is no clear 'winner' for lowest LCCE. As a result of the variations in each architecture between the best case and worst case costs for low, medium, and high performance levels, the CEWG undertook a variation of regret analysis to shed additional light on the issue. Regret analysis is a subset of decision analysis and is a basic operations research technique used to determine how much may be lost if a different decision were chosen. Used here, regret is measured by the difference in LCC between the optimal (least expensive) choice and an alternative within the same performance level and for the same conditions (LV production costs and processing time).

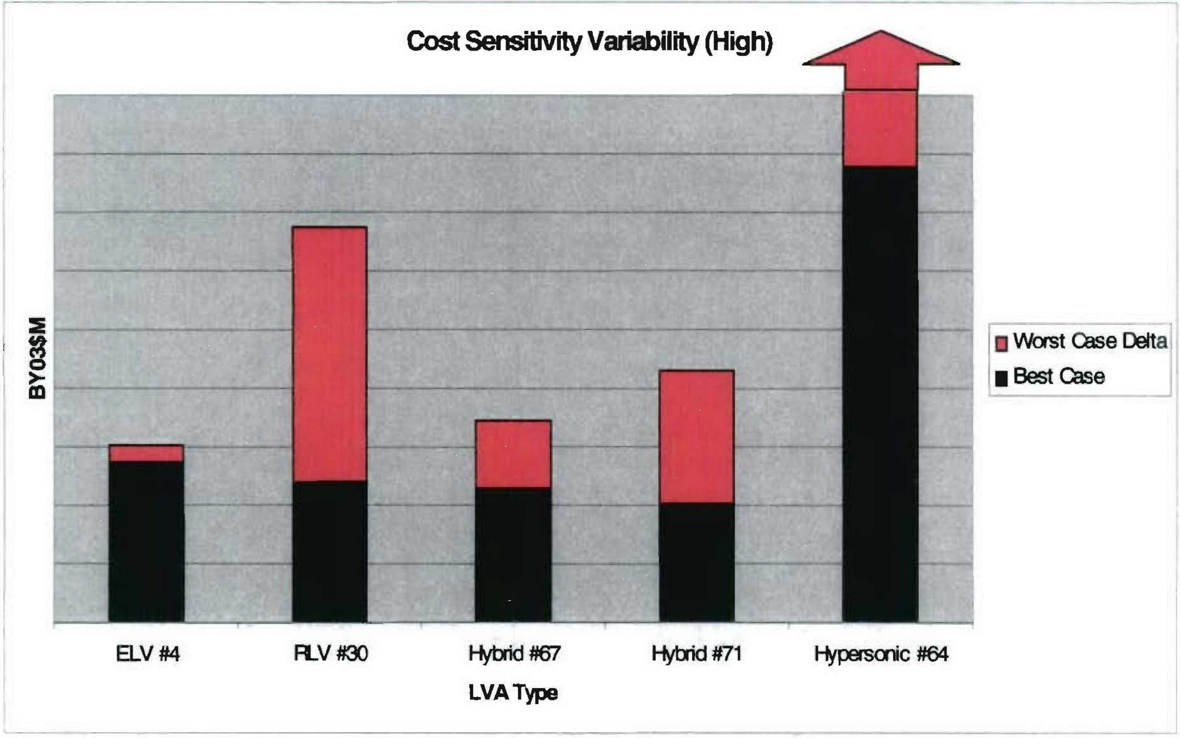

Figure 5. Best and Worst Case Conditions for High Performance.

Regret

For the case study, the author defined regret as "the difference between some choice and the best choice for a particular realization of the uncertainties." Typically, regret occurs when the selected alternative is not the least expensive of alternative choices within a given set of assumptions or conditions in which the alternative is procured. For example, System A may be selected because it appears on average to be the least expensive, but it is not the least expensive under given sensitivity conditions.

If high launch vehicle production cost and slower launch vehicle processing times actually occur, there is regret because in this particular circumstance a different alternative was estimated to cost less. Since there was no probability for the chance of the launch vehicle processing time and launch vehicle production cost variables, two methods of regret analysis were selected. To distil the vast amount of data into meaningful cost-effectiveness information for the decision-maker, the CEWG performed regret analysis on the average regret across the four conditions within a performance level as well as on the Minimax regret across the four conditions within a performance level, for every performance level and all seven SAs. The rest of this paper will discuss the selected reference SA 2.

