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A methodology for assessing acquisition technical risk

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A METHODOLOGY FOR ASSESSING ACQUISITION TECHNICAL RISK

by

William G. Harrison, Jr.

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This thesis examines the problems affecting the quantitative assessment of technical risk in Department of Defense major weapon systems acquisition. A decision Theory approach is used. Commercial techniques and current DoD methods of technical risk assessment are investigated. TASCFORM™ technology values are used in a linear regression model to characterize the growth of technology over time. The model residuals provide a probability distribution for estimating the likelihood of achieving a specified level of technical performance. The benefit of a utility function describing technical risk perceptions is considered. The Expanded Pearson-Tukey method of describing risk is also investigated. Continued research into technology valuation techniques is recommended. A test case application of the Expanded Pearson-Tukey method is also recommended, to determine its ability to provide reliable and timely quantitative technical risk information.

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ABSTRACT

This thesis examines the problems affecting the quantitative assessment of technical risk in Department of Defense major weapon systems acquisition. A Decision Theory approach is used. Commercial techniques and current DoD methods of technical risk assessment are investigated. TASCFORM™ technology values are used in a linear regression model to characterize the growth of technology over time. The model residuals provide a probability distribution for estimating the likelihood of achieving a specified level of technical performance. The benefit of a utility function for describing technical risk perceptions is considered. The Expanded Pearson-Tukey method of describing risk is also investigated. Continued research into technology valuation techniques is recommended. A test case application of the Expanded Pearson-Tukey method is also recommended, to determine its ability to provide reliable and timely quantitative technical risk information.

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I. INTRODUCTION

A. BACKGROUND

Soviet military retrenchment and political collapse have significantly affected U.S. strategic and tactical force structure and requirements. United States national defense goals and requirements presently lack the refinement and broad consensus forty years of Soviet confrontation engendered. The Federal budget deficit is viewed as a severe threat to the health and future of the nation's economy and the Department of Defense (DoD) budget will remain under severe pressure throughout the 1990s. Not only will there be less money to support existing programs and initiatives, but the Department's ability to introduce new systems will be increasingly constrained.

The systems purchased to support the changes in military doctrine that an altered international landscape requires must have greater flexibility, reliability and interoperability. Simultaneously, these systems must be brought on-line without the schedule and cost over-runs that plagued DoD during the years of sustained Soviet threat. Acquisition programs that experience perturbations in terms of schedule, cost, or performance will not only fail to mature but will cause damaging ripple effects to other programs because of the smaller total force structure.

For the last forty years the United States has relied upon an acquisition strategy of fielding technologically superior systems to counter-balance the numerical advantages of a perceived Soviet threat. Technical sophistication has permeated all levels of force structure and doctrine, requiring state-of-the-art performance from individual hardware components. Increasingly complex data acquisition, processing, and exchange networks are required to support the command and control requirements of forces equipped with these systems.

Despite continuous efforts, the United States has been unable to consistently develop, field, and maintain a force structure that possesses an effective technological advantage over Warsaw Pact/Soviet forces [Ref. 1]. This has forced the U.S. defense establishment to continually attempt the development and fielding of ever more advanced capabilities subject to increasingly rigid cost and time constraints. Aggressive performance and schedule goals sometimes have been specified without a consistent or coherent assessment of the risks.

While much criticism has been leveled at DoD because of past cost and schedule over runs and performance failures [Ref. 2:pp. xxiii-xxv], there was often sufficient breadth in new capability development efforts and elasticity in budgets to ameliorate the effects of performance short-falls, cost, and schedule over-runs in any one particular program. The Navy was able to field improvements to Anti-Air Warfare (AAW) capabilities with three systems through the 1970s and 1980s. The AEGIS ship-board radar and missile system, F-14 Tomcat/PHOENIX missile system, and the F/A-18 Hornet, were eventually fielded despite cost, schedule, and performance problems with all three. In the future, programs which experience these problems could have a devastating impact on force structures and capabilities.

The Navy's A-12 Avenger program, employing "stealth" technology, was designed as a replacement for the venerable A-6 Intruder medium attack aircraft. The A-12 enjoyed the highest priority within the service. An A-6 Upgrade program (A-6F) was cancelled so that resources available for the A-12 program would not be constrained. Cancellation of the A-12 program not only resulted in the significant delay of a vitally needed capability, but has seriously weakened the Navy's ability to fund other important aviation programs in a climate of fiscal austerity. Financial resources to meet heavy lift, maritime patrol, AAW, and carrier-based early warning programs are all jeopardized [Refs. 3, 4].

The current acquisition environment is characterized by concurrent development of systems that will operate with a wide variety of forces in numerous environments. Single-service programs tailored to meet unique service objectives will receive far greater scrutiny and will become rarities. The impact of a termination could have severe effects on the capabilities of the entire DoD force structure in this sort of environment. Termination of the A-12 has stopped Air Force efforts to develop a derivative A-12 as a replacement for the F-15 Eagle and F-111 [Ref. 3].

B. OBJECTIVE

The objective of this thesis is to examine existing acquisition program risk assessment theories and methods, evaluate their efficacy as employed in commercial settings, and look for ways that successful commercial approaches could be adapted for use within the unique DoD acquisition decision environment. Specifically, this research attempts to create a useful and flexible definition of technological risk and to identify risk assessment methods that are accessible to DoD program managers and their staffs.

C. RESEARCH QUESTIONS

Commencing with the axiomatic framework constructed by von Neumann and Morgenstern [Ref. 5], a large body of work has addressed risk assessment for individual or corporate decisions. Transference of these theories and techniques to the DoD acquisition setting requires investigation. Assumptions about the nature and availability of alternatives for subsequent "risk premium" and certainty equivalent analysis may not directly apply to the DoD environment. This thesis will examine the following aspects of risk assessment from a Decision Theory perspective:

1. What are the underlying theories and methodology supporting risk assessment in decision analysis?

2. How are these methods applied in commercial settings? What are their strengths and weaknesses?

3. What are the major factors defining the DoD technical risk assessment environment? Are these factors similar to those found in the commercial world?

4. Evaluate whether or not the techniques used by commercial acquisition program managers can be applied directly to the DoD acquisition case. If not, what changes would be required.

5. Suggest possible improvements to existing DoD technical risk acquisition methods.

This thesis will not examine cost and/or schedule issues nor the procedures for determining the performance requirements specified for new systems.

D. SCOPE AND LIMITATIONS

1. Scope

There are two basic approaches used to define risk assessment: normative or prescriptive, and descriptive. The normative approach strives to define ways in which a "rational" person should go about confronting the Universe. The descriptive approach primarily seeks to understand how real people make real decisions.

There exists a resultant tension between these two approaches that must be monitored if usable decision tools are to be fashioned. However, for the purposes of this thesis, the emphasis will be on how a normative approach can be applied to the risk assessment problem of the program manager or acquisition executive.

2. Limitations

Within the normative scheme there are three decision-making approaches, all using some form of "divide and conquer":

1. Cost Benefit Theory (CBT)
2. Social Welfare Theory (SWT)
3. Decision Theory (DT)

All three use a standard partitioning of the decision-making problem, seeking to counter-pose knowledge and values at each step of the process and synthesize these in a logically consistent manner [Ref. 6].

The CBT approach is basically an impersonal one, based upon "scientific objectivity." SWT tends to focus on the organizational dynamics and social processes. Decision Theory frames the problem within the context of the individual as the decision-making entity.

While subjective in its world view, Decision Theory seems suitable for helping individual acquisition decision makers confronted with the problem of technical risk assessment. This is particularly beneficial, since a body of objective, verifiable data is not always available at the early stages of new acquisition projects [Ref. 7].

E. LITERATURE REVIEW

One particular aspect of the DoD acquisition conundrum is the assessment of technical risk. A 1986 GAO Report, commissioned by the U.S. Senate Committee on Governmental Affairs, found numerous inconsistencies and omissions in how acquisition program offices tackled the problem of technical risk assessment. The report examined twenty-five major acquisition programs whose development and production costs exceeded $180 billion:

> DOD has identified many technical risk approaches, both quantitative and qualitative. But there is insufficient policy and training to guide program managers in the selection of suitable approaches. Further, no standard definition of technical risk exists within DOD. Accordingly, many program offices have developed their own informal definitions of technical risk and risk-rating categories, but GAO found them inconsistent and sometimes contradictory. Despite DOD's 1981 initiative, none of the 25 program offices had conducted a quantitative technical risk assessment to support budgeting for risk. [Ref. 8:p. 3]

To date, the problems enumerated by the GAO in 1986 remain largely unaddressed. While a large number of logically consistent decision tools have been developed in academic environments, accessibility and implementation by DoD acquisition authorities and their staffs remain inconsistent or even nonexistent.

Despite the daunting challenges involved in developing such a revolutionary stealth capability, the Navy characterized the A-12 program as possessing "low" risk. The Navy designated the T-45 program, a jet training aircraft to replace both the T-2 Buckeye and TA-4 Skyhawk training aircraft, also as "low" risk [Ref. 9].

The T-45 was originally a land-based British design that had to be altered for compatibility with the carrier environment. The "low-risk" designation was assigned, despite the fact that no land-based aircraft design had been successfully reengineered for carrier duty since 1945. The program suffered serious performance problems, schedule slippages, and cost overruns [Ref. 9].

The problem of aircraft acquisition technical risk assessment is not confined to aerodynamic issues. The Navy's Enhanced Modular Signal Processor (EMSP), designed to handle a wide range of acoustic and electronic processing requirements through the end of the twentieth century, has had by many problems despite its designation as a "low" risk program [Ref. 10]. The Air Force' C-17 program has been beset by performance and cost problems as well as schedule delays arising from the adoption of an ostensibly "low risk" approach to the software design for flight control computers [Ref. 11].

Despite numerous DoD and service-issued directives aimed at assessing, quantifying and controlling risk, e.g., DoD Instruction 5000.2, there are no DoD mandated methodologies for meeting these directives [Refs. 12, 13, 14]. The Defense Systems Management College (DSMC) has issued a publication that covers most of the standard methods for risk identification and assessment [Ref. 15]. However, there has been no adoption of either the DSMC's scale for low, medium, or high probability of occurrence, nor any policy guidance concerning what should constitute low, medium, or high risk for acquisition activities.

F. ORGANIZATION AND CHAPTER SUMMARY

This chapter gave on overview of the importance and problems associated with the assessment of technical risk in DoD acquisition programs. The objective of the thesis was presented, along with limitations to problem definition and subsequent research. The aim of the work will be to examine how the tenets of Decision Theory can be applied to the problem of DoD acquisition program technical risk assessment in a manner that is accessible to DoD acquisition decision-makers.

Chapter II will present specific background information and issues necessary for understanding the theoretical basis of Decision Theory and its limitations. Uncertainty and risk perception interactions will also be discussed.

Chapter III will look at how technical risk assessment issues are addressed in commercial operations. Chapter IV will define the DoD technical risk assessment and decision environment, a necessity for framing any recommendations for potential risk assessment approaches. Chapter V will attempt to provide some recommended methods for technical risk assessment. Chapter VI will contain concluding remarks, a summary of major findings and recommendations for future research.

II. BACKGROUND AND THEORETICAL FRAMEWORK

A. THE DECISION PROBLEM

Decision making is a unique human activity. Only humans seem to possess the faculty of recognizing the possibility or availability of more than one alternative or course of action in a set of circumstances over some period of time. Decision making arises from the application of some value system imposed upon a particular environment. It assumes that a selected objective or goal can be obtained through the purposeful expenditure of resources in hand, ". . . in the light of norms or general principles, or of future outcomes." [Ref. 16:p. 131]

As Bunn points out, the activity of decision making is available to individuals, organizations and society. Decision making is a characteristic of "purposeful" systems: the nature and gravity of decision making activities are tied to the attainment of objects or goals that in some fashion support or further the "good" of the entity formulating the decision [Ref. 17]. Simon's definition of the three phases of decision making applies to the DoD acquisition environment: Finding occasions for making decisions; finding possible courses of action; and choosing among courses of action." [Ref. 18].

The purpose of decision analysis is to provide a logically consistent and flexible framework for helping the decision maker generate and evaluate the various alternatives that may present themselves. The flaws inherent in innate and intuitive decision making processes have been the subject of extensive research. Numerous researchers have commented upon and measured the relatively limited human data processing capabilities [Ref. 19]. Decision types fall into three categories. There are automatic or intuitive decisions that take place in such a manner that the individual is often unaware of the process. Decision making in an athletic competition is an example of this sort of decision making. Pondering the proper course of action during an athletic event almost invariably seems to impair performance.

Some decisions may be very complex but exhibit characteristics that make their resolution tractable to strict rules or instructions. On a mechanical level, the operation of a thermostat or a fuel control unit falls into this category. The operator may not know instinctively what action to take. However, a satisfactory result can be obtained from the careful and sequential following of a set of instructions, achieving a desired temperature or power setting without weighing options or detailed process knowledge.

Lastly, there are those decisions that require careful and measured consideration. These are often characterized by a bewildering array of possible alternatives. Obtaining the knowledge necessary to determine the suitability and cost of achieving a particular course of action may be extraordinarily difficult. Howard states, "decision making is what you do when you do not know what to do." [Ref. 20].

1. Elements of the Decision Problem

Following Bunn [Ref. 17], four major factors characterize the problem and affect the subsequent formulation of any solution: Uncertainty, Multiple Objectives, Multiple Options, and Sequentiality.

a. Uncertainty

Uncertainty is the key obstacle to the resolution of most important decisions and affects the other three factors. Many times the decision maker can envision multiple possible outcomes and can place some sort of odds of occurrence on particular events. Some of the outcomes will be counter to the goals pursued and might be ruinous to the individual or organization making the decision. Decision makers simply cannot know, a priori, how events will proceed once a particular course of action is set into motion.

b. Multiple Objectives

Organizational or individual goals may be complex when carefully considered. The objective may have multiple attributes. A computer system could be characterized by the length of words it can handle, processing time, or memory size. The goal may be subject to some resource constraint or other conflicting requirement. The problems associated with nuclear power plant design and siting [Ref. 21] are classic examples of this dilemma. How should the decision maker evaluate independent and possibly conflicting goals and attributes?

c. Multiple Options

The alternatives that are generated as candidates for meeting a goal may not completely satisfy all requirements. Some combination of alternatives may be required to reach the objective. How should the decision maker eliminate inadequate options without unnecessarily reducing the resolution of any screening device? How can he ensure that he has not overlooked an efficient possibility?

d. Sequentiality

Problems often present themselves over a period of time: the entire issue is not resolvable at any particular instant but requires continual iteration as new data become available. The decision maker may be confronted with numerous paths whose existence and efficiency are contingent upon previous actions. Sequentiality may be deliberately imposed upon the problem by the organization. In his analysis of the Cuban Missile Crisis, Allison [Ref. 22] discusses senior decision makers' penchants for delaying the implementation of decisions that may be irreversible or delaying action because of fear that the set of possible options may be reduced.

2. Decision Analysis Requirements

The purpose of decision analysis is to directly address issues in a manner that helps the decision maker more completely define his problem and evaluate his possible courses of action. The analyst must remember that someone else will make the decision and will carry the onus of the results if events turn out poorly. But what are the requirements for a good decision analysis? First, the analysis must capture the essential elements of the problem in a fashion that the decision maker can grasp. This presupposes an interative format, relying upon the intuition and judgement of those charged with arriving at a decision. The investigation must be couched in such a manner that it leads to a complete understanding of the issue at hand, or at least as complete as is possible, given the ever-present constraints of time and money [Ref. 23].

Second, the rule of coherence must be followed. If the decision maker seeks to behave in a rational manner, his actions must be logically consistent and free from hidden contradictions. Rationality as a necessary condition in this sense implies that the individual or other decision making entity must seek to maintain or improve his wealth. Failure to act in a coherent fashion leads to the "perpetual money-making machine" paradox.

Suppose an individual considered event A as less likely than event B and event B as less likely than event C. Suppose further that rather than concluding that A is less likely than C, this individual decides that C is less likely than A. Assume that event A provides an outcome that is valuable to this individual, a prize of some sort, while B and C do not. In this case, the person would be willing to pay some amount of money to replace A with B. If the prize is now contingent on B, the individual could be induced to pay some fee to replace B with C. A third sum of money could be obtained by offering to replace C with A, an event he considers less likely. The individual is now at the starting point with the exception that he is demonstrably poorer. As long as the individual holds to his order of ranking, money can be made ad infinitum, or at least until he is drained of cash. Such behavior is defined as incoherent [Ref. 17].

B. DECISION CRITERIA

Decision criteria can be separated into two main categories, nonstochastic and stochastic. The nonstochastic approach ignores the existence of probability and seeks to use a restrictive concept of dominance to generate the best solution. Stochastic techniques explicitly apply notions of probability to the process of determining a best solution. There are problems associated with the application of both these approaches.

1. Nonstochastic Methods

Nonstochastic methods seek to discover the best alternative for satisfying the decision maker's goals through the discovery of a course of action that will be superior to all others, no matter the outcome of events. Dominance approaches can be defined as strict dominance, maximin, maximax, and regret strategies.

a. Outcome Dominance

Consider a matrix that lists possible results for three different alternatives in the event of three different outcomes and assume that the decision maker prefers more to less:

ALTERNATIVES

$$\begin{array}{lc|ccc} & & A_1 & A_2 & A_3 \\ \hline & E_1 & 2 & 1 & 3 \\ \text{POSSIBLE OUTCOMES} & E_2 & 6 & 5 & 4 \\ & E_3 & 9 & 7 & 8 \end{array} \qquad (1)$$

An inspection shows that for any possible event, E_1, E_2, or E_3, alternative A_1 dominates A_2. As summarized by Bunn, any alternative A_q dominates A_p, if for every E_i y_{iq} is greater than or equal to y_{ip} and y_{iq} is greater than y_{ip} for at least one E_i [Ref. 17:p. 17]. No assumptions about the relative likelihood of event occurrence have been made. While this technique is simple to use, it is only applicable to a very small set of fortunate circumstances. Additionally, the best this technique can be expected to provide is some reduction in the number of possibly satisfactory alternatives. As can be seen from (1) above, while alternative A_2 can be removed from consideration, deciding between A_1 and A_3 remains a problem.

b. Maximin

The maximin approach takes a pessimistic or conservative approach to the problem to the sorting of best alternatives. Consider (1) again. The maximin approach is to search each column and identify the smallest outcome value a particular event could generate. For this example, the column minimums have been identified by an asterisk.

$$\begin{array}{ll|lll} & & \multicolumn{3}{c}{\text{ALTERNATIVES}} \\ & & A_1 & A_2 & A_3 \\ \hline & E_1 & 2^* & 1^* & 3^* \\ \text{POSSIBLE OUTCOMES} & E_2 & 6 & 5 & 4 \\ & E_3 & 9 & 7 & 8 \end{array} \tag{2}$$

The maximin solution problem is to choose the alternative that provides the largest of the possible minimum, in this case A_3. Maximin attempts to make the best of a bad situation.

