AFIT/GOR/ENS/99M-18

TECHNOLOGY SELECTION FOR THE AIR FORCE RESEARCH LABORATORY AIR VEHICLES DIRECTORATE: AN ANALYSIS USING VALUE FOCUSED THINKING

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Abstract

A technology selection model was developed for the Air Vehicles Directorate of Air Force Research Laboratory. The model was developed and demonstrated to aid in addressing the question of what technologies Air Vehicles' should invest in to remain consistent with Air Force values. Both Value-Focused Thinking and optimization approaches were used to identify the value of Air Vehicles' technology, to provide insights to Air Vehicles' decision-makers, to determine where value gaps might exist with the scored alternatives, and to determine how sensitive the model was to changes. As a demonstration of the approach, seven technologies were scored, representing all three of the Air Vehicles' Integrated Concepts. In the process, the support to the warfighter due to technological change was quantified and analyzed.

TECHNOLOGY SELECTION FOR THE AIR FORCE RESEARCH LABORATORY AIR VEHICLES DIRECTORATE: AN ANALYSIS USING VALUE FOCUSED THINKING

Chapter 1: Introduction

Background

Organizations that perform research and development (R&D) are required to justify their investments. In this era of decreasing government budgets, increasing global competition and decreasing technological life, proper selection of R&D projects is ever more critical. Decision makers must show R&D adds value in support of a larger mission (or show an improvement of shareholder wealth in the case of private industry). This is particularly true for the public sector organizations, such as the Department of Defense (DoD). Failure to show value added can result in funding cuts and the potential dismantling of the R&D organization. In the short term, an organization's technological position may not suffer. In the long term, however, failure to perform R&D will result in obsolescence of weapons in the DoD. In the private sector, poor R&D can prevent industry from competing successfully with other commercial firms. This thesis proposes and demonstrates a methodology for the Air Vehicles Directorate (VA) of the Air Force Research Laboratory (AFRL) to construct the most valuable portfolio of programs to meet future United States Air Force (USAF) warfighting requirements. Further, it establishes a value measure for the proposed VA current and future projects.

In Aug 98, the Air Vehicles Directorate requested the Air Force Institute of Technology's (AFIT) help to analyze the following questions:

> "What direction in technology R&D should the Air Vehicle Directorate take to be most consistent with Air Force values?"

The question of what to invest in is not new. For example, the Flight Dynamics Laboratory (a precursor to the Air Vehicles Directorate) was posing a similar question about aeronautics programs over 30 years ago (Nutt, A.B. 1965:103-112). The question being asked now is analogous to the questions asked then. However, today's emphasis on "aerospace" rather than just aeronautics implies both aeronautical projects and space projects.

Determining which technologies to pursue given a large number of possible investments can be both difficult and bewildering without a systematic process of evaluation. If it were possible to know the future with certainty, it would be a much more straightforward matter to structure technology programs to meet DoD mission needs. However, not only is there uncertainty about future needs, there is also uncertainty about whether a particular technology can and will even be developed.

In the DoD, deciding what is valuable about a particular R&D program is more difficult than in industry. In the commercial world, R&D is generally performed with a profit motive in mind, which at least can be estimated via market research concepts and analysis. In the DoD, a valuable weapon is one that helps to win or to deter war. In the DoD, R&D supports current and future warfighting missions, a difficult element to predict. The consequences of poor R&D can be much higher than the failure of a business. As devastating as the loss of a business might be, the loss of national sovereignty is much more serious. The most effective measure of a successful R&D program for a nation takes place after the technology is tested in battle, where loss of life, territory, or national sovereignty are the possible price of poor decision making.