Average Regret. Average regret is the equivalent of having all equally likely outcomes. Average regret is uniformly distributed (meaning that each condition has the same probability of occurring - which is the main and very significant shortcoming of average regret - there is little discriminative ability. The regret function is:

Average Regret # = (average (LCCE of other LVA #) across the four conditions) – (average (LCCE of LVA #) across the four conditions)

Minimization of the Maximum (Minimax) Regret. The Minimax Regret Criterion was developed by L.J. Savage and uses the concept of *opportunity cost* to arrive at a decision. The Minimax Regret criterion focuses on avoiding regrets that may result from making a nonoptimal decision. The Savage Minimax regret criterion examines the regret, opportunity cost or loss resulting when a particular situation occurs and the payoff of the selected alternative is smaller than the payoff that could have been attained with that particular situation. The minimax criterion suggests that the decision-maker look at the maximum regret of each strategy and select the one with the smallest value. This approach appeals to cautious decision-makers who want to ensure that the selected alternative does well when compared to other alternatives regardless of what situation arises. It is particularly attractive to a decision-maker who knows that several competitors face identical or similar circumstances and who is aware that the decision-maker's performance will be evaluated in relation to the competitors. This criterion is applied to the same decision situation and transforms the payoff matrix into a regret matrix.

Minimax regret is distribution independent (meaning that the outcome is not dependent on an underlying statistical distribution) - which gives it its power, and is why it is found in the literature much more than average regret. Minimax regret is equivalent to being pessimistic, "The Eeyore syndrome". For the Minimax Regret analysis in the case study, all other LVAs will be compared to the least costly LVA within each performance level. The Minimax regret value was calculated across each of the four conditions in each performance level for each SA. Although these four conditions do not have any probabilities assigned to them, the analysts believed they are not all equally likely. For example, obtaining the fast launch vehicle processing time and low launch vehicle production cost will not have the same probability as obtaining the slow launch vehicle processing time and high launch vehicle production cost. Decisions made with minimizing the maximum regret are to control the remorse that inevitably accompanies hindsight. This is a form of the best, worst case selection. This regret function is:

Minimax Regret (of a particular alternative #) = (LCCE of other LVA #) – (Least costly LCCE)

Application of the Regret Analysis Process

The cost of each LVA was compared to one of the hybrid LVAs to identify a delta. Four deltas were calculated at each performance level for the four conditions given by launch vehicle production cost (high and low) and launch vehicle processing time (faster and slower). Then the four deltas were averaged for each performance level. Launch vehicle processing time and launch vehicle production cost are conditions that are not equally likely. Slower launch vehicle processing time and high launch vehicle production cost characterize space launches today. However, faster launch vehicle processing time and low launch vehicle production cost are desired for the future.

The regret value is calculated for each case in <u>each</u> performance level in <u>each</u> SA. Since there are four conditions for each performance level with no probability assigned to each case, the regret values were averaged for each performance level. If the average regret value for a specific LVA is positive, then the least expensive LVA on average is better but if the average regret value is negative, then that specific LVA is better. Of the three hybrid LVAs which made the final cut of 15 LVAs, LVA #71 was chosen as the least expensive on average to compare against the other LVAs in the final cut.

Process to Calculate Average Regret:

The steps for calculating Average Regret are pretty straight forward. For all space architectures, the following steps were performed in each performance level. Tables 4 through 6 illustrate for the reader the Average Regret calculation steps for SA2 for the low performance level. Only a portion of SA 2 is displayed.