The efficacy of this approach diminishes rapidly in cases where there are very large differences in possible payoffs. Bunn [Ref. 17:p. 18] provides the following counter-example:

$$\begin{array}{ll|ll} & & \multicolumn{2}{c}{\text{ALTERNATIVES}} \\ & & A_1 & A_2 \\ \hline \text{POSSIBLE OUTCOMES} & E_1 & 31 & 32 \\ & E_2 & 10{,}000 & 33 \end{array} \tag{3}$$

Here the maximin strategy would recommend A_2 based upon a strict observance of the decision rule. The decision maker following this recommendation, assuming again that the object is maximize monetary returns, would end up "penny-wise and pound-foolish."

c. Maximax

This strategy is the obverse of maximin, viewing the occurrence of random events in the most optimistic manner. The decision maker is required to identify the maximum payoff for each possible course of action and then select the alternative that provides the greatest return. This is clearly untenable in the event that an alternative could cause a very large loss. Consider the following payoff matrix:

$$\begin{array}{ll|cc} & & \multicolumn{2}{c}{\text{ALTERNATIVES}} \\ & & A_1 & A_2 \\ \hline \text{POSSIBLE OUTCOMES} & E_1 & 31 & 32 \\ & E_2 & -10{,}000 & 33 \end{array} \tag{4}$$

Maximax would recommend alternative A_2, oblivious to the potential for substantial monetary loss.

d. Regret

The regret strategy uses an approach similar to maximin. The selection criterion focuses upon how the decision might be viewed from the vantage of hindsight. Consider the following two alternative, two outcome payoff matrix:

$$\begin{array}{cc|cc} & & \multicolumn{2}{c}{\text{ALTERNATIVES}} \\ & & A_1 & A_2 \\ \hline \text{POSSIBLE} & E_1 & 5 & 7 \\ \text{OUTCOMES} & & & \\ & E_2 & 9 & 8 \end{array} \tag{5}$$

A minimax regret analysis would consider what the best alternative would be for each possible outcome. Clearly if E_1 occurs, the best strategy is select A_2. Likewise, A_1 is best, if E_2 takes place. The analysis continues by transforming the payoff matrix into a matrix of opportunity losses:

$$\begin{array}{cc|cc} & & \multicolumn{2}{c}{\text{ALTERNATIVES}} \\ & & A_1 & A_2 \\ \hline \text{POSSIBLE} & E_1 & 2 & 0 \\ \text{OUTCOMES} & & & \\ & E_2 & 0 & 1 \end{array} \tag{6}$$

From this step, the alternative that provides the minimum non-zero opportunity loss is selected.

This approach has certain emotional appeal, particularly in situations where hindsight evaluations can severely affect the decision maker. It may be the most regularly applied, at least subconsciously, of all decision analysis tools. A serious flaw affects this strategy. It can be shown that a decision maker employing the minimax regret approach could be turned into a perpetual money-making machine [Ref. 24], violating the coherence principle. Additionally, the technique is subject to the problem of rank reversal, which negates its effectiveness in tackling problems that unfold in a sequential fashion.

2. Stochastic Methods

The coherence principle implies that the decision maker will use all of the information at his disposal. If some opinion of the relative likelihood of various events is available, it should be explicitly brought into the analysis. Information about likelihood could arise from a body of quantified statistical data, e.g., survey sample or previous experience, from which a probability distribution could be constructed or might reside in the field of judgement and professional intuition. When dealing with the allocation of scarce resources to obtain some best possible return, it would be foolish not to incorporate as much relevant information into the decision making process as possible. Three common methods, Modal, Expected Value, and Expected Regret attack the decision problem in a probabilistic manner. All are measures of central tendency, and as such, tend to ignore or reduce the impact of outliers on the recommended decision.

a. Modal Analysis

As the name implies, modal analysis seeks to identify the most likely occurrence, based upon some set of probabilities the decision maker has provided. Consider the following example of alternatives and potential outcomes subject to the assigned probabilities.

ALTERNATIVES

	E	$P(E_i)$	A_1	A_2	A_3
POSSIBLE OUTCOMES	E_1	0.2	10	8	15
	E_2	0.5	6	9	3
	E_3	0.3	18	5	1

(7)

Note that the probabilities sum to one. It can be easily seen, that under the modal scheme, E_2 is most likely, hence A_2 should be the chosen course of action. Problems with this method arise when the resolution between probability values decreases and the potential payoff matrix possesses large differences between some values and little difference between others.

Consider the counter-example:

			ALTERNATIVES		
	E	$P(E_i)$	A_1	A_2	A_3
POSSIBLE OUTCOMES	E_1	0.21	1	98	90
	E_2	0.23	0	85	83
	E_3	0.56	18	15	15

(8)

The modal approach would yield E_3 as the preferred alternative, without investigating the possible effects of the large difference in payoff values. An argument has been made that modal analysis is subject to the same perpetual money-making criticism that afflicted the minimax regret method [Ref. 24]. Modal analysis can also be affected by the way data are aggregated. Consider the following example taken from Devore [Ref. 25:p. 11]. The length of service, in years, for 94 Supreme Court Justices who had terminated their services were tallied. If the length of service is aggregated by five year increments the following matrix is obtained:

LENGTH OF SERVICE	NUMBER OBSERVED
0 - 5	11
6 - 15	37
16 - 25	28
26 - 35	17
> 36	1

(9)

With this aggregation, the mode is 6 - 15 years of service. However if the data are processed in ten year increments the mode changes.

LENGTH OF SERVICE	NUMBER OBSERVED
0 - 2	5
3 - 7	23
8 - 12	14
13 - 17	17
18 - 22	14
23 - 27	7
28 - 32	8
> 33	6

(10)

The mode in (10) is now 3 - 7 years of service. This illustrates that the abilities of the data to explain a process are sensitive to the metrics imposed by the decision maker.

b. Expected Value

Expected value calculates the average or mean payoff value and then chooses the alternative that provides the highest mean return. Each possible alternative payoff is multiplied by its associated probability and the results are summed for each alternative. Matrix (11) provides an example of how probability is incorporated into the payoff matrix to determine the best alternative.

ALTERNATIVES

	E	$P(E_i)$	A_1	A_2	A_3
POSSIBLE OUTCOMES	E_1	0.2	10	8	15
	E_2	0.5	6	9	3
	E_3	0.3	18	5	1
		$EV(A_i)$	10.4	7.6	4.8

(11)

The expected value decision for (11) chooses option A_1 as the alternative that provides the largest return.

Since all the events are the result of random outcomes, expected value analysis requires the decision maker to be able to withstand short term losses or instances of less than ideal returns. The expected value approach may not be appropriate for one-of-a-kind decisions or for instances where exceptionally large or ruinous losses are associated with small, but potentially significant probabilities.

c. **Expected Regret**

The expected regret method applies the probabilities associated with each outcome to a regret or opportunity loss matrix similar to (6) above. Using (11) and applying the regret technique, the following payoff matrix is obtained:

ALTERNATIVES

	E	$P(E_i)$	A_1	A_2	A_3
POSSIBLE OUTCOMES	E_1	0.2	5	7	0
	E_2	0.5	3	0	6
	E_3	0.3	0	13	17
		$ER(A_i)$	2.5	5.3	8.1

(12)

Again, A_1 is the best alternative as it causes the least amount of opportunity loss. Maximizing $EV(A_i)$ will always lead to the minimization of $ER(A_i)$. As noted with expected value calculations, the decision maker will be subject to the variance associated with each of the probabilities and must be able to withstand short-term instances of contrary results.

3. Summary

The basic classical statistical methods for determining rational decisions were presented. Strengths and weaknesses of were noted. A limitation affecting all of the methods was the failure to account for individual preferences in regard to the magnitude of potential gains and losses. Methods that seeks to overcome this obstacle, while producing rational and consistent results for individual decision makers, will be presented in the following sections.

C. UNCERTAINTY AND RISK

Uncertainty stems from the problem of dealing with random events where the likelihood of an event's occurrence is subject to some measure of variability. Humans have exceptional difficulty dealing consistently with random events. Coin tosses or other binomial events where an objective and precise probability of occurrence can be specified are conceptually easier to handle than events for which no objective body of data exists from which to generate a probability distribution. Kahneman and Tversky [Ref. 26] have demonstrated that even individuals with statistical training will often be subject to three particular biases: representativeness, anchoring, and availability. These biases are, "... highly economical and usually effective, but they lead to systematic and predictable errors." [Ref. 26:p. 20] Since people have difficulty dealing with random events, the concept of risk is equally befuddling.

The risk of an event is the probability of occurrence multiplied by cost. Risk is associated with notion of the value that may be lost or unrealized as a result of a random event. An additional issue is the size of the variance affecting the probabilities applied to the problem. Because values are relative, how should a decision maker obtain a defensible solution to the problem of hazarding current resources against the attainment of value at some future time when the outcome is subject to randomness? Extensive research has shown that individual concepts of risk change dramatically as the potential payoff or loss becomes very large even if the associated probabilities become relatively small. The Allais Paradox, presented below, is an example of this behavior.

Suppose a person is offered the following wager:

A: $1 Million guaranteed

versus

B: $5 Million with a 10 out of a 100 chance
$1 Million with a 89 out of 100 chance (13)
No money with a 1 out of a 100 chance

Allais, Raiffa, and Tversky have shown that the modal response is wager B [Refs. 17, 26, 27]. When the situation is altered so that there are large difference between payoff values and small differences between probabilities people do not follow the expected value model. Compare the following wager to (13):

C: $5 Million with a 10 out of 100 chance
No money with a 90 out of 100 chance

versus (14)

D: $1 Million with a 11 out of 100 chance
No money with a 89 out of 100 chance

The expected value model selects C over D because of the larger expected value:

$$EV(C) = \$500K > EV(D) = \$110K$$

The modal response however is D. People begin to focus on the small difference probability when the differences between payoffs begin to get very large [Ref. 28]. Objective statements that are applicable to a broad range of situations are exceptionally difficult to make. The following sections will discuss some of the problems associated with the measurement criteria that have been suggested for decision analysis.

1. Historical Antecedents

Risk assessment is a very old practice. Records of assessment, valuation, and accounting procedures, dating to 3200 B.C. have been found in the Tigris-Euphrates valley [Ref. 29]. The "risk accounting" procedure that was used presages a modern proposal introduced to handle the risk and uncertainty issues surrounding nuclear energy [Ref. 30]. The determination of risk and subsequent recommendation of appropriate courses of action were placed in the hands of a priestly caste who used a form of double-entry bookkeeping to arrive at a quantified decision, carrying the weight of assurance and confidence. Modern antecedents, employing concepts of mathematical probability and scientific analysis of cause and effect, effectively began with Laplace's 1792 study of smallpox deaths.

Despite Laplace's ground-breaking effort, the abilities of organizations to gather relevant data and subsequently manipulate it in mathematically sound and useful fashion remained haphazard. Although the concept of insurance to spread the risk of commercial enterprises, as well as compensate for the vagaries of human mortality are ancient, consistent success in risk assessment and survival of risk managing entities required the establishment of professional actuaries. Covello and Mumpower cite findings of the British Government in 1867 that over 75 percent of life insurance endeavors failed in the preceding 75 years [Ref. 29]. More technically sophisticated methods for analyzing the risk in commercial undertakings other than life insurance or oceanic shipping required both more rigorous codification of economic theory and more flexible mathematical tools.

2. Modern Perspectives

All of the decision criteria examined so far either ignore the existence of random behavior, or treat the probabilistic likelihoods with certainty, failing to consider the variable inherent in random events. As discussed above, expected value or expected regret calculations fail to capture the potential impact of the loss of value to the decision maker. The following example highlights this problem.

Consider to wagers with identical probabilities of occurrence:

Wager A: Receive \$10 with probability of 0.5
Lose \$10 with probability of 0.5

(15)

Wager B: Receive \$10,000 with probability of 0.5
Lose \$10,000 with probability of 0.5

Evaluated from an expected value perspective, both wagers are identical:

$$EV(A) = EV(B) = 0.$$

However, if an individual participates in wager B, the magnitude of the loss may be radically different from that of wager A, depending on what proportion of net worth a \$10,000 loss represents. It is conceivable that an individual could be induced to pay sum amount of money or part with some quantity of value to "buy out" of wager B and into wager A. How much money an individual would be willing to give up and under what conditions forms the basic approach to current risk analysis techniques. A significant obstacle to this search is the variability of risk perception between decision makers, as well as, the variability of risk perception by individuals in different decision environments. Generically, endeavors subject to greater risk are understood to possess either greater likelihood of potentially ruinous losses or instances where the probability of occurrence may be quite small but the associated event would be devastating. Crossing a busy highway blindfolded would be an example of the former, while an accident at a nuclear power facility or an aircraft landing on a house would be examples of the latter [Ref. 31]. Risk analysis attempts to provide an additional decision criterion that focuses on the potential variability of an event, as a complement to expected value analysis, which ignores the variance issue. There are four major approaches for tackling the risk problem:

a. **Variance**

This is the usual statistical definition of estimated variance:

$$s_i^2 = \int_{-\infty}^{\infty} \left[y - y_{avg} \right]^2 \cdot f_i\,(y)\,dy$$

This captures the notion that the greater the variance, the greater the potential risk. It does not address the problem of potential skewness of the distribution governing y as Figure 2-1 demonstrates.

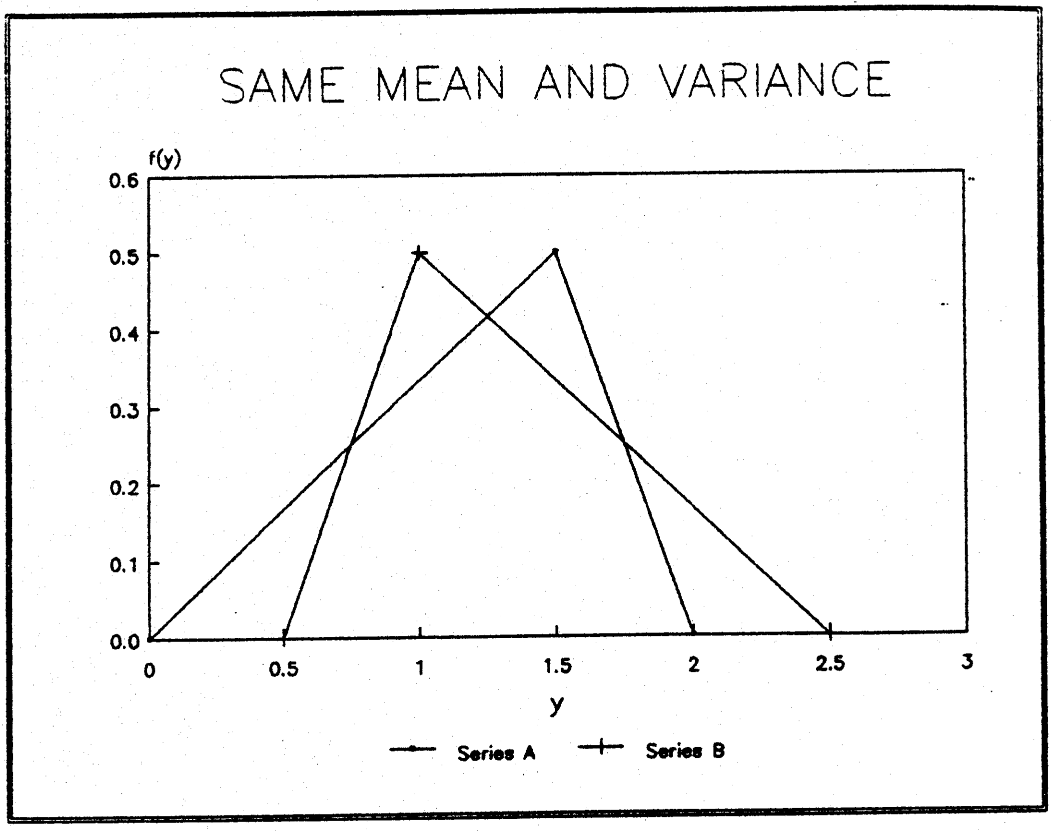

Figure 2-1 Distributions with Same Means and Variances

If the full probability density function is considered, series A would be preferred and series B considered more risky.

b. Semivariance

Semivariance attempts to concentrate on the perceived risky portion of the payoff distribution, using a pre-determined critical value:

$$s_i^2 = \int_{-\infty}^{c} (y - c)^2 \cdot f_i(y)\, dy$$

As with the variance method, distributions with equal mean and semivariance, but different risk potential, can be constructed as shown in Figure 2-2. As with the example of variance as a measure of risk, when the full probability density functions of series A and B are considered, series B would be the riskier of the two.

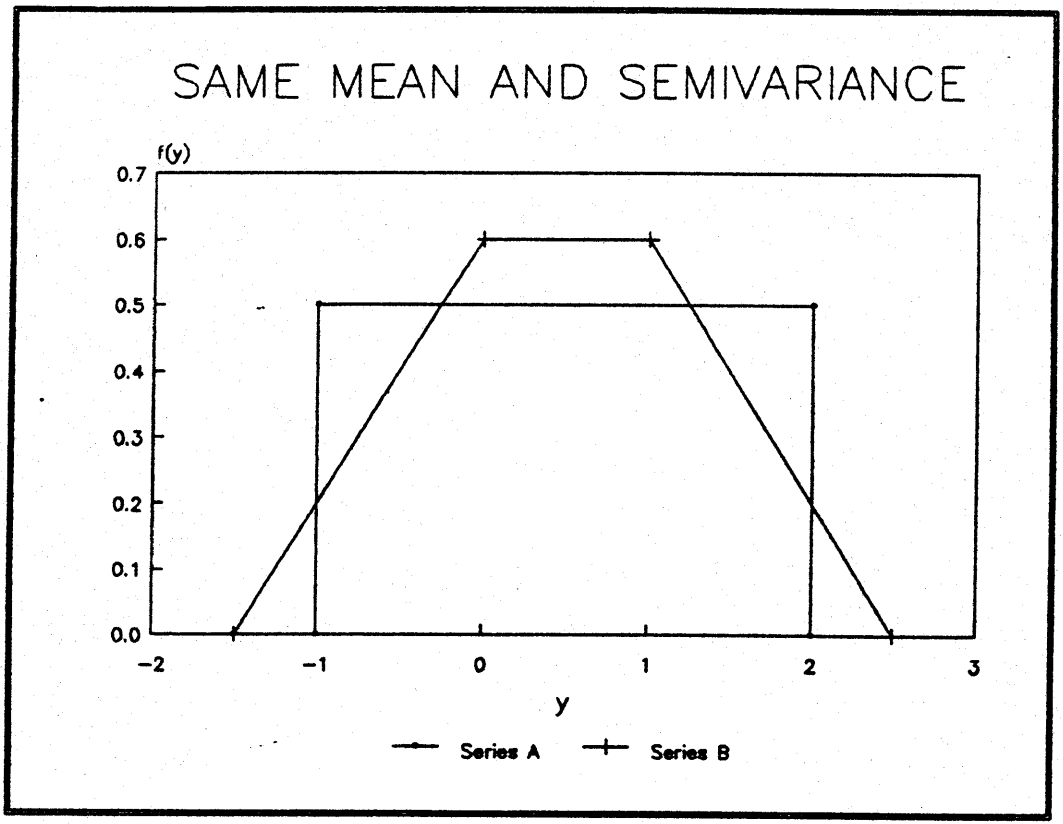

Figure 2-2 Distributions with Same Means and Semivariance

c. Critical Probability

The critical probability approach uses the same format as semivariance but substitutes a probability value for a measure of variability.

$$P(y \leq c) = \int_{-\infty}^{c} f_i(y)\, dy$$

Bunn cites a definition generated by Fishburn that links the two approaches.

$$R\left[a_j\right] = \int_{-\infty}^{c} (c - y)^b f_j(y)\, dy$$

When b = 2, the semivariance method is used and when b = 0 critical probability is operable [Ref. 17:p. 35]. The idea of a critical probability has certain intuitive appeal. The critical probability can be viewed as a goal, with reaching or surpassing the critical value defined as success and falling below the critical value defined as failure. This highlights the personal and transitory nature of risk evaluation [Ref. 26]. As with variance and semivariance, counter-examples are easy to create, as shown in Figure 2-3, where both distributions have equal area below zero but series B could be considered more risky.