In *Technology and War,* van Creveld's states "that war is completely permeated by technology and governed by it" (van Creveld, Martin 1989: 1). A second rate R&D program is measured directly in lives lost and, ultimately, in the rise and fall of nations. The introduction of *1997 Defense Technology Area Plan* states the United States cannot afford to find out its technology is second best by losing a military engagement:

> Technological superiority has been, and continues to be, a cornerstone of our national military strategy. Technologies such as radar, jet engines, nuclear weapons, night vision, smart weapons, stealth, the Global Positioning System, and vastly more capable information management systems have changed warfare dramatically. Today's technological edge allows us to prevail across the broad spectrum of conflict decisively and with relatively low casualties. Maintaining this technological edge has become even more important as the size of U.S. forces decreases and high-technology weapons are now readily available on the world market. In this new environment, it is imperative that U.S. forces possess technological superiority to achieve and maintain the dominance displayed in Operation Desert Storm. The technological advantage we enjoy today is a legacy of decades of investment in science and technology (S&T). Likewise, our future warfighting capabilities will be substantially determined by today's investment in S&T (The Military Critical Technologies List. *1997 Defense Technology Area Plan,* 1997: Introduction*).*

Predicting effectiveness for a technology, which has not yet been invented, against an unknown enemy, for an unknown battle, in an unknown environment is a daunting task. Yet, it is necessary to plan for an uncertain future.

Purpose

R&D investment in the DoD must effectively provide the warfighter the right technology. The AFRL, with its ten Directorates, is the organization that oversees and performs R&D for the United States Air Force warfighters. The purpose of this thesis is to develop a method to analyze future technology selections for the Air Vehicles Directorate. Further, the analysis method must identify technology alternatives that are consistent with choices the VA decision-makers believe are critical "to keep our Air

Force the best in the world" (*AFRL Mission*, 1998). It must be possible to identify technology alternatives in a documented and traceable fashion and propose a means to overcome shortfalls in the decision-maker's values and objectives. The technology programs proposed must also be linked to investments to provide VA the means to implement the decision-maker's values.

Scope

The Air Vehicles' Director determined the study should start with 1999 and look 10 years into the future. Various technology programs make up the possible alternatives VA may choose to support in a limited funding environment. The ultimate goal of this research effort is to help all ten directorates of the AFRL. In view of the available resources to conduct the study, however, the Air Vehicles analysis was performed to serve as a framework for a larger AFRL future effort. At the same time, it will help Air Vehicles to select the best technologies for their Directorate.

The study was limited to deterministic evaluation of the programs. It is understood that predictions about technology will be uncertain. One reason for the limitation was consideration of available resources for this effort. The second reason was that it is important to first determine what the critical uncertainties are before implementing uncertainty techniques in the model. If uncertainty is too small, it may have no effect on the modeling results and might be wasting the valuable time of decision-makers and other technical experts in Air Vehicles during elicitation of information. Clearly, only those variables that have large uncertainty (as identified by sensitivity analysis) should be considered for analysis under uncertainty.

Values (what is important to VA about choosing a technology program) are used in a value model to quantify how well the alternatives support the Air Force warfighter. The result of quantifying programs allows VA to identify the "best" programs for investment. It also allows "what if" testing or determination of how robust a particular decision policy is using sensitivity analysis. Finally, shortfalls in the overall VA portfolio (defined as low scoring alternatives or values with no alternatives to satisfy them) can be uncovered and dealt with. These insights will be provided to the Air Vehicle's decision-makers to aid them in selecting technology program investments.

Summary and Organization

Chapter 2 documents theoretical considerations from the literature for the project. It begins by identifying the dimensions of R&D and those peculiar to the military and Air Vehicles. Next, technology selection models are discussed and some examples of multidimensional models are discussed. Afterward, in-depth discussion is provided on value focused thinking and resource allocation as it applies to R&D. The chapter wraps up with a discussion of the characteristics of past R&D models and identifies limitations of these models.

Chapter 3 applies the results found in the Chapter 2 literature review. First, an overview of development of a model capable of selecting technology for Air Vehicles is presented. Next, detail discussion is provided on developing a value hierarchy and a value model. In the process, some issues peculiar to modeling R&D are discussed. With the value model completed, assumptions for the model are explained. Then, using the value model to score alternatives is explained. The chapter wraps up by discussing methods of evaluating the modeling results.

Chapter 4 shows results of an illustrative analysis on a subset of Air Vehicles' programs while Chapter 5 concludes the effort. Several appendices provide more detailed information of key areas in the thesis and are cited in appropriate places throughout this document.