1. The LCC of each LVA was compared to LVA #71 to identify a delta LCC (in Base Year 2003 millions of dollars (BY03$M)). If the delta LCC is positive, then LVA #71 is cheaper. If the delta cost is negative, then LVA #71 is more expensive.
2. Four deltas were calculated at each performance level for the four conditions:
    a. Faster Processing Time, High Production Cost
    b. Faster Processing Time, Low Production Cost
    c. Slower Processing Time, High Production Cost
    d. Slower Processing Time, Low Production Cost

Architecture	SA 2	SA 2	SA 2	SA 2
Performance	Low	Low	Low	Low
Processing Time	Faster	Faster	Slower	Slower
Production Cost	High	Low	High	Low
Expendable (4)	20,679	33,563	-8,607	16,747
Expendable (11)	26,996	39,881	-6,931	18,423
Expendable (12)	37,058	49,943	3,374	28,728
Reusable (30)	17,876	9,278	37,307	16,479
Reusable (36)	34,538	22,463	36,488	19,879
Reusable (39)	16,488	14,815	15,522	10,140
Reusable (41)	21,165	12,022	22,335	8,920
Reusable (46)	36,394	19,843	72,324	34,759
Reusable (47)	39,855	20,681	82,208	39,699
Reusable (48)	33,320	24,394	24,787	15,716
Reusable (51)	27,823	12,678	38,152	14,174
Hypersonic (64)	55,760	44,796	52,728	39,813
Hybrid (67)	5,352	14,138	-13,748	2,952
Hybrid (70)	10,183	13,502	918	7,996
Hybrid (71)	0	0	0	0

Table 4: Average Regret, Step 2, BY03$M

3. The deltas (from step 2) were summed across the four conditions.

Architecture	SA 2
Performance	Low
Total Regret	(+ is good for LVA #71)
Expendable (4)	62,383
Expendable (11)	78,369

Expendable (12)	119,104
Reusable (30)	80,940
Reusable (36)	113,368
Reusable (39)	56,965
Reusable (41)	64,442
Reusable (46)	163,320
Reusable (47)	182,443
Reusable (48)	98,217
Reusable (51)	92,826
Hypersonic (64)	193,097
Hybrid (67)	8,695
Hybrid (70)	32,599

Table 5: Average Regret, Step 3, BY03$M

4. The average was calculated (sums from step 3 divided by 4).

Architecture	SA 2
Performance	Low
Average Regret	(+ is good for LVA #71)
Expendable (4)	15,596
Expendable (11)	19,592
Expendable (12)	29,776
Reusable (30)	20,235
Reusable (36)	28,342
Reusable (39)	14,241
Reusable (41)	16,110
Reusable (46)	40,830
Reusable (47)	45,611
Reusable (48)	24,554
Reusable (51)	23,207
Hypersonic (64)	48,274
Hybrid (67)	2,174
Hybrid (70)	8,150

Table 6: Average Regret, Step 4, BY03$M

5. If the average delta is positive, then LVA #71 is cheaper.

For low performance level, LVA #71 clearly has the least regret since all other values are positive. For the medium and the high performance levels, there are a few negative regret figures indicating that LVA #71 is not the best choice. Table 7 shows the Average Regret results for each performance level for the reference architecture SA 2.

Architecture	SA 2	SA 2	SA 2
Performance	Low	Medium	High
Average Regret versus LVA #71	(+ is good for LVA #71)		
Expendable (4)	15,596	11,727	-6,034
Expendable (11)	19,592	18,455	4,764
Expendable (12)	29,776	27,023	4,299
Reusable (30)	20,235	50,253	58,743
Reusable (36)	28,342	62,334	54,426
Reusable (39)	14,241	66,073	89,367
Reusable (41)	16,110	47,311	54,096
Reusable (46)	40,830	62,298	62,382
Reusable (47)	45,611	64,472	52,762
Reusable (48)	24,554	87,401	108,274
Reusable (51)	23,207	86,647	98,980
Hypersonic (64)	48,274	153,307	228,433
Hybrid (67)	2,174	-496	-10,688
Hybrid (70)	8,150	5,974	-1,435

Table 7: Average Regret, SA 2 Results, BY03$M

As mentioned earlier, the issue or concern arising with this method is that each condition for the LVA estimates does not have the same probability.

However, consider the question, "In which instances is LVA #71 not the most cost effective answer?" The average hides the results for those conditions where hybrid does not win. The main, and very significant, shortcoming of average regret is the assumption that all outcome states are equally likely. There is no evidence they are equally likely and plenty of evidence that they are not equally likely. The distribution is skewed toward the least favorable outcome: high launch vehicle production cost and slower launch vehicle processing time.