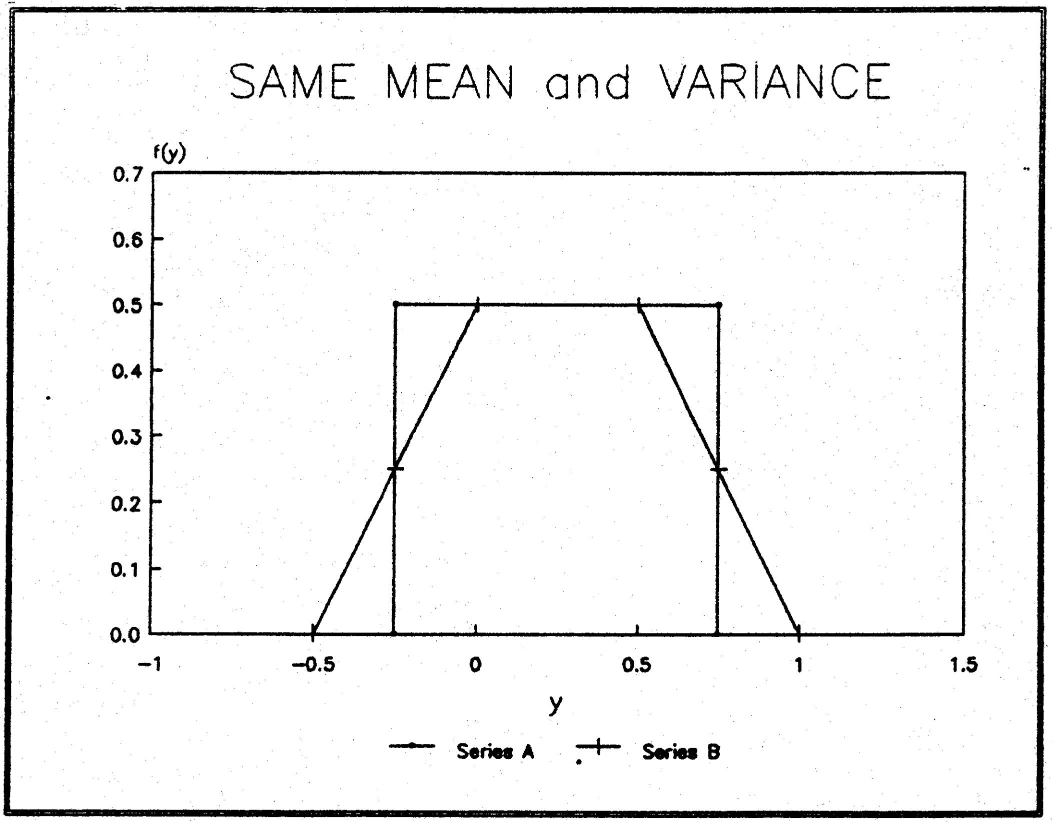

Figure 2-3 Distributions with Same Means and Equal Area Below Zero

d. Mean-Variance Dominance

This approach has its roots in financial analysis. The premise is the same as discussed for the nonstochastic dominance case. The outcomes of various alternatives are characterized by their respective means and variances. The decision rule is to choose those options that possess the greatest mean and smallest variance. While this may lead to an "efficient" set, where dominance cannot further winnow the choices, it may not identify a clear winner. Additionally, it requires a more precise knowledge of the process governing the outcomes than may be available in some decision environments. Utility Theory offers a potentially coherent avenue around some of these limitations.

D. UTILITY THEORY

In 1944, John von Neumann and Oskar Morgenstern published their influential work, "Theory of Games and Economic Behavior" [Ref. 5]. Arising from a concept originally put forward by one of the authors in 1928, the principles developed in their work and embellished by subsequent researchers form the basis for most current techniques of risk assessment. Morgenstern and von Neumann sought to develop a complete set of rules that would define "rational behavior" and could consequently be used to guide actions in any circumstance. They defined rationality as optimal behavior in an economic sense; individuals would consistently seek to improve their conditions. Optimal behavior could be achieved through the use of "... the notion of mathematical expectation" [Ref. 5:p. 32].

1. Axiomatic Structure

von Neumann and Morgenstern define seven key elements in this theory which provide a firm, logical basis of coherence. The theory is normative vice descriptive, providing a framework that guarantees a rational result. In its original form it does not necessarily describe how real-world decision makers actually arrive at a solution.

a. Structure

First, the decision maker can create an order out of the decision situation. He can describe his alternatives and can create a listing of the payoffs that would proceed from the perfect execution of these options. Sophisticated models may be required to capture the essential elements of the decision environment, but such a construction is assumed to be possible.

b. Ordering

Second, a preference order can be determined for the list of possible objectives or outcomes of a specified process. Given a choice of three items, A, B, or C, with the opportunity to select only one at a time, the decision maker can order these choices in a manner that reflects his desires.

$$A > B > C$$

This implies choice A is preferred to choice B and choice B is preferred to choice C.

c. Transitivity

The third point is transitivity. If the decision maker were provided with the choices as pairs, say A and B, or B and C, subject to the ordering $A > B$ and $B > C$, then it follows that $A > C$.

d. Indifference

Fourth is indifference. The composition of the choices may be such that for some particular grouping, the decision maker cannot categorically state a preference between choices. This indifference or substitutability holds whether the various pairs of choices are considered alone or whether they are grouped into a more complicated option.

e. Reduction of Compound Prospects

Fifth, "Any compound prospect should be indifferent to the equivalent simple prospect with probabilities computed according to the usual rules of probability." [Ref. 17:p. 54] This provides a coherent structure to the proposed solutions. Central to this notion is the requirement that the decision maker has no preference for the time-based portion of an uncertain prospect. This rules out the consideration of preferences arising from the joy of playing the game, the particular atmosphere associated with a particular decision environment, or the manner in which risks are presented.

f. Continuity

Sixth, utility values are continuous. This involves the notion that for extremely noxious outcomes, a non-zero probability exists that would lead the decision maker to accept some other alternative which may be trivial in some other circumstance. In the normal course of events, an individual may be prefer a small sum of money to a zero payoff, say $5. Then a non-zero probability exists, such that, a prospect between $5 or death would be attractive. While such an extreme seldom occurs, it is the sort of problem that explicitly confronts public policy bodies when ruling on issues that affect the welfare of society. This axiom explicitly supports the construction of a utility curve and allows for the more precise resolution of utilities in regions of rapidly changing risk perception.

g. Monotonicity

Finally, preferences must be monotonic. This implies that option A is preferred or indifferent to option B, if and only if, the probability of A, p_A, is greater than or equal to the probability of B, p_B. Monotonicity provides a necessary and sufficient condition for the preferred/indifferent ordering of various alternatives. Thus, the utilities of different alternatives can be compared through the use of expected utility. The expected utility is calculated in the same manner as expected value leading to:

$$EU(A) \geq EU(B)$$

2. Limitations

As with any theory, there are specific limitations that must be observed when applying the theory to a particular decision problem.

a. Utilities Are Not Additive

In the event that the final payoff for some prospect is the result of some sequence of alternatives, the utility of the final payoff is not equal to the sum of the individual payoff's utilities:

$$U(A + B) \neq U(A) + U(B)$$

This is the result of the curvature of the utility function. Specifically, it recognizes the possible change in risk perception governing alternative considerations, as the values of the payoffs change. The individual utilities are additive, only in the case of a risk-neutral decision maker who effectively adopts an expected value criterion.

b. Strength of Preferences Not Captured

The von Neumann/Morgenstern version of utility theory creates an ordinal scale as opposed to an interval scale. The numerical ranking is imposed only for the purpose of sorting preferences. Consider the example of team rankings in college football. A team could be rated fifth one year and fourth the following year. This does not imply that the same level of progress was made, as a team that was ranked second one year and then ranked number one the next year [Ref. 32].

c. Not Comparable Between Decision Makers

The evaluation of risk as an integral part of utility theory is very personal. Rapaport and Wallenstein have shown that, ". . . the concept of risk is highly idiosyncratic," and is a function of the risk-taking situation or environment, personality characteristics of the individual(s) involved, and their training and experience [Ref. 33]. This notion can be extended to social and corporate organizations, as well. A dramatic example of this feature of utility theory is MacArthur's decision to proceed with an amphibious invasion at Inchon, despite persistent and strident staff recommendations to the contrary [Ref. 34].

Determination of the relevant probabilities is a key to this aspect of risk assessment. As noted above, decision makers can be liable to the distortions caused by availability, representativeness, and imprecise notions of causality [Ref. 26]. Additionally, decision makers often discount assessed probabilities once a course of action is decided upon, believing that they possess the ability to control events [Ref. 35].

3. Certainty Equivalents

While the axioms of Utility Theory provide a template for determining whether or not an uncertain action is coherent, some scheme is required to help the decision maker order his preferences when faced with uncertain prospects. The use of Certainty Equivalents was developed for this purpose. If the payoff from a probabilistic outcome can be compared in some fashion with a guaranteed result, a quantifiable measurement of the individual's risk perception will emerge.

Consider again the wager proposed in the discussion of modern approaches to risk assessment:

Wager A: Receive \$10 with probability of 0.5
Lose \$10 with probability of 0.5

(15)

Wager B: Receive \$10,000 with probability of 0.5
Lose \$10,000 with probability of 0.5.

Depending upon the characteristics of the decision maker, he may not be indifferent to these two wagers which would be classified as equal under the expected value criterion. The question then becomes, under what combination of probabilities and payoffs would he subsequently be indifferent to A and B? von Neumann and Morgenstern formalized the notion of certainty equivalents as a means of addressing this issue [Ref. 5]. The method is intuitively easier to grasp if the nature of the wagers is altered somewhat.

a. Certainty Equivalent Assessment

Consider the following wager:

Wager A: \$1000 with probability = 0.5 (16)
\$0 with probability = 0.5

As the wager is presently constituted, the decision maker might agree to participate as there is no potential loss and it costs nothing to participate. Now suppose the wager is amended as follows:

Wager A: \$1000 with probability = 0.5
\$0 with probability = 0.5
(17)
Wager B: \$300 with probability = 0.5
\$300 with probability = 0.5

In this instance, the decision maker is required to choose between the wagers, one affected by uncertainty, and another one a guaranteed prospect. As presented, the decision maker would choose alternative (A). Based upon an expected value calculation and dominance reasoning:

$$EV(A) = \$500 \qquad EV(B) = \$300$$

and

$$EV(A) > EV(B)$$

By similar dominance reasoning, if the decision maker were offered $600 not to participate in the wager, the individual would take the $600. Therefore, there is some value between zero and $600 which if offered to the decision maker as certainty, would result in the decision maker being indifferent to the choice of either A or B. Through an iterative process it should be possible to determine the decision maker's certainty equivalent for the wagers presented in (17). For argument's sake, say this value is $400, i.e., if offered $400 to forego the wager between the uncertain prospect and the guaranteed payoff, the decision maker would accept the $400. This idea can be encoded into a payoff matrix as follows:

			ALTERNATIVES	
	E	$P(E_i)$	A_1	A_2
POSSIBLE OUTCOMES	E_1	0.5	1000	400
	E_2	0.5	0	400

(18)

At a monetary certainty level of $400, the decision maker would be indifferent between A_1 and A_2. Additionally, the sensitivity of this Certainty Equivalent (CE) to small perturbations could be uncovered. If the CE is changed to say, $410, then the decision might be to choose A_2. Likewise, if the CE is reduced to $390, then A_1 would be chosen. A formal presentation of this hypothesis developed by Bunn is:

Preference is indifferent between :

X with probability p

or

Y with probability 1 - p

and Z for certain [Refs. 17:p. 41, 5:p. 24].

The advantage of this principle is that, in theory, it provides a means of uncovering coherent choices in the presence of uncertainty. An additional benefit is that values, other than money, can be used to achieve coherent decision solutions. Payoff matrices more complex than the simple binary example presented in (18) can be evaluated with this approach and finer resolution of the curvature of the utility function can be obtained by successively examining segments of an initially binary problem.

b. Single Attribute Utility Functions

The standard approach is to scale the utility values between zero and one, with the best case being assigned a utility of one. The resultant CE can then be used to further partition the utility scale for as many points as desired, as demonstrated by the following utility function constructed from wager (17) above. Matrix (19) contains the payoff-utility values and Figure 2-4 displays the results graphically.

PAYOFF - UTILITY MATRIX

x	U(x)
1000	1.00
700	0.75
500	0.50
375	0.25
300	0.00

(19)

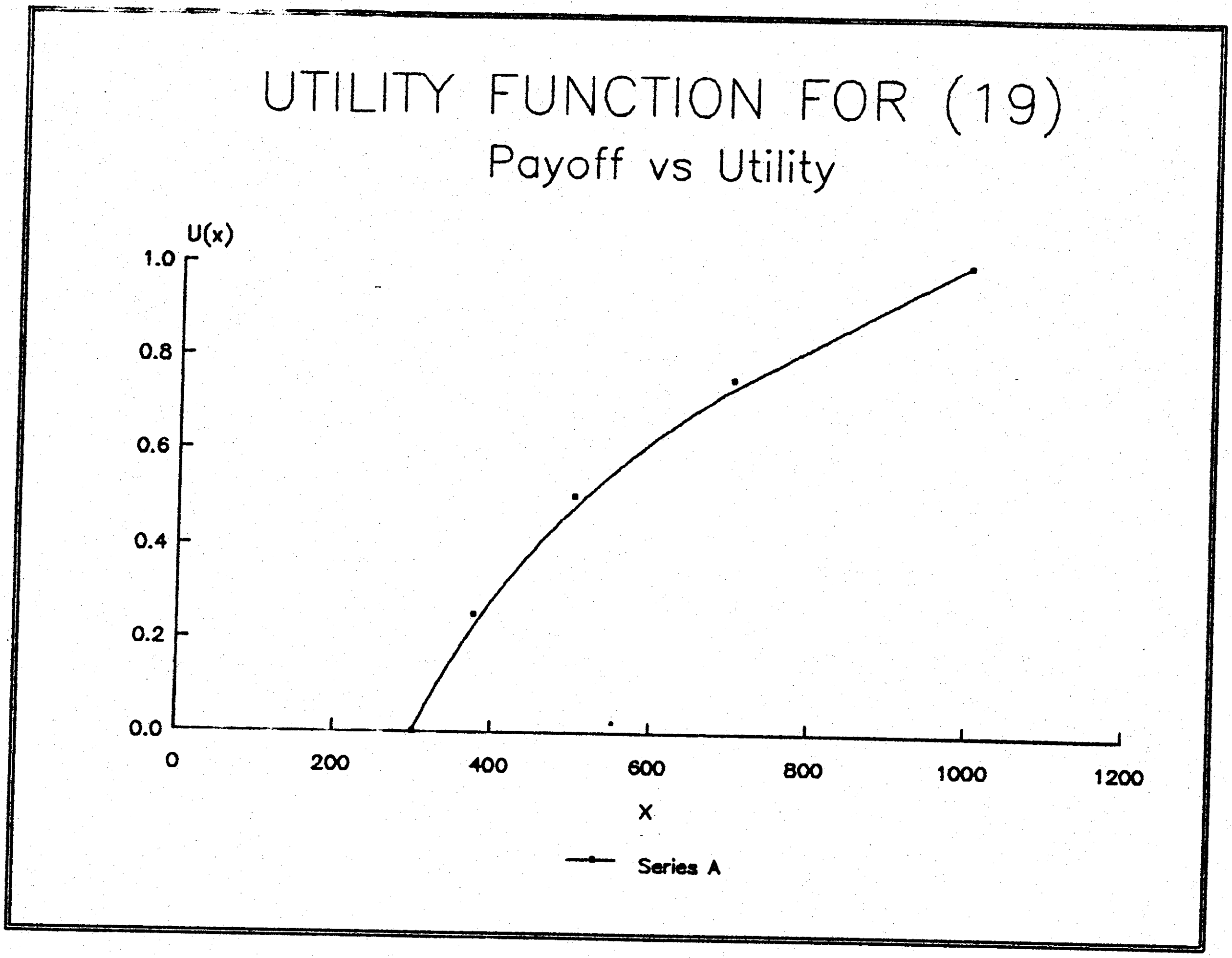

Figure 2-4 Single Attribute Utility Function

As can be see from the graph, intermediate utility values can be obtained by interpolating between points. A word of caution is necessary: if the decision maker feels that great importance can be attached to fitted utility values in close proximity to each other, then a detailed sensitivity analysis may be required to obtain the resolution necessary to support the decision. In such a case, the decision may not be solvable graphically [Ref. 17: p. 63].

The final benefit of a utility function approach is that the utilities can be compared using Expected Utility values, EU(x), thus capturing the risk assessment attributes of the decision-maker. This is accomplished through a calculation similar to the determination of expected value. The derived utility values are multiplied by their associated probabilities and then summed across the range of possible outcomes. A coherent solution is that prospect which has the highest expected utility value.

4. Risk Attitudes and Premiums

In wager (17) above, it was posited that the CE would be \$400. The expected value of wager A was determined to be \$500. Can anything about the decision maker's perception of risk be determined from this fact? A Risk Premium (RP) can be defined that is the difference between the CE assigned to a prospect and that prospect's expected value:

$$RP(x) = EV(x) - CE(x)$$

If the decision maker's RP is greater than zero, he is considered risk-averse, i.e., he would part with some value equal to the RP in lieu of participating in the wager. If the RP is identically zero, he is risk-neutral. If the RP is less than zero, he is risk-seeking, i.e., he would be willing to pay some amount equal to the RP in order to participate in the prospect. Figure 2-5 provides a graphical presentation of these three cases.

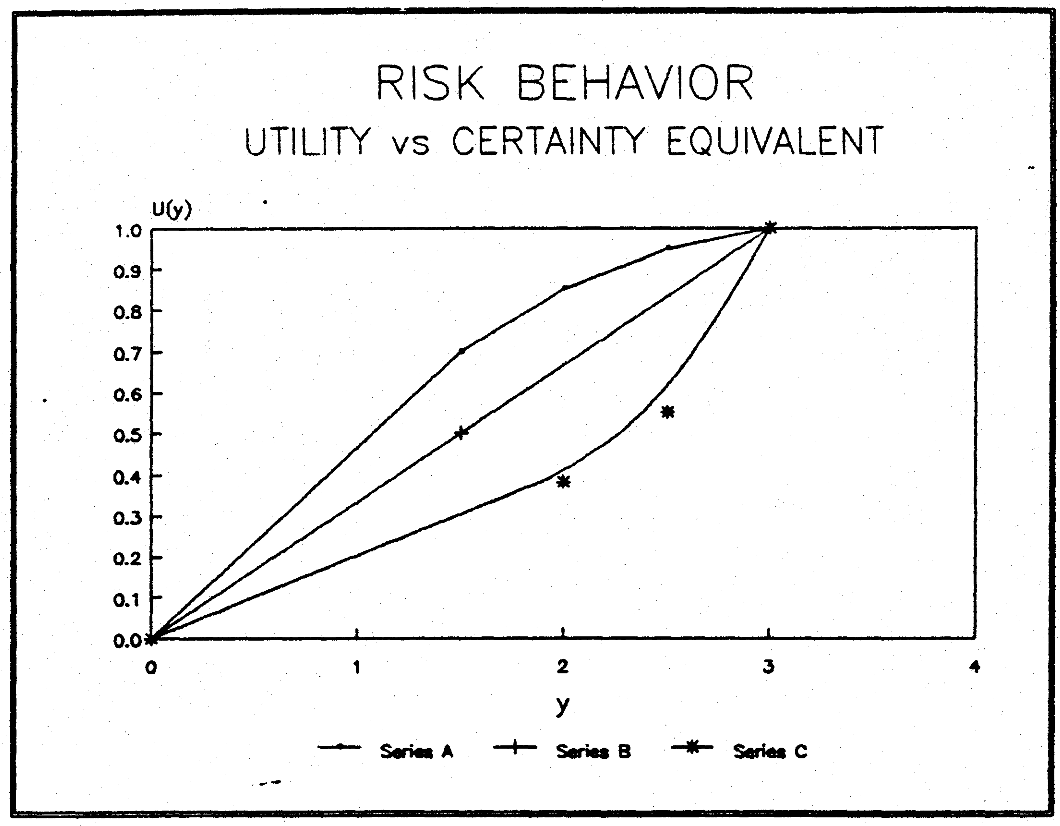

Figure 2-5 Utility as a Function of Certainty Equivalent

Series A, the convex curve, is a risk-averse case. Series B, the straight line, is the risk-neutral case. Series C, the concave curve, is the risk-seeking case.