Chapter 2: Literature Review

Introduction

Biondi and Galli argue that innovation in technology is caused by the efforts of people. If innovation has no causality, there is no basis for technology forecasting. (Biondi and Galli, 1992: 580). In this chapter, the literature is reviewed to determine what dimensions make up aerospace research and development. The literature is first used to define science and technology. It is used to identify basic research, applied research and development research. Next, dimensions for basic research, applied/development research, and all three types of research are identified. A model for technological change is discussed and then technological dimensions specific to aeronautics, astronautics and the military are discussed.

Having discussed dimensions of aerospace R&D, technology selection models are reviewed and some examples of multidimensional scoring studies are provided. The discussion is followed by an in-depth review of Value-Focused Thinking and resource allocation models. The review is completed by examining characteristics and limitations of R&D technology selection models.

Aerospace Research and Development (R&D)

Definitions

Science can be defined as acquiring of " . . . general, fundamental and abstract forms of knowledge" (Organization for Economic Co-operation and Development, 1992: 16). The objective of basic scientific research, is to gain knowledge that is more comprehensive or to gain understanding of the subject under study, without specific applications in mind. In industry, basic research is defined as research that advances scientific knowledge but does not have specific, immediate commercial objectives, although it may be in fields of present or potential commercial interest (National Science Foundation, *Science & Engineering Indicators - 1996, NSF 96-21*, 1996).

Basic research is rarely valuable by itself, but requires linkage to developments in technology (Pavitt, 1991: 112). According to van Creveld, "technology is perhaps best understood as an abstract system of knowledge, an attitude towards life and a method for solving its problems" (van Creveld, 1989: 312). The Organization for Economic Co-operation and Development observes technology is " . . . specific and practical," and "requires the development of a number of 'transfer sciences' situated at the interface between basic knowledge and the solution of concrete problems arising from economic and social needs" (Organization for Economic Co-operation and Development, 1992: 16). A link exists between science and technology in that technology builds on what science has discovered and it applies advances in science to solve human problems.

The National Science Foundation defines two types of technology development. Applied research is aimed at gaining knowledge or understanding to determine the means by which a specific, recognized need may be met. In industry, applied research includes investigations oriented toward discovering new scientific knowledge that has specific commercial objectives with respect to products, processes, or services. Development research is the systematic use of the knowledge or understanding gained from research directed toward the production of useful materials, devices, systems, or methods, including the design and development of prototypes and processes (National Science Foundation, *Science & Engineering Indicators - 1998, NSF 96-21*, 1998). A link can be seen between applied research and development research in that the first feeds the latter.

Dimensions Specific to Basic Research

Martin finds basic research contributes to many dimensions of human activity and knowledge. It can contribute to the scientific stock of knowledge, it can be used to train and improve skills of people, it can improve technological capabilities and it can contribute to the culture of society. Scientific contributions are not limited to just the field they originated in, but can affect many fields of study. Further, the work can be theoretical, empirical or methodological. The advances made by research can be revolutionary or incremental. Education to people includes the corporate knowledge and the ability to solve complex problems. Technological capabilities can include new products and services, new instrumentation, and new methodologies that can be used in applied research efforts. The results of basic research can result in direct economic and social benefits (Martin, 1996: 346).

Evolutionary change takes place in step-by-step increments, with each increment building on the knowledge of the previous increment, resulting in cumulative learning. "Technological discontinuity" is possible, though rare (Biondi and Galli, 1992: 583). It is defined as "radical innovation, which replaces a wide range of earlier techniques, . . . and leads to revolutionary changes in a system's economic and institutional arrangements" (Biondi and Galli, 1992: 585).

Another characteristic of basic research is risk.

> When you are organized to apply knowledge, you require a high degree of certainty from the outset. In basic research, everything is just the opposite. What you need at the outset is a high degree of uncertainty; otherwise it is not likely to be an important problem (National Academy of Sciences, 1982: 30).