Process to Calculate Minimax Regret for the ORS AoA

For all space architectures, the following steps were performed in each performance level. Tables 8 and 9 are shown to assist the reader in following the Minimax Regret calculation process. Only a portion of SA 2 is displayed.

1. The lowest LCCE was found for each of the four conditions:
    a. Faster Processing Time, High Production Cost
    b. Faster Processing Time, Low Production Cost
    c. Slower Processing Time, High Production Cost
    d. Slower Processing Time, Low Production Cost
2. The regret value was calculated by subtracting the lowest LCCE (from step 1) from each of the other LVAs within the respective condition

Architecture	SA 2	SA 2	SA 2	SA 2
Performance	Low	Low	Low	Low
Processing time	Faster	Faster	Slower	Slower
Production Cost	High	Low	High	Low
Expendable (4)	20,679	**33,563**	5,141	16,747

Expendable (11)	26,996	**39,881**	6,817	18,423
Expendable (12)	37,058	**49,943**	17,122	28,728
Reusable (30)	17,876	9,278	**51,055**	16,479
Reusable (36)	34,538	22,463	**50,236**	19,879
Reusable (39)	16,488	14,815	**29,269**	10,140
Reusable (41)	21,165	12,022	**36,083**	8,920
Reusable (46)	36,394	19,843	**86,072**	34,759
Reusable (47)	39,855	20,681	**95,956**	39,699
Reusable (48)	33,320	24,394	**38,535**	15,716
Reusable (51)	27,823	12,678	**51,900**	14,174
Hypersonic (64)	55,760	44,796	**66,475**	39,813
Hybrid (67)	5,352	**14,138**	0	2,952
Hybrid (70)	10,183	13,502	**14,666**	7,996
Hybrid (71)	0	0	**13,748**	0

Table 8: Minimax Regret, Step 2, BY03$M

3. Then the maximum regret value for each LVA was determined by taking the largest regret value of the four conditions

Architecture	SA 2
Performance	Low
Expendable (4)	33,563
Expendable (11)	39,881
Expendable (12)	49,943
Reusable (30)	51,055
Reusable (36)	50,236
Reusable (39)	29,269
Reusable (41)	36,083
Reusable (46)	86,072
Reusable (47)	95,956
Reusable (48)	38,535
Reusable (51)	51,900
Hypersonic (64)	66,475
Hybrid (67)	14,138
Hybrid (70)	14,666
Hybrid (71)	13,748

Table 9: Minimax Regret, Step 3, BY03$M

4. Lastly, the minimum of the maximum regret values for was determined in each performance level

The Minimax Regret analysis results for SA 2 are shown in Table 10.

Architecture	SA 2		
Performance	Low	Medium	High
Max Regret			
Expendable (4)	33,563	39,004	35,574
Expendable (11)	39,881	47,482	47,305
Expendable (12)	49,943	56,713	48,609
Reusable (30)	51,055	130,510	185,371
Reusable (36)	50,236	133,708	155,299
Reusable (39)	29,269	146,831	233,414
Reusable (41)	36,083	116,009	172,178
Reusable (46)	86,072	145,051	187,384
Reusable (47)	95,956	150,581	171,974
Reusable (48)	38,535	178,474	257,857
Reusable (51)	51,900	200,298	267,315
Hypersonic (64)	66,475	281,238	478,988
Hybrid (67)	14,138	**14,777**	**21,107**
Hybrid (70)	14,666	23,869	47,700
Hybrid (71)	**13,748**	26,226	64,576
Mini-Max Regret			
	Hybrid (71)	Hybrid (67)	Hybrid (67)
	13,748	14,777	21,107
Delta (LVA #67 – LVA #71)	-390	11,449	43,468

Table 10: Minimax Regret, SA 2 Results, BY03$M

It is important to examine the first and second choices for inconsistencies. Looking at the Minimax numbers, LVA #71 only wins for the low performance case ($13,748M), and LVA #67 ($14,138M) comes in as a close second. In the medium performance case, LVA #67 ($14,777M) is the clear winner while LVA #71 has the greatest regret ($26,226M) within hybrids. The same is true only more so at the high performance level. In fact, at the high performance level every expendable has less regret than LVA #71. In the high performance level, hybrid LVA #67 is the clear winner at $21,107M; expendable LVA #4 is next at $35,574M, then expendable LVA #11 at $47,305M.