It has been noted by many researchers that risk attitudes are not necessarily constant over the range of possible payoffs or utilities [Refs. 36, 37, 38]. This behavior was noted above in the Allais Paradox example. While numerous analytic descriptions have been formulated to describe individual risk-perception curves [Ref. 39], a graphical approach is useful for depicting a decision maker's effective risk-perception attitudes. Once plotted, the regions in the vicinity of inflection points can be more closely researched to provide feedback to the decision maker about his perception of the problem under consideration.

5. Comments on Multi-Attribute Utility Theory

While the von Neumann - Morgenstern formulation is sufficient to handle individual attributes of a problem, many decisions involve a combination of attributes, some of them potentially conflicting. The Multi-Attribute approach developed by Raiffa and Keeney extends the coherence of Utility Theory to a broader range of problems. While conceptually simple in formulation, in practical terms it requires extensive checks to ensure mutual preferential and utility independence for all possible pair combinations. A theorem provided by Keeney and Raiffa allows the set of all possible pairs involving $2^n - 2$ potential tests to be reduced to n tests [Ref. 17]. As in the case of single attribute utility functions, a value for the joint utility function can be calculated for those instances where the joint utility function can be decomposed into a linear or multiplicative form. The multiplicative form is applicable for those cases where a particular attribute must be included in the solution [Ref. 17]. Weighting factors, whose sum is one, are used in a manner analogous to probabilities in the single attribute case to provide a composite utility value for some particular multi-attribute solution set. The various solutions can then be compared based upon a maximization rule.

Other approaches to the multi-attribute problem have been suggested, most notably Saaty's Analytical Hierarchy Process (AHP) [Ref. 40]. While easier to implement in practice than Multi-Attribute Utility, these techniques are subject to criticism on a number of grounds, most notably coherence [Ref. 41].

E. SUMMARY

This chapter has discussed the nature of the decision problem and the requirements that must be met to guarantee a rational or coherent solution. Various methods of decomposing the problem into simpler elements under stochastic and nonstochastic conditions were examined. The difficulties associated with capturing potential variability in uncertain outcomes were presented. Utility Theory was presented as a means of encoding an individual decision maker's preferences and risk perceptions into a coherent solution. The concept of Certainty Equivalents was developed as a method for eliciting preferences and risk perceptions consistent with the axioms of Utility Theory. Some limitations of the theory were presented and the general requirements for conducting analysis of multi-attribute problems were defined. The existence of alternative means of analyzing multi-attribute problems was noted along with their potential problem of providing coherent results.

III. COMMERCIAL TECHNICAL RISK ASSESSMENT

A. BACKGROUND

The purpose of this chapter is to examine some aspects of technical risk assessment as practiced by commercial enterprises. The Defense Science Board concluded in its 1985 study of Department of Defense development programs that the creation of the IBM 360 mainframe computer, the Boeing 767 aircraft, the ATT telephone switch, and the Hughes commercial communications satellite all compared, "in complexity and size to a major weapon system development, yet each took only about half as long to develop and cost concomitantly less." [Ref. 2:p. 49] There are two questions to consider. Are the risk assessment techniques used by commercial enterprises successful, i.e., do they provide sufficient information for planning and system design? Secondly, can risk assessment techniques used in commercial operations be applied to Department of Defense acquisition operations? The first question will considered in this chapter. The applicability of commercial techniques to the DoD environment will be discussed in Chapter IV.

B. COMMERCIAL RISK ASSESSMENT PRACTICE

As discussed in Chapter II, the inception of modern risk assessment and mathematical probability theory began with Laplace's study of smallpox mortality. It was only in the mid-nineteenth century that commercial concerns developed sufficient understanding of the required mathematical tools to begin analyzing risk in a quantitative and rational fashion. von Neumann and Morgenstern built upon the economic equilibrium theory of the Lausanne School when developing their Utility Theory model [Ref. 5:p. 15]. Since the publication of their ground-breaking work in 1943, many additions to inventory of risk assessment and decision tools have been made. Farquhar listed twenty-eight different techniques for tackling various aspects of the risk assessment problem [Ref. 39]. A natural expectation would be that the commercial practice of risk assessment is well developed and that some modicum of success is enjoyed in accurately identifying risky projects. Upon a closer look, it is apparent that this is not so.

C. RISK AND AMBIGUITY

Any commercial enterprise faces two key questions: (1) What do consumers want? (2) Can the firm satisfy particular consumer wants in a profitable manner? Tremendous resources are expended in the attempt to define consumer wants and preferences in everything from cars to political parties. However, as Kosnik observed, ambiguity exists as to the extent of consumer needs. This complicates corporate efforts to satisfy these needs by matching existing and emerging technologies with a constantly changing marketplace. The marketing approach views the business process as a , "highly integrated effort to discover, create, arouse, and satisfy customer needs . . . unfortunately customers cannot articulate what they need." [Ref. 42:p. 121] This has led to some inconsistencies in the application of classical Utility Theory as discussed below.

1. Ambiguity Concerns

Classical Utility Theory is based upon knowledge of the underlying probability distribution governing a particular group of events. As discussed in Chapter II, expected utilities can be calculated in these instances if the magnitude of potential gains and losses is known. A risk premium can be specified, based upon the risk-seeking behavior of the firm, such that the firm would be indifferent to the outcome of the event under consideration. However, if there is ambiguity affecting the probabilities governing the outcomes, empirical evidence suggests that the associated risk premiums will be larger. Instances have been noted where the resultant risk premium for small, but ambiguous probability cases exceeded that applied to higher, non-ambiguous, loss probabilities. In these cases, firms seem to rely upon the "gut feelings" of the appropriate decision maker, than upon rigorous mathematical analysis [Ref. 38].

2. Risk Perceptions

The size of the potential loss relative to the value of the company is usually the key feature in the practice of commercial risk assessment. This is countered by classical economic theory. Higher performance levels, i.e., greater profits, will accrue to firms that undertake more risk [Ref. 36]. The application of probabilities to estimates of potential gains and losses is the first step in analyzing the risk associated with a commercial undertaking. Those prospects possessing the largest expected value would be selected for exploitation. However, in some instances, firms may deliberately pursue prospects having a large expected loss because of the potential "windfall" gain that may accrue. In the long-run such actions would be ruinous. The rationale behind this behavior is poorly understood, but these actions can be seen by firms that are in extremis. In such an instance, the survival of the enterprise, as perceived by management, may be contingent upon the recovery of a "windfall" profit [Ref. 43]. This seems to argue for the application of Utility Theory to commercial decisions as opposed to the strict application of Expected Value. The risk-seeking behavior of the firm apparently changes with its overall fiscal health [Ref. 38].

3. Problems with Utility Theory

As stated above, the Utility Theory approach implies that the underlying probability distribution can be discovered. This can occur through elicitation of management's subjective probability estimates or through the careful investigation of some physical process governing the prospects in question. Does this, in practice, represent what commercial enterprises are doing? March and Shapira discovered that, while possessing risk preferences, commercial managers act in a fashion different from the von Neumann and Morgenstern model. Specifically, managers were willing to accept risks because they did not expect to bear them [Ref. 38].

a. Perceptions of Probability

Managers appear to be insensitive to probability estimates of events. Managers focus on target levels and make, "sharp distinctions between taking risks and gambling." [Ref. 38:p. 1404] As discussed in Chapter II, the notion of a "reference gamble" to elicit utility values is central to the classical utility approach. Winkler found that if the decision maker is an "expert" in some field, then success will be attributed to knowledge, while failure will be the fault of chance. Conversely, if the underlying process is poorly understood, then success will attributed to chance [Ref. 44].

b. The Value of Knowledge

Given the above, the assumption could be made that managers possessing expertise in a particular field could sift through the relevant data describing some process and arrive at a profitable decision. This is not always the case. Capen, et al. conducted a study of the profitability of petroleum companies when bidding for Government leases. The problem studied by Capen, et al. was the poor success rate and subsequently poor profitability of firms engaged in Alaska oil field development. Both the Atlantic Richfield Company and the Humble Oil Company had cooperated in the investigation of the Alaska North Slope oil fields. The relevant information about parcel petroleum characteristics was pooled and known to both companies. However, during the bidding process for subsequent field development, extremely large bid variances for the same parcels existed. The authors cited ratios of 100 for some parcels, with 5-10 being the most common. The authors concluded that the winner of a particular parcel was the firm that, "most over-estimates the true tract value." [Ref. 45:p. 643]
Access to the same body of data and analysis by highly skilled professionals did not guarantee success. The value experts placed upon a particular tract was significantly

different. Thus, recourse to expert knowledge in estimating the probability of success in a venture does not guarantee the expected pay-off.

D. TECHNICAL RISK ASSESSMENT ISSUES

The above quotation from the Defense Science Board (DSB) implied that commercial firms may generally be successful in their analysis of the technical risks affecting the implementing of new ideas. While the projects cited by the DSB were resounding successes for their manufacturers, successes of this magnitude are not commonplace.

1. Accuracy of Assessment

The RAND Corporation conducted a study of chemical pioneer process plants. The corporations building the pioneer plants were all successful operations, possessing large capital and information resources, and management structures attuned to the strategic challenges facing their companies. The study concluded that satisfactory performance required in excess of ten years additional development work and that large cost overruns where common. The study attributed this to the establishment of fixed budget values prior to the completion of a final design and incomplete understanding of the challenges to be surmounted [Ref. 45].

Similar findings were reported by Davis. Initial construction cost estimates for new facilities were typically less than half the eventual amount. Davis attributed this to under-estimating costs as opposed to true cost overruns. Additionally, eighty percent of new projects failed to achieve their predicted market share [Ref. 47]. A study by Battelle Memorial Laboratories discovered an average of 19.2 years between invention and commercial production [Ref. 48].

2. Technological Uncertainty

A slightly different conclusion was reached in a recent survey of 108 San Francisco based companies spanning service-based to high technology firms. The ability to accurately ascertain the difficulties associated with new ventures were more acute for organizations relying upon advanced technologies, irrespective of company size. The more advanced the technology providing the company's profits, the greater the potentially negative consequences of inadequate technical risk assessment. The higher the level of technological advancement, the higher the level of opportunity costs for a successful decision. Greater technological complexity implies a greater degree of uncertainty or ambiguity for the key decision maker [Ref. 49].

Ghemawat agrees with this conclusion. High technology companies are faced with the dilemma of choosing between a high-risk, high-return prospect or, "foregoing a head start (and also experience related cost advantages) by waiting until technological uncertainty is resolved." [Ref. 50:p. 148]

3. Summary

Commercial operations have had minimal success in solving the probability estimation problems cataloged in Chapter II. Corporations are hampered by judgement biases which result in schedule delays and cost overruns. Issues of risk assessment and technological uncertainty are as severe for firms marketing high technology products as for DoD acquisition decision makers attempting to maintain a technologically superior force. Risk assessment methods that have proven to be successful are not suitable for firms operating in very dynamic markets.

E. EVALUATION TECHNIQUES

1. Discounted Cash Flows

The primary method for evaluating the potential of any project is through the use of Discounted Cash Flows (DCF). The basic premise is, "a dollar today is worth more than a dollar tomorrow." [Ref. 52] In theory, the DCF approach provides a rational and sound method for estimating the cash generated by a project during different time periods. Projects competing for limited corporate dollars can be readily compared with this technique. Additionally, a firm can compare the projected cash flow of a project against what the firm could earn by simply putting the money in the bank or through the use of similar financial instruments. The DCF method is not foolproof. It relies upon accurate and unbiased estimation of three key factors: Inflation, riskiness of the project over its projected life, and risk reduction through diversification.

a. Inflation

Changes in the monetary inflation rate can dramatically affect the profitability of a project. The effects of inflation become more pronounced as the time horizon of the projects expected life becomes longer. While an accurate estimate of inflation rates is crucial, the firm is limited in its ability to control the effects on cash flows. Uncertainty in this regard tends to push firms toward projects having quick payoffs [Ref. 51].

b. Project Risk

The technical risks associated with any project decrease over time. This is a natural result of the learning process. Maintenance of a fixed risk factor for the life of the project tends to under-value the cash flows that would occur as the project reached maturity. Older technology does not necessarily imply useless technology.

Large-scale projects can continue to provide significant cash flows long after the original payback has been satisfied [Refs. 51, 52]. A further complication arises from the methods used by firms to estimate the probabilities of high risk events. Firms operating in established, slowly growing markets have enjoyed success by employing these techniques. However, "for fast moving and world-wide industries, they have been a disaster." [Ref. 53:p. 124]

c. Diversification

A key tool available to commercial operations is diversification. While there are many diversification techniques, the basic concept is that of portfolio management. The commodity future markets are, in principle, an example of this. An individual takes actions such that potential losses are balanced by gains, so that the basic financial position is protected. Futures contracts are bought or sold to match, hedge, the individual's current holdings and risk perceptions. The purchase of life and property insurance policies are other examples. Corporations can manage their various risk exposures through the use of financial instruments or through investing internally in a range of projects possessing varying degrees of risk. The idea is to compensate for risk in a way that maintains the company's desired risk-seeking position. Companies desiring a low risk position would not invest in programs having potentially high risks [Refs. 51, 36].

2. Simulation Techniques

A modification of the basic DCF approach is to apply a Monte Carlo simulation to the firm's estimation of its business environment. Many software programs are available that allow the user to specify the nature of the underlying probability density function. A truncated log normal distribution is typically applied to new projects. Its shape matches the expected occurrence of budget overruns versus underruns: Overruns at multiples of the original estimate are far more likely than very large underruns [Ref. 52]. While this approach allows a firm to quickly examine a multitude of scenarios with varying risk estimates, the basic problem of determining the relevance of the probabilities applied to the problem remains. The numbers produced are subject to the biases and misunderstandings examined in Chapter II. Strassman admits that the probabilities of occurrence that he uses are based upon personal experience and are not empirically defensible [Ref. 52]. The simulation approach simplifies the "number-crunching" aspect of analyzing a lot of prospects, but does not necessarily deliver an unbiased result.

a. Risk Adjusted Discounted Cash Flow

Strassman advocates the use of Risk Adjusted Discounted Cash Flow (RADCF) analysis [Ref. 52]. This approach splits the DCF into two segments: financial and operational risk. Operational risk covers all risks other than those associated with the cost of capital [Ref. 52]. Low risk projects are those possessing at least a 97.5 percent chance of providing profits over the life of the project. High risk projects are those with less than or equal to a 2.5 percent chance of providing profits over the life of the project. Moderate risks fall between these two extremes [Ref. 54:p. 19]. While providing better quantitative data for decision makers, this approach still begs the question of how applicable probabilities should be determined.

3. The Venture Capitalist Approach

The Venture Capitalist represents a different entity than the standard commercial firm. While interested in profits, he does not necessarily have to worry about defending market share or finding new uses for his inventory of technologies. The Venture Capitalist is generally free to pick his area of exploitation and arranges the timing and scope of his efforts accordingly.

a. Decision Criteria

A Venture Capitalist typically looks at three items: business potential, i.e., market, pending solution of technical problems, expertise and commitment of the development team, and lastly, financial requirements [Refs. 55, 56].

b. Number of Projects

A typical Venture Capitalist will look at two to three hundred prospects a year. Perhaps ten percent of these will be selected for further consideration. Actual project commitments will be only two or three [Refs. 55, 56]. The average Venture Capitalist will be involved in a total of five to seven projects at any time. The size of the commitment is dependent upon the Venture Capitalist's familiarity with the technologies in question and his estimate of the technical expertise of the development team. Financial arrangements often call for those whom the Venture Capitalist is backing, to invest a substantial portion of their net worth in the project [Refs. 55, 56].

c. Expectations

The goal of the Venture Capitalist is to quickly turn the project into a successful business venture and then divest himself of the asset. Despite the careful selection of projects and the relatively large commitment of funds and personal effort, on average, the successful Venture Capitalist can expect about twenty percent of his projects to be complete failures and about twenty percent to meet his profit goals. The remaining sixty percent will fall in the middle, requiring additional time to reach business goals and substantial divestiture effort [Refs. 55, 56]. These results seem to match those of the larger, more conventional firms discussed above [Refs. 46, 48, 53].

F. SUMMARY

This chapter examined the ways in which commercial operations seek to assess their risk exposure. The use of classical statistical tools and Utility Theory was discussed. Some of the common evaluation techniques were described, and their strengths and weaknesses noted. The susceptibility of commercial operations to biases in judgement, and over-estimation of the occurrence of favorable events described in Chapter II, were highlighted. While quantitative approaches to technical risk are available, methods for probability estimation rely exclusively upon individual judgement and assessment. Standard probability estimation methods, e.g., reference gambles or probability wheels, are spurned by corporate decision makers. Risk compensation and diversification was also discussed.

IV. DoD ACQUISITION DECISION ENVIRONMENT

A. INTRODUCTION

The Department of Defense acquisition process is exceedingly complex. Managers and decision-makers struggle to achieve the technical performance characteristics required to support combatant forces within schedule and cost constraints. They must deal with a host of agencies and oversight bodies charged with monitoring all aspects of cost, schedule, and performance progress. Acquisition decision-makers must be responsive to the directives and requests for information from various service, Department of Defense, and Congressional entities that may have an interest in some portion of the acquisition process. In 1985, the Pentagon submitted almost 24,000 pages of documentation to Congress, "stemming from prior years' defense authorization and appropriations bills and their accompanying reports." [Ref. 57:p. 76] Between 1970 and 1985, the number of congressionally mandated reports increased 1000 percent [Ref. 57:p. 76].

The Department of Defense acquisition process encompasses a multitude of functional disciplines other than the contracting for a particular piece of hardware or software. Careful consideration must be given to areas such as maintenance and logistics support over the life of the system. The number of personnel qualifications and training requirements for operators and maintenance personnel must be taken into account. Basing requirements, support facilities, and environmental impact of the new system or its production process have to be planned. Unique test and evaluation facilities may be required to ensure that an accurate estimate of the system's real operational performance is obtained. The interoperability of the equipment with other services or U.S. allies must be weighed during the definition, design, and testing of new capabilities.