Since R&D projects do not always succeed, experts typically estimate (often subjectively) probability of success. The probability of success is subjectively determined by experts (Bretschneider, 1993: 129).

Dimensions Specific to Applied and Development Research

Attributes that characterize a device developed by an R&D effort fall into two general groups (although they have different names in the literature). Alexander and Nelson divide technology characteristics between performance parameters that provide value to the user and technical parameters that "make the performance parameters possible . . ." (Alexander and Nelson, 1973: 190). Alexander and Mitchel divide technology characteristics between product user and product producer (Alexander and Mitchel, 1985: 162). Majer categorizes attributes of technologies into those that describe "its condition or nature and that reflect its use or purpose" (Majer, 1985: 337).

Biondi and Galli identify six technological trajectories they maintain are historically stable: 1) cost reduction, 2) incidence of capital cost, 3) space time dimension of goods and services, 4) incidence of specific resource consumption, 5) lifetime, and 6) size/scale effects (Biondi and Galli, 1992: 585-587).

Cost reduction, due to "innovation selection," results in more costly processes being rejected in favor of less costly processes. It is possible for cost reduction to stop at some point, but it cannot be reversed. Capital costs are investments in artificial tools used to reduce labor and resources in a process. Some investments in R&D have the goal of reducing this cost.

Time space dimensions in goods and services are reductions in volume, weight, or time to exploit services. A reduction in volume or weight takes place when a technology can perform the same job in less volume or with less weight than a previous technology. Reductions in time takes place using special equipment, which automates human activities.

Incidence of Specific Resource consumption is defined as a reduction in resource inputs while maintaining quality and quantity of a process. Lifetime is defined as a process with longer useable time a technology can be use for. A product with a longer lifetime is preferred to one with less lifetime. All processes deteriorate over time and eventually become too costly to maintain. A process can be increased in size, sometimes resulting in economies of scale. All size and scaling effects must result in reductions in total cost to be useful.

Dimensions General to Basic, Applied and Development Research

The trajectories identified by Biondi and Galli of "preferential paths" followed by technology, can be both qualified and quantified. Quality is defined as "a characteristic set of performances appreciated by users." The authors imply quantity is a specific measurement level of a quality. Examples of qualities of a vehicle are roominess, image, speed, fuel consumption and price. The quantity of a specific quality can be measured as a continuous set of values (such as price or speed) or it can be measured as discrete discontinuous levels. An example of a discrete measurement of a television is black and white or color (Biondi and Galli, 1992: 582).

Werner and Sounder further breakdown quantitative and qualitative R&D effectiveness measures. Measures can be based on either subjective judgements or objective data. They categorize metrics as either quantitative-objective, quantitative-subjective and qualitative-subjective. The qualitative-objective category is ignored since the authors consider it to be a contradiction in terms (Werner and Sounder, 1997: 34).

Quantitative-objective metrics are "numerical indicators of R&D performance using well-defined algorithms that focus on tangible, countable dimensions." Quantitative-subjective metrics are "based on intuitive judgments that are converted to numbers." Qualitative-subjective measures do not attempt to mathematically compare different levels of the measure. Raw evaluations of expert assessors are relied upon and no attempt is made to convert the judgements to numbers. (Werner and Sounder, 1997: 34-37).

Technological Change

Alexander and Mitchel model technological change from the views of the producer and the user. They develop two systems of relationships, which transform inputs to outputs as:

$$F(R_P, P, t) = 0$$
$$G(R_U, U, t) = 0$$

Equation 1

> where P and U are vectors of "product" and "use variables; R_P a vector of factors inputs (resources) of the product producer, and R_U a vector of resources consumed by the product user to produce the vector of outputs U. The vector R_U includes as an input the output of the product producer as well as additional inputs such as labor, materials, and energy (Alexander and Mitchell, 1985: 167).

The authors then state:

> Technological change will then be $-\partial R_P/\partial t$ . . . and $-\partial R_U/\partial t$ . . ., with P and U constant. Alternatively, technological change can be defined as $\partial P/\partial t$ and $\partial U/\partial t$ . . . with the respective R vectors constant (Alexander and Mitchell, 1985: 167).