Upon comparing LVA #67 and LVA #71, the last row of Table 10 shows the minimax regret delta between the two. When LVA #71 is the clear winner, the delta is negative when compared to LVA #67. This happens only for the low performance case. The medium and high performance cases clearly show that LVA #67 has less regret since those numbers are positive.

Comparison of Average Regret versus Minimax Regret

Average Regret hides results for the conditions where hybrid does not win. For low performance hybrid LVA #71 had the least regret on average. However, for medium and high performance, hybrid LVA #67 has the least regret on average. We do not have insight into the combination of conditions (cost and processing time) for which LVA #71 is better than LVA #67; therefore we do not know which conditions directly affected the LCCEs of LVA #67 and

LVA #71. This led the CEWG to Minimax Regret analysis.

Minimax regret revealed that the hybrid type launch vehicle had the least regret for all levels of performance. Through Minimax regret analysis, the decision-maker can see which hybrid launch vehicle to pursue if growth in performance (low, medium, or high utility), funding, or risk were priorities. For low performance LVA #71 has the least regret ($13,748M), but for medium and high performance LVA #67 has the least regret ($14,777M and $21,107M respectively).

The existing condition of our country's ability for ORS is that we currently have slower launch vehicle processing time (more than 48 hours) and high launch vehicle production cost. The ideal condition is faster launch vehicle processing time (24 to 48 hours) and low launch vehicle production cost. The distribution of conditions is skewed toward the least favorable outcome: high launch vehicle production cost, slower launch vehicle processing time. That is, the probability of high launch vehicle production cost and slower launch vehicle processing time is greater than the probability of low launch vehicle production cost and faster launch vehicle processing time:

P (high production cost & slower processing time) > P (low production cost & faster processing time)

The data do not seem to support the conclusion that LVA #71 is the best. LVA #71 wins on average regret only at the low performance case, with LVA #67 a close second. LVA #71 is tied with LVA #67 at medium performance, and loses to LVA #67 (and LVA #4) at high performance. Choosing LVA #71 ignores indications that LVA #67 is a more robust choice, especially if a decision-maker wishes to procure a system with the potential to increase performance. If LVA #71 is somehow better from a demonstrator (or political) point of view, no evidence of that is presented here. All of this is evidence indicating the lack of information for a specific hybrid-type vehicle to make a sound acquisition decision.

Further analysis needs to be accomplished to get a better picture of risk and regret for an operationally responsive launch system. An operationally responsive hybrid vehicle demonstration would reduce cost and operability uncertainties as well as technical risk. The ORS AoA recommendation was to pursue a first stage reusable launch vehicle with expendable upper stages demonstrations to assess cost, operability, technology readiness levels; to test operations concepts/processes; and to assess scalability of cost and operations data and test more realistic operations concepts.

Since completion of this study, the HQ AFSPC Commander gave permission in January 2005 for the ORS Demonstrator to begin. A Phase I Program Research and Development Announcement (PRDA) notice was posted on February 16, 2005 for the **A**ffordable **RE**sponsive **S**pacelift-**S**ubscale **D**emonstration (ARES-SD). The ARES Phase I Concept Development and Demonstration Planning Program is contracted by the Department of the Air Force, Air Force Space Command, SMC - Space and Missiles System Center.

Summary

In closing, this paper defined the differences between risk and regret. Although risk has no one definition, some theorists have defined general methods to assess risk as an expected after-the-fact level of regret. Two types of regret analysis, Average Regret and Minimax Regret, were demonstrated using the HQ AFSPC ORS AoA as a case study. Average Regret was a very high level analysis while Minimax Regret 'peeled back the onion' a little further. Minimax Regret analysis improves the chance making the right decision, achieving a more positive outcome.

Since there is not enough detailed information to determine if faster processing time and low production cost are achievable assumptions, the ORS AoA team recommended that an operationally responsive hybrid vehicle demonstration would reduce cost and operability uncertainties as well as technical risk. The bottom line: different tools and types of analysis yield different analysis results. To achieve unbiased analysis, the analyst cannot overlook one tool or type of analysis over another. When used appropriately, Average Regret and Minimax Regret can be powerful analytical tools if limitations of each are known and understood.