An in-depth analysis of all aspects of the acquisition process is outside the scope of this thesis. This chapter will focus only on the assessment of technical risk and its impact on the overall acquisition process as described in DoD Instruction 5000.2, "Defense Acquisition Management Policies and Procedures". [Ref. 12] This document requires that essential program elements

> "Include clearly defined criteria for elements leading to the risk assessment events. The satisfaction of these criteria must be documented to support the rigor necessary in the risk assessment process."
> [Ref. 12:p. 5-B-2]

The intent here is to provide a broad overview of the decision criteria mandated by the "5000" series documents [Refs. 12, 13, 14] and highlight the essential chronological features facing the acquisition decision-maker.

B. ACQUISITION PROCESS OVERVIEW

Office of Management and Budget Circular A-109 [Ref. 58], specifies requirements necessary for the conduct of any federal acquisition. DoD Directive 5000.1 and DoD Instruction 5000.2 are the governing documents for DoD acquisition decision-makers. They detail the procedures that must be followed and the objectives that must be met for a major new system start or an upgrade to a system's existing capabilities.

1. Decision Makers

The Under Secretary of Defense for Acquisition is the Defense Acquisition Executive (DAE). He is supported by the Defense Acquisition Board (DAB). The DAB is the top-level review body for major weapons systems acquisition decisions. The DAB is chaired by the DAE. Other members of the Board include the Deputy Under Secretary of Defense for Acquisition; Service Acquisition Executives of the Military Departments; Director of Defense Research and Engineering; the Assistant Secretary of Defense for Program Analysis and Evaluation; the Comptroller of the Department of Defense; and the Director of Operational Test and Evaluation. The Vice Chairman of the Joint Chiefs of Staff serves as Board Vice Chairman [Ref. 12:p. 13-A-2].

a. Supporting Committees

The DAB is supported by three committees: Strategic Systems (SSC); Conventional Systems (CSC); and C3I Systems (C3IC). The committees provide specific expertise to support the acquisition review process [Ref. 59:p. 3].

b. DAB Responsibilities

The DAB convenes for each milestone review to ensure compliance with previously specified performance objectives. Additionally, the DAB is to act as an independent assessor of program health and future viability. The DAB provides recommendations to the Under Secretary of Defense for Acquisition on the various performance, cost, and schedule trade-offs that may be proposed by the new system's program manager. Consideration of relevant risk areas, threat, technology, design and engineering, etc., is an integral portion of this process during Milestone review [Ref. 12:p. 13-A-2, Ref. 13:p. 4-E-1]. Specific information on the mechanics of the decision process are provided in the following section.

2. Decision Process

DoD uses a phased, systematic approach to analyze the military requirements problem, develop satisfactory solutions that meet performance goals, and manufacture and support an operational system in a timely fashion at an affordable cost. Five basic milestones are imposed on the acquisition process to ensure that these requirements are met. Milestones are paired with follow-on phases. The phases are structured toward developing an operational system while satisfying the interim goals set by the DAE and the DAB. The goal is to develop an event-driven acquisition strategy, "that links program decisions to demonstrated accomplishments in development, testing, and production." [Ref. 59:p. 2] This structure is discussed below.

a. Mission Need Statement

The acquisition process begins with the determination of the basic system performance requirements necessary to either support new military obligations, combat emerging threat capabilities, or take advantage of new technologies that could substantially reduce, "ownership costs or improve the effectiveness of existing materiel." [Ref. 12:p. 3-2] The procurement process for new capability only begins after a determination that military requirements cannot be met via changes to, "doctrine, operational concepts, tactics, training, or organization." [Ref. 12: p. 3-2] These requirements are formulated in a "Mission Need Statement" (MNS).

(1) Mission Need Validation. Mission needs identified at lower echelons are validated by a designated "operational" authority: a Unified Command, e.g., Atlantic Command, a Specified Command, e.g., Aerospace Defense Command, the Military Departments, the Office of the Secretary of Defense, or the Joint Staff [Ref. 12:p. 3-2].

If the validated requirement could potentially involve the use of new technologies or require a major upgrade to existing performance capabilities, then the requirements also must be validated by the Joint Requirements Oversight Council (JROC).

(2) Performance Requirements. The intent of the MNS is to capture perceived operational requirements in a broad fashion. The statement should be sufficiently detailed to enable subsequent technical and engineering studies, but must avoid identifying a specific system solution to the military requirements [Ref. 13:p. 2-1-1]. As an example, a Mission Need could be generated for the collection, evaluation, and distribution of high quality battlefield imagery, without specifying the use of a particular technique. The MNS would specify the resolution required, size of imagery field of view provided to combatant forces, data transmission rate, cryptographic requirements, etc. It would then become the responsibility of the relevant DoD acquisition element to investigate and develop feasible technical approaches that meet the military requirements consistent with schedule and cost constraints. DoD will often engage industry to supplement or fulfill these requirements.

(3) Threat Assessment. DoD Manual 5000.2-M specifically requires that the Mission Need Statement identify the specific threat to be countered and provide a description of the likely threat environment [Ref. 13: p. 2-1-1]. This information is used at later milestones to validate the sufficiency of proposed technical approaches and help ensure consistency of evaluations.

(4) Joint Requirements Oversight Council. The purpose of the MNS review by the Joint Requirements Oversight Council (JROC), is to ensure development of capabilities that may benefit more than one service or enhance overall force qualities in a rational manner, while accounting for the requirements of joint operations and deployment. Validation of the requirements set forth in the MNS is also an integral part of this review.

b. Milestone 0: Concept Studies Approval

Upon validation of a legitimate military need, the Defense Acquisition Executive (DAE) will direct the initiation of concepts studies. The purpose is to begin the investigation and research process necessary to define the specific technical characteristics or "concepts" a new system must possess to satisfy the MNS. The DAE will issue an Acquisition Decision Memorandum (ADM), specifying the minimum number of possible ideas that should be investigated and identifying the lead DoD agency responsible for conducting the necessary research [Ref. 59:p. 5]. At this juncture, no definite date is established for the discovery of a set of satisfactory solutions but a minimum set of requirements will be established for progression to the next milestone.

c. Phase 0: Concept Exploration and Definition

Successful completion of Milestone 0 marks the formal beginning of the "Concept Exploration and Definition" phase. The purpose of this phase is to identify a set of possible technical solutions to the MNS requirements. The accuracy of the threat environment posed by the original MNS and the requirements for a new capability are also investigated. Additional Phase 0 objectives are to meet feasibility requirements specified by the DAE so that the program may progress to Milestone I and to begin the development of an acquisition strategy [Ref 12: p. 3-8].

d. Milestone I: Concept Demonstration Approval

Successful completion of Milestone I marks the official beginning of a new DoD acquisition program. The purpose of this checkpoint is to ensure that the requirements specified at Milestone 0 have been met. The most promising candidate solutions to the MNS are considered along with their availability. The accuracy of the projected threat environment is validated and the military requirements contained in the MNS examined. A complete set of acquisition documentation must be submitted at this review, including the Integrated Program Summary (IPS). The

IPS contains seven annexes addressing all relevant portions of the acquisition process. At this juncture, technical risk is specifically considered in Annex D to the IPS [Ref 13:p. 4-E-1].

As mentioned in the previous section, the program manager is required to categorize the risks of threat, technology, design and engineering, etc. A ranking scale of low, medium, or high is used. Numerical data is not required. No guidance is provided as to what constitutes admission into one of the categories. The technical approach chosen will determine the magnitude of potential gains or losses and the likelihood of their occurrence.

The ADM issued at completion of Milestone I will specify a concept baseline containing initial cost, schedule, and performance objectives. Exit criteria will be specified. These will form an interim set of goals to be achieved during Phase I.

e. Phase I: Demonstration and Validation

The purpose of Phase I is to improve the design characteristics and better define the expected capabilities of the system. Efforts are made to improve the design team's understanding of the technical processes involved in the selected approach(s). Requirements necessary for the successful completion of the Milestone II review are pursued. A Development baseline for the most promising alternative is created during this phase. High risk areas and their potential compensators are to be identified as well [Ref. 12:p. 3-14]

f. Milestone II: Development Approval

The key aspect of this milestone is to determine whether the results of the Demonstration and Validation phase support continuation of the program. Specific areas of concern at this juncture are the validity of the potential threat assessment and countering Mission Need and whether or not the proposed technical solutions are understood and actually employable. Technical risk problems can significantly delay passage of this milestone, resulting in potential trade-offs between original performance, cost, and/or schedule goals. An update IPS with revised risk assessment information, Annex D, is provided. Resource allocation in terms of personnel and money are reviewed. Successful passage of this checkpoint results in a further refinement of base-line cost, schedule, and performance goals. The ADM will address specific criteria that must be met for passage of Milestone III, Production Approval and this ADM approves entry into Phase II: Engineering and Manufacturing Development.
[Ref. 12:p. 3-18]

g. Phase II: Engineering and Manufacturing Development

During this phase the most promising technical approach will be converted into a, "stable, producible, and cost effective system design." [Ref 12:p. 3-21] The manufacturing process will be validated and contract compliance will be determined through system testing. The operational suitability of the system will be determined and a production baseline will be formulated. [Ref. 12:p. 3-21]

h. Milestone III: Production Approval

As with previous decision points, the purpose of this checkpoint is to verify that the exit criteria specified by the Milestone II ADM have been met. The results of engineering and manufacturing evaluations must support a conclusion that the new system design can be efficiently produced, is operationally acceptable and logistically supportable. By this time, most technical risk factors should have been eliminated. The status of program risk issues will be contained in the IPS. The cost, schedule, and performance characteristics of the new system will be defined by how well risk was identified and countered. Successful completion of a Milestone III review leads to the authorization for full-scale production of the new system. The resultant ADM will specify any program-specific exit criteria that must be accomplished during Phase III, including refined program cost, schedule, and performance objectives. [Ref. 12:p. 3-24]

i. Phase III: Production and Deployment

The goal of Phase III is to field an operational capability that meets the MNS. This is achieved by a stable design and efficient production and support processes. The system performance is monitored to ensure compliance with MNS requirements and maintain system capability against projected threats. [Ref. 12:p.3-27]

j. Milestone IV: Major Modification Approval

As required, the key objective here is to determine whether upgrades to existing systems are required, prudent, and cost-effective in light of projected threat capabilities or emergent military requirements. Technical risk issues re-enter at this point. The technical approach selected for a potential upgrade will affect not only the performance of the upgrade but also the underlying capabilities of the host platform. The resultant ADM will specify at what phase of the acquisition process the proposed modification will enter and approve the modified acquisition strategy and baseline. [Ref. 12:p. 3-29]

C. RISK ASSESSMENT PROCEDURES

The assessment and monitoring of technical risk by DoD acquisition authorities is a continuous requirement [Ref. 12:p. 6-A-3]. Senior Department of Defense managers recognized in the early 1980s that broad reforms were required in the total acquisition mechanism. As a result, Deputy Secretary of Defense Frank Carlucci issued thirty two initiatives in 1981. The initiatives were aimed at improving management control and the efficiency of the acquisition process [Ref. 57:p. 47]. Initiative 11 was directed at improving the manner in which quantitative program risk was identified and its magnitude estimated by Program Managers [Ref. 8:p. 33]. As a result, DoD Instruction 4245.7-M, "Transition from Development to Production," was issued.

1. DoD Instruction 4245.7-M

A review, conducted by the Defense Science Board, on acquisition program viability was conducted and they concluded that there is, "no structural mechanism that can articulate with any degree of certainty the risk associated with the engineering and manufacturing elements of the weapon system acquisition process." [Ref. 14:p. 1-3] Inadequate understanding of technical risk factors was determined to be a major source of risk in itself [Ref. 14: p.9--8]. Currently, DODI 5000.2 PART 5, Section B addresses Risk Management and specifically calls out Program Manager use of DoD 4245.7-M to identify areas of program risk.

DoD Instruction 4245.7-M segregates the acquisition process into a rational grouping of industrial design problems covering design, testing, production, facilities, logistics, and management [Ref. 14:p. 1-8]. Technical risk is explicitly identified and a template was created to aid program managers and senior decision makers in making better use of the technical risk information available to them [Ref. 14:p. 9-8].

The instruction does not specifically address techniques for estimating the likelihood of adverse consequences, nor give guidance on how decision-makers should rank the riskiness of various alternatives. What is provided however, is an outline for program management. This outline calls for the development of a system that provides early identification of technical risk factors, instantaneous assessment of program status, and early indications of potential success or failure. Guidance on the development of such a risk assessment and monitoring system is absent. Program Managers are apparently left to their own initiative [Ref. 14:p. 9-9].

2. The Legacy of Carlucci Initiative 11

The commitment of senior DoD acquisition officials to the Carlucci Initiatives did not filter down. A study conducted by the General Accounting Office (GAO) in 1986 concluded that DoD had, "not carried through with its action plans on most of the Carlucci initiatives." [Ref. 57: p. 48] An additional GAO study of technical risk assessment concluded, "The net effect of Initiative 11 on technical risk assessment procedures has thus far been negligible." [Ref. 8:p. 33]

a. GAO Findings

The GAO study cited above surveyed 25 major program offices from all three services. Standardization of assessment techniques was completely lacking. Additionally, there was limited direction from the appropriate service acquisition authorities concerning how risks should be ranked. Subsequent GAO investigations of major programs has revealed no change in DoD technical risk assessment practice [Refs. 9, 10, 11]. Both DoD Instruction 5000.2 and DoD Manual 5000.2-M [Refs. 12, 13] are devoid of the explicit guidance recommended by the GAO in 1986 [Ref. 8:p. 77].

b. Risk Compensation

Compounding DoD technical risk problems is the apparent practice of examining the technical risk of various programs as discrete events. While some commercial compensation options are unavailable to DoD management, e.g., hedging or other financial strategies, there is no direct mechanism for combining risk information into a department-wide risk profile. Risk compensation and reduction is tackled at the program level by individual program managers. The absence of a standardized technical risk quantification scheme hampers senior management's attempts to establish and manage a departmental risk portfolio. Lacking quantifiable and comparable technical risk data and common baseline, technology trade-off decisions are difficult [Ref 8:p. 51].

3. Corporate Information Management Initiative (CIM Initiative)

Paul Strassman, Director of Defense Information, is attempting to implement CIM within the DoD. CIM is built upon a "business case" approach to analyze the, "potential costs-saving Alternatives for DoD information management." [Ref. 54:p. 1] A key feature of the CIM initiative is the use of the quantitative risk assessment techniques he developed in his book, <u>The Business Value of Computers: An Executive's Guide</u> [Ref. 52]. Strassman's goal is to conduct a Risk Adjusted Cash Flow analysis of new information technology acquisitions using Monte Carlo simulations. The Institute for Defense Analysis created a spreadsheet software package that will run a user-specified number of trials with user-entered probability values. The output of the package is a series of graphs and tables depicting the relative costs and benefits accruing from different information technology alternatives. An Expected Value comparison is the decision criterion. While the program accepts user-defined probability values for the likelihood of achieving various outcomes, individual judgement is relied upon for probability generation [Ref. 54:pp. 19-23].

D. SUMMARY

This chapter highlighted the key features of the major weapon systems acquisition process. Basic decision criteria and considerations were presented. The functions of the Defense Acquisition Board (DAB) and the primary decision authorities were listed. The importance of technical risk assessment to the acquisition process was presented. The origin of current directives addressing technical risk assessment in the 1981 Carlucci Initiatives was noted. The continuing absence of formal and explicit guidance on methods to be used to assess and rank the technical risk associated with new system acquisitions was also discussed.

The consideration of technical risk on a project-by-project basis without specific guidance for quantifying technical risk robs senior decision makers of valuable information necessary to manage a Department of Defense-wide technical risk portfolio. Without quantifiable technical risk data, the overall impact of the risk associated with the technologies DoD is developing is uncertain. Categorization of risks as low, medium, or high is left to individual program managers and no baseline for comparison exists. As Paul Strassman has observed, "To understand your risks, you need to know how much money you could lose." [Ref. 52:p. 217]

While certain risk compensation strategies employed by commercial operations are unavailable to DoD, e.g., hedging and alternative financial markets, a portfolio approach based upon quantifiable and comparable risk data is still applicable. It allows for a more rational and systematic improvement of any desired DoD technical risk profile. The overall Department of Defense technical risk position needs to be examined and explicitly managed to provide an overall technically superior military force with limited funds.

V. PROPOSED METHODOLOGY

A. BACKGROUND

Although the axioms of Utility Theory are logically consistent and lead to coherent solutions in principle, significant problems remain with the elicitation of specific utility values [Refs. 17, 26, 27]. As discussed in Chapter III, the approaches used by commercial ventures, many decision makers are reluctant to use the recommended techniques of standard devices of 50:50 reference gambles, probability wheels or urns full of different colored balls. The most strident reclama in DoD's response to the GAO report on the Navy's T-45 program was reserved for use of the phrase "calculated gamble" by the report's authors [Ref. 9]. Probability assessment approaches are fraught with considerable peril and often require significant assistance from analysts who are outside of the decision making organization. Significant time and resources may have to be committed to familiarize a decision analysis team with the nature of the problem. Several iterations involving coherence and sensitivity checks may be required to ensure a satisfactory result. Finally, the results of the analysis may require considerable distillation and explanation. Previous systems hailed as possible solutions to various risk problems have frequently drawn criticism from program managers because of these factors [Ref. 60]. The expertise often resides outside the program office, requiring the program manager to rely upon systems he may not fully understand and personnel who are not directly accountable to him.

1. Limitations of Expert Opinion

An intuitive approach to the solution of any complex problem is the elicitation of engineering or scientific expert opinion. While a group of experts can provide valuable insights into likely solution methods and their individual opinions codified into a consensus, their estimation of the associated probabilities of success or failure may be tremendously ambiguous and overconfident [Ref. 26]. In a 1980 study conducted for the U.S. Department of Energy, Salem et al. [Ref. 31] cite an instance where expert opinion was elicited to determine the likelihood of a catastrophic seismic event involving several different nuclear reactor installations. The seven experts polled were from the fields of civil engineering, geology, and geophysics.

> There (sic) opinions as to the probabilities of large earthquakes varied by as much as four orders of magnitude (i.e., a factor of 10,000) in more than one instance. Equally as interesting is the fact that several of the seven participants estimated their uncertainties at less than a single order of magnitude (two estimated their general uncertainties as a factor of two or less). [Ref. 31:p. 34]

In an article on competitive bidding strategies for the purchase of government-owned oil reserves, it was noted that even though two companies had worked closely together on the surveying and evaluating of potential reserve size and had completely shared all the resulting data, the subsequent bids submitted for individual parcels where dramatically different [Ref. 45].

2. Utility Assessment Issues

Assuming the decision maker is willing to investigate a utility function approach to his problem, then his decision problem can be reduced to a number of smaller sub-problems. This approach is favored by various engineering disciplines and matches the DoD Work Break-Down Structure required during program review. As discussed in Chapter II, the value of utility function analysis lies in its ability to incorporate preferences and risk perceptions in a coherent fashion.

While risk-neutral behavior is often suggested for governmental operations, implying strict adherence to Expected Value maximization, individual decision makers and distinct governmental entities, i.e., DoD, Department of Energy, Food and Drug Administration, etc., may be extremely risk averse [Refs. 17, 31] because of the immense consequences of particular decisions. Obtaining reliable Expected Values requires the use of probability distributions characterizing a well understood process. This can be extremely difficult to obtain for some "one-of-a-kind" problems.