The authors analyze milling machines (data spanning over 100 years, although with some gaps), commercial turbine-powered transports, and turbine engines. In their transport data, the vector P is made up of elements such as "lift-to-drag ratio, structural efficiency, engine thrust, wing loading, and energy content of fuel," (Alexander and Mitchell, 1985: 167). The U vector are quantities such as "seat-miles or ton-miles, noise, pollution, and the costs of obtaining (or avoiding) these activities" (Alexander and Mitchell, 1985: 168). The authors note that the use of technical parameters as a proxy to measure value and performance to the user do not properly measure technological change from the user's point of view.

Dimensions Specific to U.S. Air Force and Aerospace R&D

The Air Vehicles' strategic plan, *Air Force Research Laboratory Air Vehicles Directorate 2010: Strategic Business Plan (Working Draft #3)* is critical to understanding what is important to Air Vehicles in R&D. This document identifies Air Vehicles' three Integrated Concepts of Aircraft Sustainment, Space Superiority, and Uninhabited Air Vehicles (UAV) (AFRL/VA Corporate Planning Group, 1998: 15-17). It also brings out Air Vehicle's commitment to maintain competency in aerospace technologies (AFRL/VA Corporate Planning Group, 1998: 18). The "Strategic Position" states Air Vehicles will "deliver the best air vehicle technologies for aerospace dominance against all threats . . ." (AFRL/VA Corporate Planning Group, 1998: 5) or support the warfighter with technology. The document highlights the importance of preeminence in research performed by talented and dedicated people (AFRL/VA Corporate Planning Group, 1998: 6).

Other information from Air Vehicles is the programs that are proposed and currently in work. Documentation of programs can be found in the Air Vehicles Strategic Plan (AFRL/VA Corporate Planning Group, 1998: 15-17) and it can be found in *FY98 Air Vehicles Technology Area Plan Annexes* (*FY98 Air Vehicles Technology Area Plan Annexes*, 1998: Annex B and C). The most current information is available from the Air Vehicles' Plans and Programs office, which consists of the latest briefings and individual "Internal Program Summary" sheets. Additionally, the most current programs are listed in the Air Vehicles' roadmap briefings (Boudreau, February 1999; Weber, 1999; Ziegler, January 1999).

Air Force Basic Doctrine contains the classic principles of war with definitions. Because the ultimate goal of Air Vehicles is to support the warfighter, the principles of war provide an excellent framework for thinking about how the warfighter might employ technology to win a war. The classic principles of war are unity of command, objective, offensive, mass, maneuver, economy of force, security, surprise, and simplicity (Air Force Basic Doctrine, Sep 97: 12-21).

Joint Vision 2010 identifies four operational concepts of dominant maneuver, precision engagement, full dimensional protection, and focused logistics as challenges for all services of the military in the future. At the same time, it documents the importance of technological superiority, how it is achieved and why it is important. *Global Engagement* identifies and defines the USAF's core competencies that work closely with *Joint Vision 2010.* The core competencies are rapid global mobility, precision engagement, global attack, air and space superiority, information superiority, and agile combat support.

Another group of documents, which many of the USAF documents build on, is *New World Vistas*. This document brings out the concepts of global awareness, dynamic planning and execution control, mobility, projection of lethal and sublethal power, space operations and people as important tenants for winning future wars. These documents are future thinking, strategic planning documents and implementation plans. They provide important clues of what is important to the USAF and Air Vehicles.

The *Air Force Strategic Plan* contains the mission of the USAF and the vision statement. The vision of the USAF is defined as "Air Force people building the world's most respected Air and Space Force global power and reach for America." Global power and reach are key concepts of what is valuable to the USAF. Reach and power are fundamental properties air forces bring to a battlefield.

Another interesting study, which examines the past to understand the future, was written by van Creveld. The author examines the impact of technology on warfare from the beginning of recorded human history to the present. Understanding how technology has affected warfare over much of recorded human history provides indications of how technology may affect future warfare.