Disclaimer

The views, opinions, and/or findings contained in this report are those of the author and should not be construed as an official Government position, policy, or decision, unless designated by other documentation. No classified documents or sources were referenced in the preparation of this paper.

Acronyms

AFSPC/DR	HQ AFSPC Directorate of Requirements
ARES-SD	**A**ffordable **RE**sponsive **S**pacelift-**S**ubscale **D**emonstration
BY03$M	Base Year 2003 millions of dollars
CEWG	Cost Effectiveness Working Group
HQ AFSPC	Head Quarters Air Force Space Command
ICWG	Integrated Concepts Working Group
ISR	Intelligence, Surveillance and Reconnaissance
LCC	life cycle cost
LCCE	life cycle cost estimate
LVAs	launch vehicle architectures
Minimax	Minimization of the Maximum
MOEs	Measures of Effectiveness
MOPs	measures of system performance
NAV	Navigation
OCS	Offensive Counterspace
ORS	Operationally Responsive Spacelift
PRDA	Program Research and Development Announcement
SAs	Space Architectures

References

Webster's Revised Unabridged Dictionary (1913), Version published 1913 by the C. & G. Merriam Co. Springfield, MA, under the direction of Noah Porter, D.D., LL.D.

Bibliography

Aseeri, Ahmed. "Planning Under Uncertainty Regret Theory." University of Oklahoma. July 27, 2004 <http://www.ou.edu/class/che-design/che5480-03/Regret%20Theory.ppt>

Book, Stephen A. "Estimating Probable System Cost." Crosslink, Winter 2000/2001 Issue; July 2004 <http://www.aero.org/publications/crosslink/winter2001/contributors.html#02>

Boutilier, Craig ; Patrascu, Relu ; Poupart, Pascal ; and Schuurmans, Dale. "Regret-based Utility Elicitation in Constraint-based Decision Problems." Department of Computer Science University of Toronto. July 2004 <http://www.cs.toronto.edu/~cebly/Papers/elicitation-CP.pdf>

Brand, Stewart. "How Buildings Learn: What Happens After They're Built." Chapt 11. Penguin, 1994

Garvey, Paul. "Implementing a Risk Management Process for a Large Scale Information System Upgrade - A Case Study.' Acquisition Community Connection Defense Acquisition University. INCOSE/PMI Risk Management Symposium 9 & 10 May 2001, INCOSE INSIGHT, Vol 4. Issue 1, April 2001, <https://acc.dau.mil/simplify/ev_en.php?ID=5658_201&ID2=DO_TOPIC>

Headquarters Air Force Space Command Directorate of Requirements (HQ AFSPC/DR) "Analysis of Alternatives (AoA) Final Report for Operationally Responsive Spacelift (ORS)." April, 2005

Hillier, Frederick S.; Lieberman, Gerald J. "Introduction to Operations Research." McGraw-Hill Inc., New York, p 475-478, 6th Edition

Hillier, Frederick S.; Lieberman, Gerald J. "Operations Research." Holden-Day Inc., San Francisco, p 285, 599-600, 2nd Edition

Pittman, Matthew. "A Landscape of Risk." Project Managers Network. 29 June 1999, Document ID: PCPL-ART-002, July 1999 <http://www.pmnetwork.com.au/download%20filesNEW/articles/risk%20management%20by%20M%20Pittman.pdf>

Reynolds, Brian; Schaeffer, Brian. "Decisions Under Uncertainty." University of Maryland. ENME 808s Product & System Cost Analysis, End of Semester Class Project, [Online] Available, July 2004 <http://www.glue.umd.edu/~sandborn/courses/808S_projects/reynolds.html>

Winston, Wayne L., "Operations Research Applications and Algorithms." Wadsworth Publishing Company, Belmont CA, 94002, p 729, 3rd Edition

"Decision Theory." page 5, Decision Modeling DecisionModeling@groups.msn.com. June 2004 <http://groups.msn.com/DecisionModeling/decisiontheory5.msnw>

"Risk." Dictionary.LaborTalk.com. June 2004 <http://encyclopedia.laborlawtalk.com/Risk>