By resorting to an analysis of his preferences between two separate prospects, subject to some probability distribution, a decision maker's risk function can be encoded to provide as much detail as desired. The assessment method involves the comparison of two prospects presented as follows:

X = A guaranteed payoff

$$Y = \begin{cases} \text{Payoff of value } G \text{ with probability } p \\ \text{Payoff of value } L \text{ with probability } (1 - p) \end{cases}$$

The values of G and L are not constrained to be greater than zero. If any three of the four variables, X, G, L, and p, are fixed, then the fourth can be determined. The decision maker must establish the effective end points of the problem, the maximum assigned a utility value of one and the minimum a value of zero. The assessment process then seeks to uncover the value/utility pairs for the defined interval. There are four basic methods for eliciting the requisite information: Certainty Equivalence, Probability Equivalence, Gain Equivalence, and Loss Equivalence [Ref. 17].

a. Certainty Equivalence

Recall from Chapter II that a Certainty Equivalent (CE) is a guaranteed payoff used to determine the values of gain, loss, and associated probability of an opposing prospect. Gain, loss, and/or probability are adjusted by the decision maker so that he is indifferent between the value of a certain payoff and the expected value of a prospect operating under conditions of uncertainty.

In this approach, G, L, and p are fixed and the decision maker is requested to provide an X, the value of the guaranteed payoff. Bunn states that this method tends to emphasize more risk averse behavior relative to potential gains and more risk-seeking behavior relative to potential losses [Ref. 17]. Goodwin and Wright point out that the manner in which the elicitation question is phrased substantially impacts the nature of the response [Ref. 27]. Goodwin and Wright use the following example of certainty equivalent elicitation to underscore this point:

Insurance Formulation

A: You have one chance out of 1,000 of losing $1,000
B: You can buy insurance for $10 to protect against this loss.

Gamble Formulation

A: You stand one chance out of 1,000 of losing $1000
B: You will lose $10 with certainty

It was discovered that 81 percent of the subjects preferred option B in the Insurance formulation as opposed to 56 percent who preferred B when the prospects where framed in terms of a gamble [Ref. 27:p. 81].

A further consideration with certainty equivalence occurs if the operable probability distribution is skewed. If the decision problem involves only very high or very low probabilities, the 50:50 construct should be avoided.

b. Probability Equivalence

In similar fashion, probability equivalence fixes the values of X, G, and L and requires the decision maker to assess p. While this tends to provide an average risk attitude, it is subject to the kinds of limitations discussed previously about human probability assessment capabilities, particularly when dealing with very large or very small probability values or when attempting to elicit responses for small changes in likelihood, e.g., moving from 0.90 to 0.95 [Ref. 27]. Despite this, Certainty and Probability equivalence are the two more popular techniques.

c. Gain Equivalence

In the Gain Equivalence method, value for certainty, loss, and probability of gain are fixed and the decision maker is required to assess an appropriate gain value. An issue with this approach, as with Loss

Equivalence, is the affect of anchoring bias as described by Kahneman and Tversky [Ref. 26]. The manner of incrementing the Gain value, as well as the determination of the initial value, can affect the response.

d. Loss Equivalence

Loss Equivalence follows the above procedure with the certainty equivalent, gain, and probability values now fixed and the corresponding potential loss value assessed by the decision maker.

e. Summary

As developed in Chapter II, theoretically, the utility function approach allows the decision maker to bring his perceptions and judgements about the potential risk of an endeavor explicitly into a problem solution in a coherent manner. The four techniques discussed above provide methods for accomplishing this in a generic way but the limitations of each must be recognized. As pointed out in Chapter II, the development of utility theory arose through the consideration of monetary results. Much subsequent research has been spent on various means of equating monetary and non-monetary values [Refs. 17:pp. 102-107, 31]. The acquisition decision maker faces a similar problem. How should technology be "valued" and what constitutes "technical risk?" These questions will be considered in the next two sections.

B. TECHNICAL RISK

As was pointed out in Chapter I, the force employment strategies favored by the United States rely upon the fielding and maintaining a technologically superior military. Many resources are expended in monitoring the technological capabilities of potential adversaries. As DoD approaches the problem of maintaining a qualitative technical edge, an element of uncertainty is introduced. Solutions to force capability problems will be selected that ideally will provide the requisite technical performance. However, the resultant system may not possess the necessary performance when finally fielded. Any technical performance less then the specified value may result in a system that once fielded, is unable to meet force employment needs in all intended theaters of action. Alternatively, the system may not possess the effective lifetime originally intended because of failure to achieve the specified technical performance.

1. Technical Risk Factors

Technical risk is affected by two related factors: realized technological value of the proposed system versus intended performance and obsolescence.

a. Realized Technical Value

Despite the best of intentions, a particular level of performance may not be achieved, given the characteristics of the technical approach followed.

This can occur because the overall level of technical capability was insufficient to reach the goal or because other program constraints forced a reduction in the resources available for goal attainment. As a result, the fielded system, even if developed within the specified time period may fall below its performance goals. The risk in this instance is whether the nearest competitor system can exceed the performance of the fielded system. While this aspect of technical risk may be mitigated by pursuit of parallel approaches, at some point the acquisition decision maker will have to commit himself to one system to meet force requirements.

b. Obsolescence

The time required to move a system from the design phase to IOC will ultimately affect its useful life. Systems are designed to provide a specific amount performance over a designated period. The primary consideration being some amount of qualitative edge, i.e., better than the nearest competitor by some specified amount. Useful system life hinges upon what else is occurring in related technological development efforts while pursuing a particular approach: What is happening to the state-of-the-art? If the project takes longer than anticipated to bring to IOC, and even if technical performance goals are met, the useful life of the system may be significantly shortened.

2. Technology Valuation

Technology has no intrinsic value. Its worth, like money, is only in the services it provides. Any attempt to measure a technological value must resort to comparative techniques. Automobiles are valued more highly than a horse and carriage, by some, because of the flexibility in transportation and perceived ease of ownership. Likewise, many people prefer mass transit systems to automobiles. The value of the automobile is relative to the perceptions and environment of the individual conducting the valuation.

Similarly, military systems are valuable only in relation to potentially competitive military systems. The muzzle-loading rifle may have some value to antique gun collectors but its value as a present-day weapon is nil. It is non-competitive with its host of potential competitors. Given a mission or goal, it should be possible to state, whether a particular system is capable of functioning in a manner sufficient to lead to the accomplishment of a mission or attainment of a goal. This implies the use of judgement by the individual or group responsible for the mission or goal to determine the capabilities of the technology in question.

The problem then becomes of one of quantification versus qualification. If scarce resources are to be expended to obtain the services of a particular piece of technology, it would be worthwhile to be able to state how much better one proposed technological implementation is than another. The quantification process forces the careful consideration of potential alternatives, counter-poised with the likely environments, in which the candidate technologies may be required to operate and the potential missions requiring support. The valuation method adopted here is the TASCFORM™ model, developed by The Analytic Sciences Corporation for the Director, Net Assessment, Office of the Secretary of Defense, which will be explained in the following section.

C. TECHNOLOGY VALUATION MODEL

1. The Technology Valuation Model

The TASCFORM™ model, Technique for ASsessing Comparative Force Modernization, is means of indexing the technical performance characteristics of fielded military systems [Ref. 61]. It provides a non-dimensional number or figure of merit intended to capture the multiple attributes associated with various weapons platforms. This approach provides a decision maker with an ordinal scale which can be used to compare and rank the technological value of different systems. Additionally, it allows the decision maker to observe how much more technical performance one system may have when compared with another. TASCFORM™ uses an additive and multiplicative multi-attribute approach with "operationally-oriented" subjective weighting factors to handle the magnitude and importance of various attributes.

The TASCFORM™ approach incorporates a variety of salient characteristics such as payload, range, speed, mobility, navigation and target acquisition measures [Ref. 61]. The basic form of the additive model is:

$$I = k_1V_1 + k_2V_2 + . . . +k_nV_n$$

where I is the overall platform index, $k_1, . . . , k_n$ are the subjectively assigned weights and $V_1, . . . , V_n$ are the technology values of the respective attributes.

The multiplicative form is:

$$I = V_i(k_1V_1 + k_2V_2 + . . . +k_nV_n)$$

This approach is used when some Vi, a particular technological variable, must be included in the system. Possible examples of this requirement would be a survivability, range, or payload value.

2. TASCFORM™ Application

While TASCFORM™ indices have been developed for a wide range of forces, for the purposes of this thesis, the values developed for tactical and ASW aircraft were used. The baseline for the indices is the technology incorporated in the F-4B, a circa 1959 aircraft. Composite technology values representing the synthesis of basic airframe performance (speed, maneuverability, range, and payload) and imbedded weapon system capabilities (target acquisition, navigation, counter-measure susceptibility, etc.) were used, because this represents a technology index relevant to mission employment.

3. Limitations

The indices produced by the TASCFORM™ model are not, in themselves, predictors of the potential combat success or failure of the platforms under consideration. While not scenario specific, the weighting factors incorporated in the sample reflect operational criteria relevant to a U.S.-Soviet engagement in Central Europe. Application of the indices to other theaters involving Soviet or other nationality weapons would necessitate readjustment of the values. The indices obtained are independent of the likelihood of occurrence of a particular scenario. Thus, while the probability of a conflict between U.S. forces and those of the erstwhile Soviet Union may now be very small, such a scenario represents an extremely challenging technical environment. Cost data are not incorporated in the model, which facilitates a direct approach to the assessment of technical risk unmodified by other considerations [Ref. 61].

D. PROPOSED TECHNICAL RISK ASSESSMENT METHOD

Any method for assessing technical risk that seeks to provide coherent solutions must be sensitive to both the axiomatic requirements of Utility Theory and the practical issues of implementation. Two critical obstacles to the effective application of Utility Theory have been the issue of probability assessment and the use of reference gambles. The "standard device" procedure is subject to trivialization on the part of the decision maker. The following proposed method for assessing technical risk, attempts to circumvent these problems through the provision of an explicit probability distribution and a valuation system that keeps the technology utility function assessment process confined to issues of technical value.

1. Assumptions

Following the work of Moses, Dodson, and Knight [Refs. 62, 63, 64], the following assumptions were made:

a. Technological value can be quantified and measured.

b. The growth of U.S. military technological value over time can be modeled using linear regression techniques.

c. A probability distribution can be derived from the resulting regression equation that will allow an acquisition decision maker to determine his likelihood of obtaining a system possessing some specified technological performance value based upon the results of previous technological development.

d. The performance value of the closest likely competitor technology can be estimated using the TASCFORM™ method [Ref. 61].

e. Using the Certainty Equivalent technique described above, the acquisition decision maker can quantify his technological risk perceptions directly and incorporate these into a utility curve that would assist him in determining a satisfactory approach to meeting the mission needs of military forces while incorporating a notion of technical risk.

2. System Technology Sample

Following the work of Moses [Ref. 62], the statistical model used a sample of 49 U.S. Navy and Air Force aircraft developed between 1950 and 1979. The sample was restricted to tactical and anti-submarine fixed wing platforms for which TASCFORM™ performance index values where available. Source data for year of IOC and composite technology values were obtained from the U.S. Military Aircraft Cost Handbook [Ref. 65] which contained TASCFORM™ composite technical values for the aircraft in the sample. The technology values contained in the Handbook were derived using the TASCFORM™ methodology discussed above and derived [Ref. 61]. The Aircraft System Performance (ASP) values were used. The ASP value adjusts basic airframe measures of payload, range, speed, etc., for mission requirements of target acquisition, navigation, survivability, etc. and thus more truly reflect platform capabilities [Ref. 61]. The resultant values are tabulated in Table 5-1 by airframe designator, year of IOC, and composite technology value.

AIRCRAFT TECHNOLOGY MEASURES
TABLE 5-1

AIRCRAFT	IOC YEAR (1950-79)	TASCFORM COMPOSITE PERFORMANCE INDEX
F-89C	50	2.46
F-9F/H	51	4.19
F-89A	51	4.05
F-84F	51	5.13
F-86F	51	4.03
F-86D	51	3.68
F-2C	51	3.91
F-3A/B/C	52	9.02
F-1B/C/M	52	5.29
F-86H	52	5.68
F-100A/C	52	4.80
F-11A	53	5.80
A-3A/B	53	10.74
F-102A	53	9.71
F-6A	53	7.58
A-4A/B	53	3.93
F-1E	54	5.44
F-101A/B	54	13.55
F-100D	54	5.99
F-8A/B/C	55	8.40
A-1J	55	3.34
F-9F	55	4.02
A-1E/G/H	56	3.34
F-104A/B	56	6.79
F-106A/B	57	13.05
F-105B/D	57	14.86
A-4C	57	5.45
F-4A/B	59	9.32
A-6A	61	13.83
A-4E/F	61	7.27
F-4C/D	62	10.07

AIRCRAFT TECHNOLOGY MEASURES
TABLE 5-1

AIRCRAFT	IOC YEAR (1950-79)	TASCFORM COMPOSITE PERFORMANCE INDEX
P-3C	65	30.33
A-7A/B	65	12.10
F-111A	65	18.46
F-4E	66	13.96
F-111B	66	24.81
F-4J	66	13.39
A-7E	68	19.77
A-7D	68	16.17
F-111D	68	24.39
S-3A	69	20.21
F-111F	70	31.01
A-4M	70	8.52
A-6E	70	22.40
F-14A	71	31.51
F-15A	73	16.14
A-10A	75	12.12
F-16A	78	15.69
F/A-18A	79	25.42

3. Regression Equation

The regression model was hypothesized to be linear of the form:

$$\text{FLYTECH} = \text{CONSTANT} + A * \text{YEAR} + e,$$

where "FLYTECH" is the TASCFORM™-derived composite ASP technology value, "YEAR" the year of platform IOC, "A" a regression coefficient, and "e" any residual error not explained by the model. The regression was run using the

Student Version of MINITAB, Version 1.1. Regression coefficients are provided below. Regression results are presented in Table 5-2:

FLYTECH = -32.493 + 0.73724 * YEAR

REGRESSION RESULTS
TABLE 5-2

```
Predictor    Coefficient   Standard        t-ratio     p
                           Deviation

Constant     -32.493       5.507           -5.90       0.000
YEAR           0.73724     0.09112          8.09       0.000

s = 5.228      R² = 58.2%        R²(adj) = 57.3%

Analysis of Variance

SOURCE        DF        SS         MS          F            p
Regression     1    1788.9     1788.9      65.46            0.000
Error         47    1284.4       27.3
Total         48    3073.3
```

The regression coefficients vary slightly from those Moses obtained [Ref. 62] because of the inclusion of P-3C Orion and S-3A Viking platforms.

4. Regression Goodness of Fit

The proposed regression model adequately describes the aircraft technology data. The model is significant at the p = 0.000 level. Five different plots of the resultant regression data were constructed, as recommended by Devore [Ref. 25:pp. 498-503], to assist in the analysis of the regression's "goodness-of-fit." Figure 5-1 displays a plot of the regression line and the actual technology values over time. Figures 5-2 and 5-3 are plots of the standardized residuals. An analysis of the data contained in these figures shows that the distribution of the residuals appears to be random and most of the points fall with plus/minus two standard deviations of the expected residual value of zero. Figure 5-4 displays actual versus estimated technology values. The graph corroborates the R^2 value that time in the form of year of IOC is a reasonable explanatory variable for technical value. Figure 5-5, a normal probability plot of the standardized residuals, shows that the residuals follow a straight line and are contained within the interval (-2, 2). This tends to confirm the assumption that the error term is normally distributed. Figure 5-4 is a plot of estimated versus actual technology values. Figure 5-5 is a normal probability plot of the standardized residuals. A listing of fitted values, residuals, standardized residuals and normal probability scores is contained in Appendix A.