Other specifics to aeronautical R&D are standard texts on aeronautics used to understand standard aeronautical design parameters such as the lift to drag ratio (Anderson, 1985: 256) or range of an aircraft (Anderson, 1985: 298-302). Additionally, Air Vehicles is researching space capable vehicles (AFRL/VA Corporate Planning Group, 1998: 15-17), which is part of astronautics. As such, launch vehicle design is becoming more important. Launch vehicle design basics and considerations are well known (see Ryan and Townsend, 1997: 192-198 for review and lessons learned from some launch vehicles). Current launch vehicle performance (both expendable launch vehicles and the space shuttle) can be found on the internet (NASA: Kennedy Space Center, 1999).

Another standard work specific to military aerospace systems discusses concepts of how survivable an aircraft is to battle damage (Ball, 1985, 1-2). The probability of an aircraft surviving a combat sortie is a function of its susceptibility and its vulnerability. Susceptibility is defined as the probability the aircraft is hit; it covers detection and the ability of an adversary to hit the aircraft with a weapon system. Vulnerability is the probability the aircraft is killed given that it has been hit. This concerns how much battle damage is caused by an adversary's weapon and whether or not a vital system of the aircraft has been damaged.

Summary

Table 1 summarizes the many dimensions that apply to aerospace R&D. The dimensions can be broken down into specific to Basic research, specific to Applied and Development research, specific to all of R&D or specific to a field of study. For Air Vehicles, field specific technology covers the military, aeronautics and astronautics.

R&D Dimension	Specific to	Author(s)
Aerospace Specific Measurements	Aeronautics and Astronautics	Anderson; Ryan and Townsend; Ball
Contribute to Society	Basic Research	Martin
Evolutionary versus Revolutionary	Basic Research	Martin; Biondi and Galli
Improve Capability -Theoretical - Empirical - Methodological	Basic Research	Martin
Performance versus Technical	Applied and Development Research	Alexander and Nelson; Alexander and Mitchel; Majer
Programs	All Research	Air Vehicles' Documents
Qualitative and Quantitative - Quantitative-objective - Quantitative-subjective - Qualitative-subjective	Basic, Applied and Development Research	Biondi and Galli; Werner and Sounder
Risk	Basic Research	National Academy of Science; Bretschneider
Scientific Knowledge	Basic Research	Martin
Technological Change	Basic, Applied and Development Research	Alexander and Mitchel
Technological Trajectories - Cost Reduction - Incidence of Capitol Cost - Space Time Dimension of goods and services - Incidence of Specific Resource Consumption - Lifetime - Size/scale effects	Applied and Development Research	Biondi and Galli
Train and Educate	Basic Research	Martin
Military Specific - U.S. Air Force Strategic Planning - U.S. Air Force Doctrine - Historical Analysis of War	Military Field	AFRL Air Vehicles 2010: Strategic Business Plan (Working Draft #3); Air Force Basic Doctrine; Joint Vision 2010; Global Engagement; New World Vistas; Air Force Strategic Plan; van Creveld

Table 1: Aerospace Dimensions of Research and Development

Technology Selection Models

Having identified the dimensions of aerospace R&D, a model is needed to support technology selection. Bretschneider defines two types of analysis in R&D assessments. He defines "ex ante" R&D as when "... evaluation occurs prior to initiation of the research or development activity" and "ex post" R&D as when "... evaluation occurs after a project has been completed and therefore focuses on outcomes and impacts." The principle use of ex ante analysis is to select projects (Bretschneider, 1993: 123). Since this thesis is an ex ante analysis for Air Vehicles, discussion will be confined to ex ante analysis.

Ex ante studies can be divided into valuation or benefit measurement models and resource allocation models (Bretschneider, 1993, 124; Baker and Freeland, 1975, 1164). Valuation models are: 1) models that develop a measure of value through a comparative technique, 2) models based on obtaining a multidimensional score, or 3) techniques that link a project's value to the overall economic objective of the firm or organization. Resource allocation models are: 1) constrained optimization models, 2) emulations of organizational and human processes (simulation), or 3) Ad-hoc in nature (Bretschneider, 1993: 124).

Comparative approaches examine two measures at a time and are time consuming if many projects are to be compared. If comparisons are binary, then for n projects, $n(n-1)/2$ comparisons are required. The resulting relative results can be difficult or impossible to aggregate for analysis. Computer programs are used to check for consistency between evaluators, but it is often difficult to maintain consistency because there is no standard on which to base an evaluation (Bretschneider, 1993: 127-128).

In Bretschneider's approach, multidimensional scoring models develop a small number of criteria for R&D projects. Each project is then scored by experts for each attribute. A formula is developed to aggregate the attributes across multiple dimensions (Bretschneider, 1993: 128).

Value focused thinking (VFT) and the analytical hierarchy process (AHP) are two types of multidimensional scoring models. VFT is described by Keeney and by Kirkwood (Keeney, 1992; Kirkwood, 1997). VFT places values in a hierarchical structure and quantifies the values with evaluation measures, known as a value model. Alternatives are scored using the value model allowing quantification of how well the values are being achieved. The AHP (Saaty, 1980) structures priorities, which are similar to values in a hierarchy. Pairwise comparisons of the alternatives are combined with the hierarchy to develop a ranking of the alternatives.

Proponents for VFT and AHP are documented in the literature. Bard concludes that AHP is simpler to use for a decision-maker inexperienced in either VFT or AHP and that AHP is better for a large number of attributes that can only be measured on a subjective scale (Bard, 1992: 120). A weakness of VFT is the inability of it to systematically check for consistency of judgements (Belton, 1986: 18). However, AHP is known to have theoretical problems, which makes it less attractive for use than VFT. Belton compares VFT with the AHP and finds the AHP has major weaknesses in the way questions are asked to determine criteria weights and in the assumption that the measurement scores can be compared using a ratio. Further, the AHP always results in additive weighted value functions and should not be used for risky decisions, where as

VFT is not restricted in these ways (Belton, 1986: 10; von Winterfeldt and Edwards, 1986: 275-276).

Another strength of VFT is the ability to create previously unknown new alternatives. Keeney observes that a VFT value model can be used to systematically probe for new alternatives that may be better than those that are first identified without systematic analysis (Keeney, 1994: 38-39). The value model eliminates "anchoring" to possibly narrowly defined alternatives.

Models that relate projects to the overall economic objectives of an organization can also be used for R&D analysis. Examples are traditional cost benefit analysis, rate of return analysis and risk assessment. These models are extensions of standard capital decision making economic models (Bretschneider, 1993: 129).

Examples of Government Multidimensional Scoring Studies

An example of a major AHP study is "Implementing an Investment Strategy for CVX" (Christian and Hacker, 1998). This recent U.S. Navy analysis is being used in planning a new aircraft carrier to replace the current Nimitz class ships. Since no research and development for an aircraft carrier has been done in over 30 years, the Navy performed the study to determine what technologies they should invest in to build into the new carrier (Christian and Hacker, 1998: 1). The study used linear programming techniques to optimize the benefits of its programs while meeting cost constraints.

Examples of major VFT studies in the U.S. Air Force are the Spacecast 2020 study (Burk and Parnell, 1997: 60-73) and the Air Force 2025 study (Parnell et. al., 1998: 1336-1350). Spacecast 2020 concentrated on space technologies needs for 2020. Air Force 2025 broadened the perspective and included both Air and Space (Aerospace).

While both studies are landmarks in Air Force Strategic planning, they do not fully address how to develop the technologies needed to make future weapon systems a reality. The studies do provide starting points to understand values for technology and help to identify some possible measures.

Golabi, Kirkwood, and Sicherman performed a study for the Department of Energy. They used a value model to identify the technical worth of R&D solar energy projects to score in response to a Request for Proposal (RFP). The value model measured the technical worth of the proposed projects. A mixed integer program was used to identify the technical worth of a portfolio of programs. Some theoretical work was completed allowing the value of individual programs to be added together to find the overall value of a portfolio. The constraints for the math program considered the "geographic diversity of awards, selection of redundant or complementary efforts, funding of small or minority business proposals, and selection of proposals including cost sharing provision" (Golabi, Kirkwood, and Sicherman, 1981: 176).