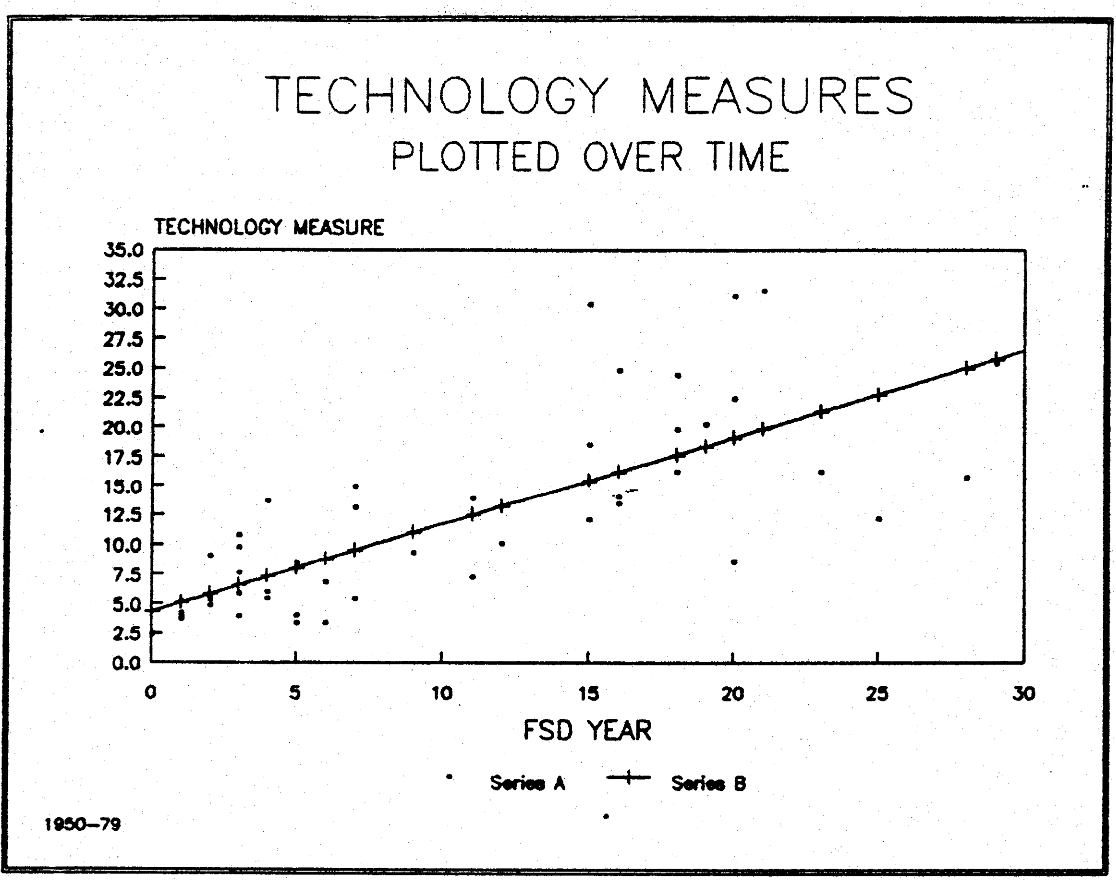

Figure 5-1 Plot of Technology Indices over Time

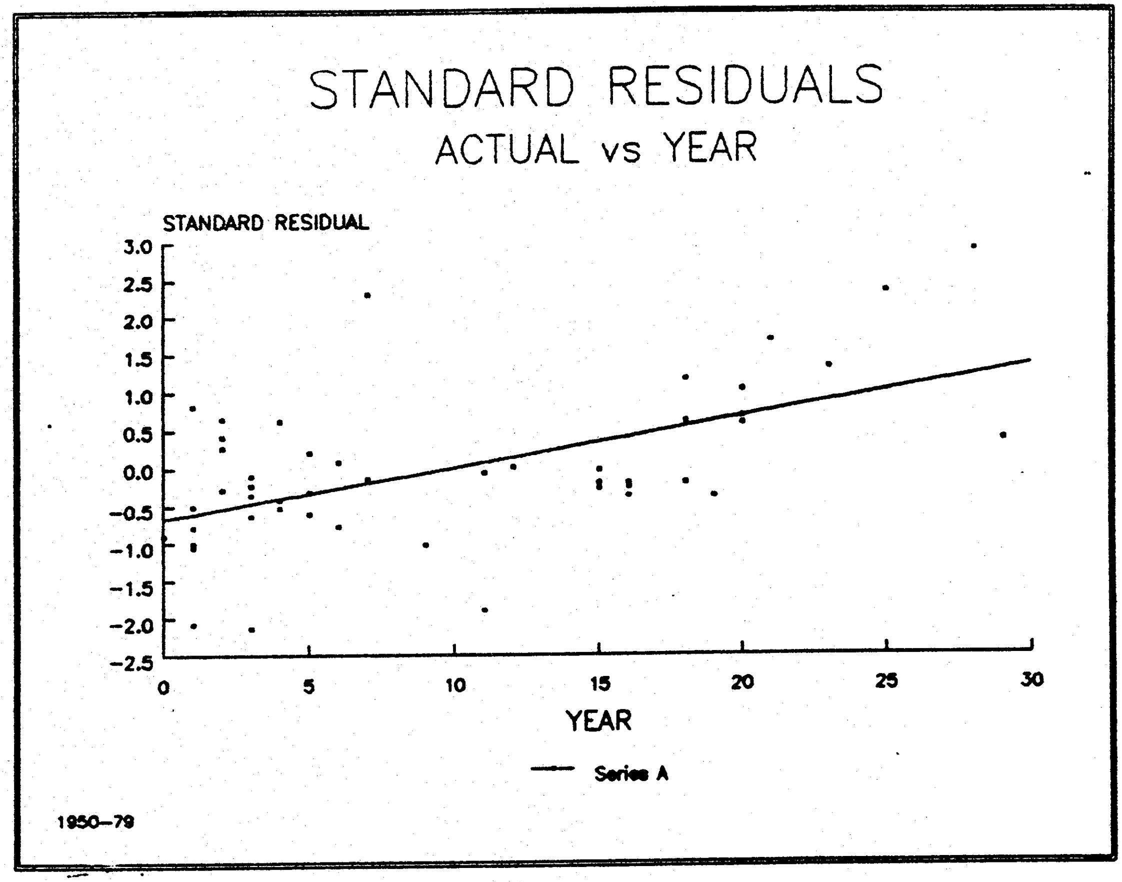

Figure 5-2 Plot of Standard Residuals vs Year

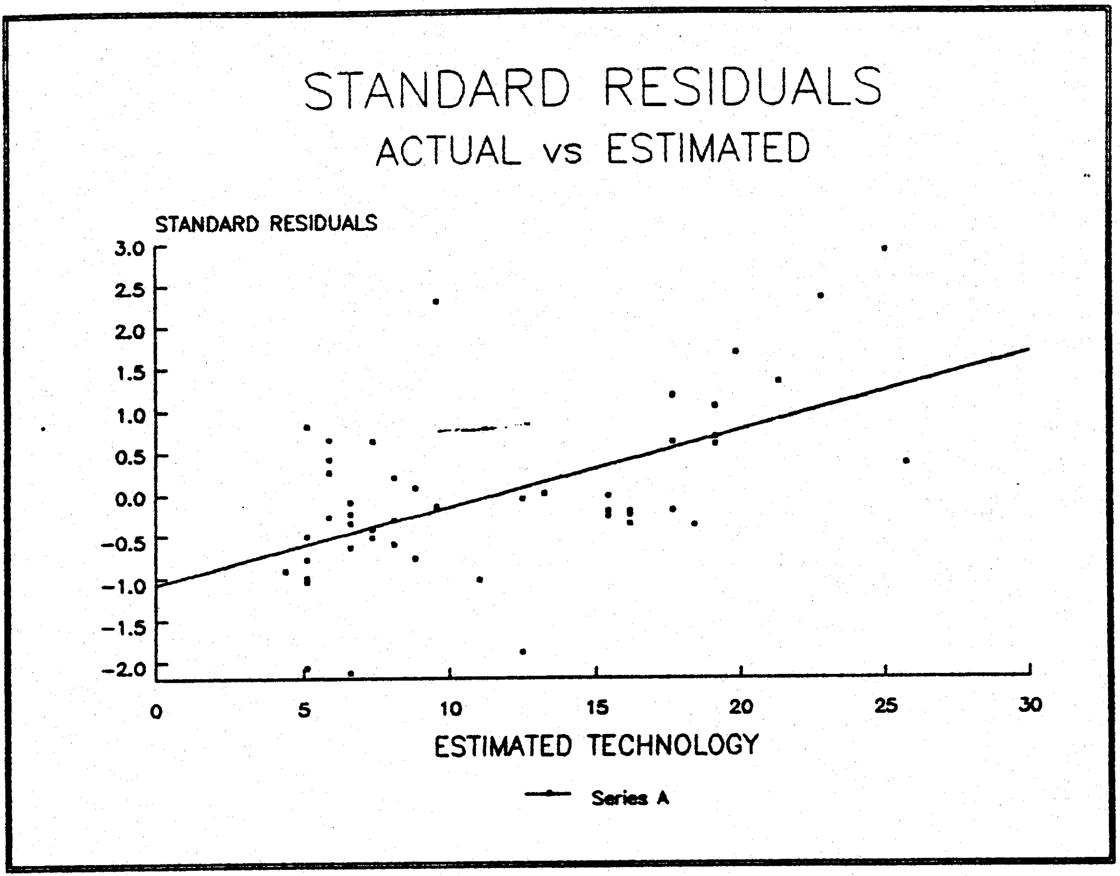

Figure 5-3 Plot of Standard Residuals vs Fitted Technology Indices

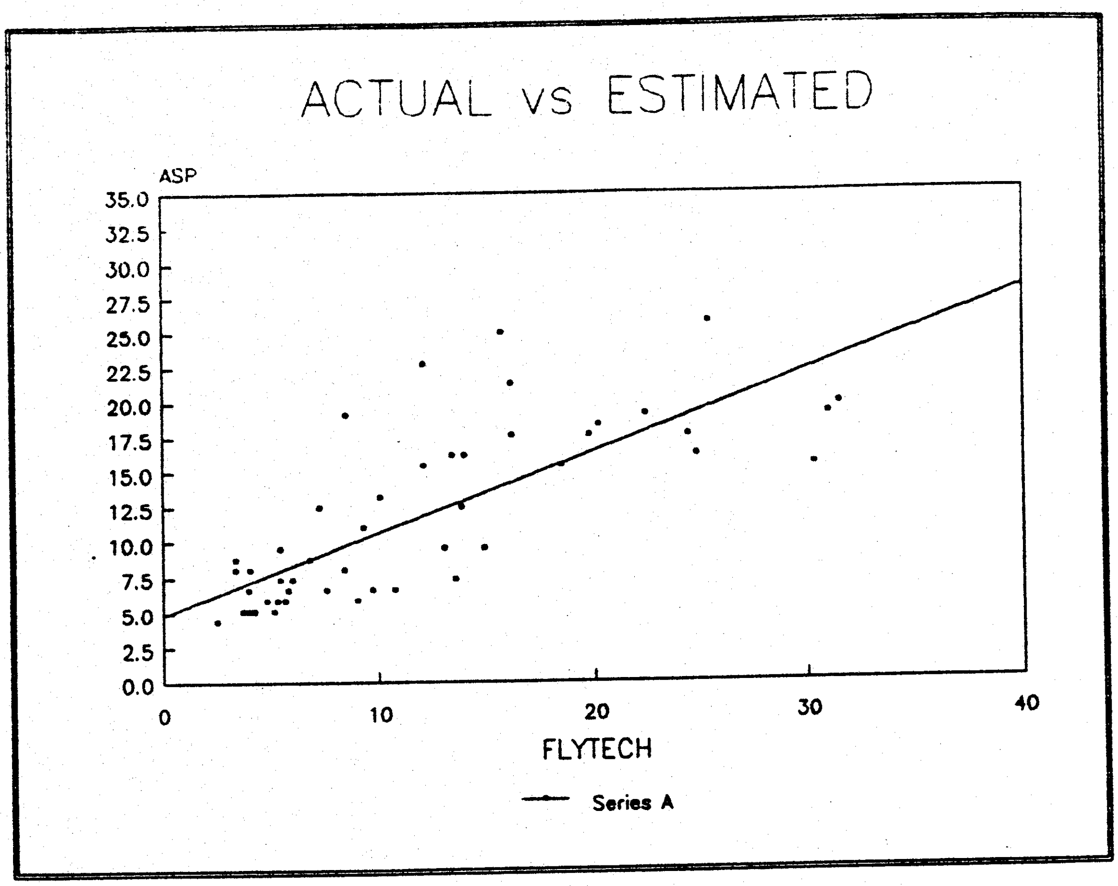

Figure 5-4 Plot of Actual Versus Estimated Technology Values

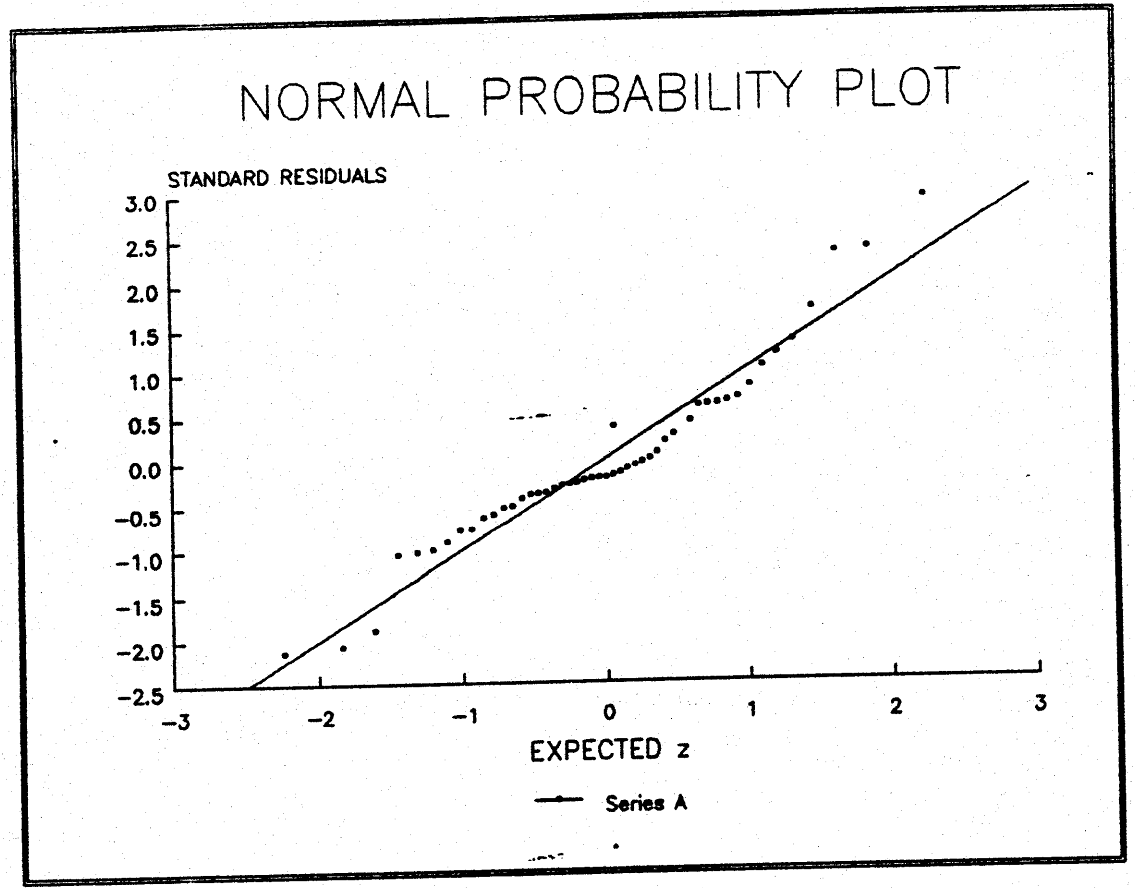

Figure 5-5 Plot of Normal Probability vs Standard Residuals

Following a method suggested by Montgomery [Ref. 66], a check was made of the standardized residuals to determine if there is a significant difference in the behavior of the positive residuals as compared to the negative residuals. An F-test with 19 and 30 degrees of freedom was constructed as follows: The the sum of the variances for the 19 positive residuals was divided by the sum of the 30 negative residual values. The null hypothesis was that this ratio should be equal to one:

H_0: $\frac{s^2(i+)}{s^2(i-)} = 1$ where $s^2(i+)$ are positive residuals and $s^2(i-)$ are negative residuals

H_1: $\frac{s^2(i+)}{s^2(i-)} /= 1$

The results are provided in Table 5-3.

ANALYSIS OF VARIANCE RESULTS
TABLE 5-3

$s^2(i+) = 29.1547$ $s^2(i-) = 20.3376$

$\frac{s^2(i+)}{s^2(i-)} = 1.43354$

$F = 1.43354$ $p = 0.184$

The test result indicates that the sums of the respective variances are the same at the $p = 0.184$ level. The differences in the sums of the respective variances be partially explained by the large effect of the F-14A and F-111F technology indices. These values in particular are greater than two standard deviations away from the expected technology value for the year of IOC.

5. Technical Advance

Obtaining the services of a technology that performs better than the state of the art is an essential driver in the DoD acquisition process. Not only does this provide a potentially large quantitative edge over likely competitor systems at the time of IOC, it also tends to lengthen the use life of the system, in the presence of steadily progressing technological performance.

An estimate of technology performance value different from the state of the art, for a given year, can be obtained by taking the difference between the actual and estimated technology values:

$$\text{ADVANCE} = \text{FLYTECH} - \text{SOA},$$

where "FLYTECH" is the TASCFORM$^{\text{TM}}$ composite technology index and "SOA" is the state-of-the-art technology index based upon year of IOC estimated by the regression equation. A positive Advance Value indicates a system that possessed better than state of the art technology, while a negative value indicates a system that was below the SOA at time of IOC. The more positive the Advance Value, the greater the system's qualitative edge over systems that are state-of-the-art. Table 5-4 provides a listing of Advance Values by aircraft designator.

TECHNOLOGY VALUES: MEASURED VERSUS ESTIMATED
TABLE 5-4

AIRCRAFT	IOC YEAR (1950-79)	TASCFORM COMPOSITE INDEX	CALCULATED INDEX	ADVANCE
F-89C	50	2.46	4.35	-1.89
F-9F/H	51	4.19	5.09	-0.90
F-89A	51	4.05	5.09	-1.04
F-84F	51	5.13	5.09	0.04
F-86F	51	4.03	5.09	-1.06
F-86D	51	3.68	5.09	-1.41
F-2C	51	3.91	5.09	-1.18
F-3A/B/C	52	9.02	5.82	3.20
F-1B/C/M	52	5.29	5.82	-0.53
F-86H	52	5.68	5.82	-0.14
F-100A/C	52	4.80	5.82	-1.02
F-11A	53	5.80	6.56	-0.76
A-3A/B	53	10.74	6.56	4.18
F-102A	53	9.71	6.56	3.15
F-6A	53	7.58	6.56	1.02
A-4A/B	53	3.93	6.56	-2.63
F-1E	54	5.44	7.30	-1.86
F-101A/B	54	13.55	7.30	6.25
F-100D	54	5.99	7.30	-1.31
F-8A/B/C	55	8.40	8.03	0.37
A-1J	55	3.34	8.03	-4.69
F-9F	55	4.02	8.03	-4.01
A-1E/G/H	56	3.34	8.77	-5.43
F-104A/B	56	6.79	8.77	-1.98
F-106A/B	57	13.05	9.51	3.54
F-105B/D	57	14.86	9.51	5.35
A-4C	57	5.45	9.51	-4.06
F-4A/B	59	9.32	10.98	-1.66
A-6A	61	13.83	12.46	1.37
A-4E/F	61	7.27	12.46	-5.19
F-4C/D	62	10.07	13.19	-3.12
P-3C	65	30.33	15.41	14.93
A-7A/B	65	12.10	15.41	-3.31
F-111A	65	18.46	15.41	3.06
F-4E	66	13.96	16.14	-2.18
F-111B	66	24.81	16.14	8.67
F-4J	66	13.39	16.14	-2.75

TECHNOLOGY VALUES: MEASURED VERSUS ESTIMATED
TABLE 5-4

AIRCRAFT	IOC YEAR (1950-79)	TASCFORM COMPOSITE INDEX	CALCULATED INDEX	ADVANCE
A-7E	68	19.77	17.62	2.15
A-7D	68	16.17	17.62	-1.45
F-111D	68	24.39	17.62	6.77
S-3A	69	20.21	18.35	1.86
F-111F	70	31.01	19.09	11.92
A-4M	70	8.52	19.09	-10.57
A-6E	70	22.40	19.09	3.31
F-14A	71	31.51	19.83	11.68
F-15A	73	16.14	21.30	-5.16
A-10A	75	12.12	22.78	-10.66
F-16A	78	15.69	24.99	-9.30
F/A-18A	79	25.42	25.72	-0.30

The Advance Value is calculated to provide a comparative technology value in determining the technology utility function. It is not the absolute measure of the index that is important, but rather the comparative difference between alternatives and likely competitors as viewed over time that provides a more meaningful measure of a system's technical advantages. An example of the value of a relatively large Advance Value can be seen in the TASCFORM™ F-14A performance value compared with "SOA" at time of IOC.

The 11.68 1971 IOC Advance Value is greater than two standard deviations above the regression estimate. The state-of-the-art did not achieve this value until approximately 1987. The attainment of this Advance Value provided for exceptional platform longevity. On the other hand, the A-6E was characterized by an Advance Value of only 3.31 at the 1971 IOC, necessitating efforts in the early 1980s to obtain a successor system .

E. TECHNICAL RISK AND UTILITY DETERMINATION

The Advance Value information generated by the regression equation can now be combined with the Certainty Equivalent utility assessment technique, described above, to create a utility function that incorporates the decision maker's risk perception. The necessary steps are presented below.

1. Functional Limits

Functional limits define the interval on which the utility function will operate. These are necessarily judgemental, but can be specified. The functional limits define the space in which the design engineers will work to create a system that meets military mission needs. The maximum value is scaled as a utility value of one and the minimum acceptable value is assigned a utility value of zero.

2. Utility Elicitation

The proposed method uses the certainty equivalence technique, posed in the form of an "insurance" premium, and nests the responses working inward from the functional limits. Initial minimum and maximum values are determined from the DoD Mission Needs statement as discussed in Chapter IV. This document reflects the requirements of Unified and Specified Commanders, Military Departments, the Office of the Secretary of Defense, or the Joint Staff to meet national military objectives and or counter current threat capabilities [Ref. 12]. These values reflect the desired and minimum performance requirements any candidate system must possess to meet the requirements of the entities listed above. Subsequent interval endpoints are obtained during the utility elicitation process.

a. Certainty Equivalence

A certainty equivalence form, with probability equal to 0.5, is appropriate in this case. The sample Advance Value distribution appears to have a symmetric, normal shape [Refs. 17, 27]. This approach also abides by the requirement that the certainty equivalent, Z, lie within the interval $X < Z < Y$, where X is the functional minimum and Y the functional maximum for the interval under consideration.

b. Functional Limit Determination

Based upon the analysis of mission needs and estimated performance of likely competitor systems, the initial minimum acceptable Advance Value for the projected year of IOC can be specified from the TASCFORM™ process and the SOA regression calculations. The functional maximum can be similarly determined from the regression results using either a plus three standard deviation value from the regression estimated SOA or some increment to immediate predecessor technology performance. Subsequent subintervals will result from the iterative utility assignment process.

3. Example

Figure 5-6 shows a representative plot of U.S., series A, and Soviet tactical air, series B, performance indices derived from the TASCFORM™ method as a function of time. As can be seen, U.S. platforms enjoyed an average advantage of about four index units when compared with competitor Soviet platforms. Soviet technical capabilities are used for comparison purposes as these represent systems widely used throughout the world and pose a significant military challenge to U.S. forces even if not actually employed by Soviet forces.

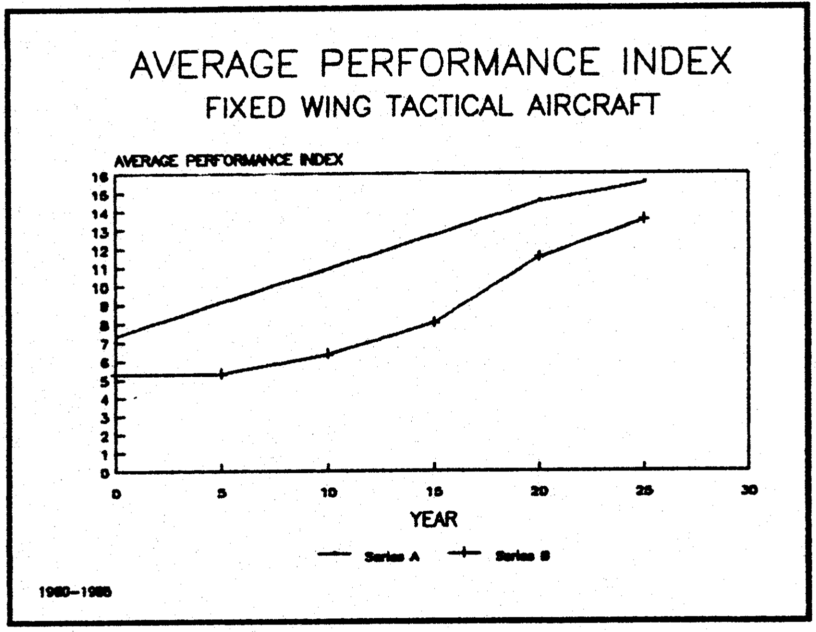

Figure 5-6 U.S. and Soviet Technology Indices Over Time

The following is an example of how the proposed utility assessment process would work. The utilities assigned to the various technology performance values are those of this researcher.

a. Functional Limit Determination

Suppose the overall force structure requires that any new air combat system possesses a minimum technical performance value of at least 2.5 index units above an anticipated Soviet competitor at time of IOC. The resultant performance index specifies the utility minimum and is assigned a value of zero. For this example, the minimum Advance Value will be specified as -4. The initial functional Advance Value maximum will be specified at 16. This value is assigned a utility value of one.

b. Certainty Equivalence Assessment

The initial prospect is framed in the following manner:

A. Obtain a platform with an Advance Value of 16 with probability of 0.50

B. Obtain a platform with Advance Value of -4 with probability of 0.50

The expected value of this prospect has an Advance Value of 6.

C. Specify the Advance value you would accept to protect against obtaining a system with an Advance Value of -4.

The answer to C provides the Advance Value corresponding to a utility value of 0.5. The two new sub-intervals, (C, 16) and (-4, C), are subsequently decomposed into their respective utility values by means of the nesting technique discussed previously. Examples of possible results are presented in Table 5-5 and Figure 5-7.

TECHNOLOGY UTILITY ASSESSMENT EXAMPLE
TABLE 5-5

ADVANCE	U(ADVANCE)
-4.00	0.00
0.00	0.125
2.00	0.25
4.00	0.50
8.00	0.75
14.00	0.875
16.00	1.00

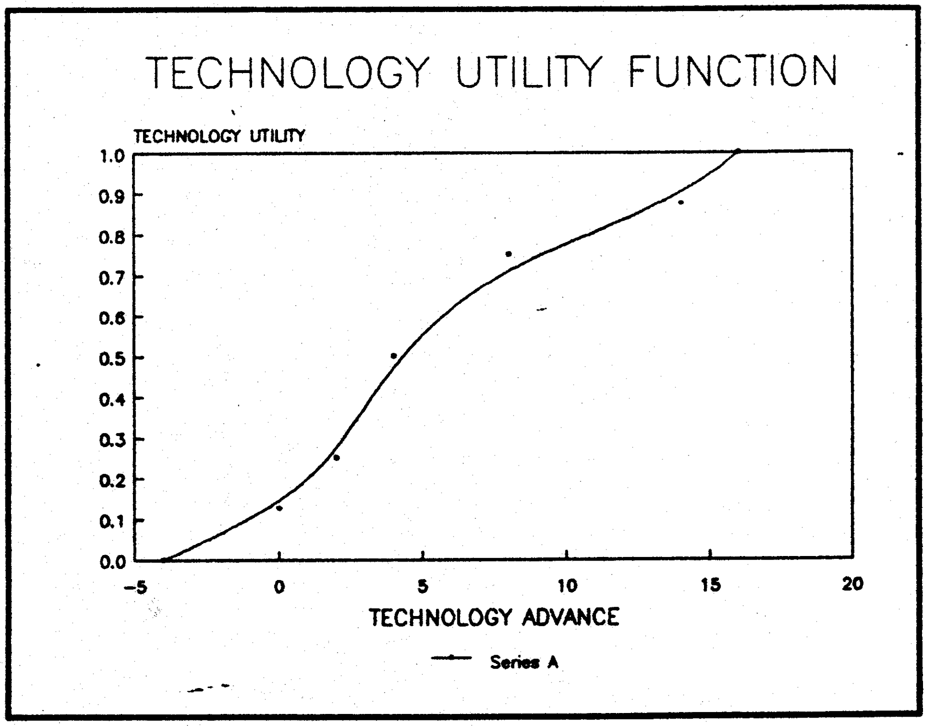

Figure 5-7 Example Utility Determinatoin

c. Analysis

The utility curve in Figure 5-7 displays risk-seeking behavior on the interval (-4, 4), risk averse behavior over the interval (4, 10), and risk-seeking on the interval (10, 16). The results are consistent, in general, with the axioms of Utility Theory, as there is no requirement to display a constant risk behavior. The combination of risk behaviors over the sub-interval precludes recourse to Mean - Variance analysis. The next step in the analysis would be to closely examine the results, particularly in the region of inflection points, to ensure that they truly reflect the decision maker's preferences and sensitivities.

4. Utility Function Application

Once the function has been determined and the decision maker is confident that it captures his preferences, probabilities determined from the regression can applied. The resultant Expected Utility can then be used to select candidate system technologies for goal accomplishment. Each candidate would possess some Advance Value whose likelihood of success can be ascertained by the use of the normal probability distribution associated with the SOA regression. Given a particular Advance Value, the probability of achieving that value or greater can be directly calculated. This probability, when multiplied by the corresponding utility value, gives an Expected Utility value (EU), which can be subsequently ranked against other candidates.

F. UTILITY FUNCTION ALTERNATIVE

Although the Utility Function approach presented above will capture the individual decision maker's risk perceptions, it does require careful iteration. Individual sensitivities in regions of curvature changes must be thoroughly examined. An additional consideration is the organizational environment in which the acquisition decision is made. An alternative approach is to employ the Extended Pearson-Tukey (EP-T) method.

1. The Extended Pearson-Tukey (EP-T) Method

The EP-T method, as described by Goodwin and Wright, [Ref. 27] has been found useful in a variety of continuous distribution cases. It breaks the ranking scale into three segments, high, medium, and low. The three categories requiring decision maker estimation correspond to:

a. Value which has a 95% chance of being exceeded (Low). This value is assigned a probability of 0.185.

b. Value which has a 50% chance of being exceeded (Medium). This is assigned a probability of 0.63.

c. Value which has only a 5% chance of being exceeded (High). This is assigned a probability of 0.185.

The probabilities reflect the symmetrical nature of the implied distribution and sum to one. The specific values in this case can be obtained by analyzing the regression results in terms of the normal distribution of Advance Values.

a. Example

Using the results of the regression analysis, a possible risk-assessment approach using the EP-T method would be conducted as follows: Since the residuals appear to belong to a normal distribution, z-values for the respective 0.95, 0.5, and 0.05 technology values can be obtained from a standard normal table. The standard deviation value of 5.288, obtained from the regression, is then used to arrive at specific technology values. The results are summarized in Table 5-6.

EP-T METHOD EXAMPLE
TABLE 5-6

% Chance of Exceeding	z-value	Advance Value	Risk
95	-1.645	-8.6	Low
50	0	0	Medium
05	1.645	8.6	High

As can be seen from Table 5-4, 30 of the 49 aircraft in the sample would be considered low risk, 15 would rank as medium risk, and four would be high risk cases. Expected Value (EV) methods, discussed in Chapter II, are then applied to select the candidate systems which provide the highest EV. This may provide a faster solution to the problem. The disadvantage lies within the probabilities assigned to the three levels. As pointed out in the discussion of Utility Theory, risk perception is intrinsically personal. While organizationally, critical probability levels can be assigned by fiat, these may tend to represent the perceptions of senior personnel, not the entire organization.

G. SUMMARY

This chapter began by highlighting some of the concerns and problems associated with obtaining the probability values necessary for the Utility Assessment approach. Recourse to expert opinion was shown to be inadequate for this task. The four basic methods of Utility Assessment, Probability Equivalence, Gain Equivalence, Loss Equivalence, and Certainty Equivalence, were discussed and their respective strengths and weaknesses noted. Two major factors affecting technical risk, realized technical value and obsolescence, were explained. A means of measuring technology on an ordinal scale was introduced. The TASCFORM™ technology valuation model was presented and discussed as a means of measuring technology for subsequent utility assessment determination. A regression model of technology over time was constructed using TASCFORM™ values for a sample of 49 U.S. Navy and Air Force aircraft spanning the period 1950-1979. The purpose of this model was twofold: To obtain a probability distribution that characterized the attainment of technology values unaffected by the individual biases described by Tversky and Kahnemann, and to obtain a measure of technological advantage, an "Advance Value", that could be used to construct an utility function for varying technology values. An Utility Assessment technique, using Certainty Equivalence, was proposed and an example of a possible risk-assessment scenario was put forward. The notion of Expected Utility using the probabilities determined from the regression model was discussed. An alternative means of risk assessment, the Extended Pearson-Tukey method, was discussed, and the example reworked using this approach. Problems associated with both methods were discussed.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Technology can be valued and measured using an ordinal scale.

The technological characteristics of a weapon system can be assigned numerical values in a coherent fashion. These values can be subsequently used to order alternative systems from most capable to least capable. The numerical differences between alternatives can provide an indication of how much better one alternative is than another.

2. The increase in technological state-of-the-art over time can be explained by a linear regression as a first approximation.

As organizations become more familiar with technological requirements and capabilities, the technological value of new systems increases over time. This value can be split into state-of-the-art and technological advance components. The projected state-of-the-art can be estimated via a linear regression. Technological advance represents capability over and above the state-of-the-art at the time the system is fielded.

3. **The probability of achieving a particular level of technological value can be estimated.**

The probability distribution characterizing the regression residuals can be used to estimate the likelihood of achieving a particular technological value at a specific moment in time. This removes a serious problem in risk assessment: estimating the probability of obtaining a certain level of technical performance. Expert judgement can be focused on determining the technical requirements of a system and valuing the technology inherent in a new weapons system.

4. **Utility functions for technology can be created.**

A utility function for technology values characterizing a range of system alternatives can be created, representing the risk preference behavior of an individual. The utility function can be found using the Certainty Equivalent method for technology valuation systems possessing symmetrically distributed residuals.

5. **The Extended Pearson-Tukey (EP-T) method can be applied to determine the risk inherent in a range of alternatives.**

The EP-T method can be applied to technology valuation systems possessing symmetrically distributed residuals. This approach, while less sensitive to individual risk preferences, is much faster and lends itself to conventional Expected Value comparisons between competing options.

B. RECOMMENDATIONS

1. **The Department of Defense should continue exploring the utility of TASCFORM™-like technology valuation methods for technical risk assessment.**

This would focus expert knowledge on areas of value, which would be more amenable to expert judgement. and avoid estimating probabilities by human judgement. Probabilities can be analytically determined for those cases where a linear regression approximates the growth of technological value over time.

2. **DoD should investigate the application of the Extended Pearson-Tukey (EP-T) method for characterizing technical risk via a pilot program approach.**

While the generation of individual technology utility functions can represent an individual's risk perception and risk seeking behavior, a Utility Theory approach may be too cumbersome to employ in a complex organization. The EP-T method is simpler and faster to use. It lends itself to those applications where the probability distribution governing some process is symmetrical. It has the added advantage of supporting traditional Expected Value analyses.

C. AREAS FOR FURTHER RESEARCH

1. Investigate the potential dichotomies between the Program Manager's (PM) perception of technical risk and those of the Defense Acquisition Board (DAB).

As documented in this thesis, risk perception is a specifically individual characteristic. The technical risk inherent in a new system acquisition project may be perceived differently by the DAB, the PM, and various supporting staffs.

2. Investigate ordinal technology valuation schemes applicable for all military systems.

A family of technology valuation schemes using ordinal scales would allow for explicit quantitative comparison. Such a device would allow senior management to conduct technologically based comparisons between U.S. and potentially hostile forces.

3. Investigate methods of conducting Department of Defense-wide risk portfolio management.

Methods for pooling individual quantitative project technical risk assessment information into a central portfolio should be explored. Techniques for managing the overall DoD technical risk position should be investigated. This could provide senior decision makers with a more useful risk indicator of DoD's exposure to technical risk. It would also provide quantitative data on which to base coherent departmental risk seeking or risk avoiding actions.

APPENDIX A
TECHNOLOGY REGRESSION DATA

AIRCRAFT	IOC YEAR	TASCFORM COMPOSITE INDEX	CALCULATED STATE-OF-THE ART
F-89C	50	2.46	4.35
F-9F/H	51	4.19	5.09
F-89A	51	4.05	5.09
F-84F	51	5.13	5.09
F-86F	51	4.03	5.09
F-86D	51	3.68	5.09
F-2C	51	3.91	5.09
F-3A/B/C	52	9.02	5.82
F-1B/C/M	52	5.29	5.82
F-86H	52	5.68	5.82
F-100A/C	52	4.80	5.82
F-11A	53	5.80	6.56
A-3A/B	53	10.74	6.56
F-102A	53	9.71	6.56
F-6A	53	7.58	6.56
A-4A/B	53	3.93	6.56
F-1E	54	5.44	7.30
F-101A/B	54	13.55	7.30
F-100D	54	5.99	7.30
F-8A/B/C	55	8.40	8.03
A-1J	55	3.34	8.03
F-9F	55	4.02	8.03
A-1E/G/H	56	3.34	8.77
F-104A/B	56	6.79	8.77
F-106A/B	57	13.05	9.51
F-105B/D	57	14.86	9.51
A-4C	57	5.45	9.51
F-4A/B	59	9.32	10.98
A-6A	61	13.83	12.46
A-4E/F	61	7.27	12.46
F-4C/D	62	10.07	13.19
P-3C	65	30.33	15.41
A-7A/B	65	12.10	15.41
F-111A	65	18.46	15.41
F-4E	66	13.96	16.14
F-111B	66	24.81	16.14
F-4J	66	13.39	16.14
A-7E	68	19.77	17.62
A-7D	68	16.17	17.62
F-111D	68	24.39	17.62
S-3A	69	20.21	18.35
F-111F	70	31.01	19.09
A-4M	70	8.52	19.09
A-6E	70	22.40	19.09

APPENDIX A

TECHNOLOGY REGRESSION DATA

AIRCRAFT	IOC YEAR	TASCFORM COMPOSITE INDEX	CALCULATED STATE-OF-THE ART
F-14A	71	31.51	19.83
F-15A	73	16.14	21.30
A-10A	75	12.12	22.78
F-16A	78	15.69	24.99
F/A-18A	79	25.42	25.72

APPENDIX A

TECHNOLOGY REGRESSION DATA

AIRCRAFT	IOC YEAR	ADVANCE	STANDARD RESIDUALS	NORMAL PROBABILITY VALUES
F-89C	50	-1.89	-0.91478	-1.10394
F-9F/H	51	-0.90	-1.05636	-1.45013
F-89A	51	-1.04	0.80981	1.01428
F-84F	51	0.04	-0.78958	-1.01428
F-86F	51	-1.06	-2.08095	-1.84145
F-86D	51	-1.41	-0.51618	-0.65252
F-2C	51	-1.18	-1.00697	-1.20356
F-3A/B/C	52	3.20	0.26118	0.47355
F-1B/C/M	52	-0.53	0.64542	0.85598
F-86H	52	-0.14	-0.28700	-0.30897
F-100A/C	52	-1.02	0.41603	0.59076
F-11A	53	-0.76	-0.64585	-0.85598
A-3A/B	53	4.18	-2.14163	-2.23702
F-102A	53	3.15	-0.10807	0.15261
F-6A	53	1.02	-0.36498	-0.41745
A-4A/B	53	-2.63	-0.23414	-0.15264
F-1E	54	-1.86	0.61989	0.78453
F-101A/B	54	6.25	-0.42871	-0.59076
F-100D	54	-1.31	-0.53953	-0.71693
F-8A/B/C	55	0.37	-0.32561	-0.36267
A-1J	55	-4.69	-0.60852	-0.78453
F-9F	55	-4.01	0.19452	0.41745
A-1E/G/H	56	-5.43	0.06684	0.36267
F-104A/B	56	-1.98	-0.78286	-0.93217
F-106A/B	57	3.54	-0.17934	0.05069
F-105B/D	57	5.35	-0.15207	0.10151
A-4C	57	-4.06	2.29787	1.61546
F-4A/B	59	-1.66	-1.03021	-1.31686
A-6A	61	1.37	-1.90119	-1.61546
A-4E/F	61	-5.19	-0.06761	0.20411
F-4C/D	62	-3.12	0.00460	0.30897
P-3C	65	14.93	-0.27914	-0.25618
A-7A/B	65	-3.31	-0.21065	-0.10151
F-111A	65	-3.06	-0.03196	0.25618
F-4E	66	-2.18	-0.37473	-0.47355
F-111B	66	8.67	-0.20674	-0.05069
F-4J	66	-2.75	-0.25810	-0.20411
A-7E	68	2.15	-0.20370	0.00000
A-7D	68	-1.45	1.17210	1.20356
F-111D	68	6.77	0.60925	0.71693
S-3A	69	1.86	-0.38799	-0.53122
F-111F	70	11.92	1.03150	1.10394
A-4M	70	-10.57	0.68122	0.93217
A-6E	70	3.31	0.58843	0.65252
F-14A	71	11.68	1.68065	1.45013

APPENDIX A

TECHNOLOGY REGRESSION DATA

AIRCRAFT	IOC YEAR	ADVANCE	STANDARD RESIDUALS	NORMAL PROBABILITY VALUES
F-15A	73	-5.16	1.31825	1.31686
A-10A	75	-10.66	2.33663	1.84145
F-16A	78	-9.30	2.89203	2.23702
F/A-18A	79	-0.30	0.35896	0.53122

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