A very recent study completed by Parnell et. al., conducted an analysis for the Operational Support Office (OSO) of the National Reconnaissance Office (NRO) using value focused thinking to identify high value projects that support strategic objectives and "select the best portfolio of products and services within resources and programmatic constraints" (Parnell et. al., 1998: 1). Their process was to develop a value model by interviewing decision-makers and examining relevant documents. They used the value model to score alternatives and then used a mixed integer linear program to optimize the results.

Value Focused Thinking

Fundamental Objectives Hierarchy or Value Hierarchy Theory

According to Keeney, "Values are what we care about" (Keeney, 1992: 3). They are the reason anyone cares about a decision. Without values, anything that occurs is acceptable since there is no reason to care about the consequences of a decision's outcome. Alternatives are possible actions, which will bring about consequences. Values measure how desirable or undesirable an alternative is, based on the consequences an alternative will bring about. "Value-focused thinking essentially consists of two activities: first deciding what you want and then figuring out how to get it" (Keeney, 1992: 3-4).

Keeney states value focused thinking is not always used by decision-makers because there is no formal process to use the method. That is, "the concepts and procedures have not been developed or integrated into an explicit approach" (Keeney, 1992: 29). While the decision-maker does use values to guide his decisions, they are not always explicitly expressed.

The decision frame for a decision is defined by its decision context and its fundamental objectives. The decision context defines the alternatives to consider for a particular decision situation. "The fundamental objectives make explicit the values that one cares about in the context of a decision and define the class of consequences of concern" (Keeney, 1992: 30).

Values of decision-makers are turned into objectives. The objectives state all that is important in a decision and are the only reasons to be interested in a decision. The objectives provide guidance for action and are the basis of all decision analysis modeling.

"An objective is a statement of something that one desires to achieve. It is characterized by three features: a decision context, an object, and a direction of preference" (Keeney, 1992: 33-34).

Keeney identifies how value hierarchies are constructed. Fundamental objectives or values can be built into hierarchies. Adjacent objectives or objectives at the same level in the hierarchy are distinct and are called a tier. Lower tier objectives are part of the higher-tier objective. Higher-tier objectives are defined by the two or more lower tier objectives. Adjacent objectives must be mutually exclusive and collectively exhaustive for the higher tier objective (Keeney, 1992: 78). The highest tier of the hierarchy is the overall fundamental objective, which "characterizes the reason for interest in the decision situation and defines the breadth of concern" (Keeney, 1992: 77).

Value Hierarchy Development Methods

There are several different accepted ways to develop value hierarchies. Kirkwood identifies a top down or a bottom up approach as possibilities (Kirkwood, 1997: 19-23). The top down approach is used when alternatives are not well specified. The values are built starting at the highest tier and then broken into lower and lower tiers. Typically, information for this method comes from mission, vision and strategic documents. The process is called the "Gold Standard" when used to develop a value hierarchy (Parnell et. al., 1998: 1338). If access to decision-makers in charge of the organization is possible, then results from the "Gold Standard" can be combined with the decision-maker's inputs identified through interviews.

In the bottom up approach discussed by Kirkwood, alternatives are known and can be examined to determine how they differ from each other. Grouping the differences in alternatives together into higher and higher tiers forms values (Kirkwood, 1997: 19-23). Another approach similar to Kirkwood's is to determine what tasks the organization perform with a group of people and name the tasks using verbs. The words can be grouped together in affinity diagrams and then structured into different value hierarchy tiers. This approach is called the "Silver Standard" (Parnell et. al., 1998: 1340).

In all approaches, values are placed in the hierarchy only if using the value to score an alternative would change its ranking. Value hierarchies are used as a guide for information collection, to help identify alternatives, to facilitate communications, and to evaluate alternatives (Kirkwood, 1997: 19-23).

Measurement Theory

An evaluation measure, sometimes called an attribute, measures the degree to which an objective or a value has been obtained (Keeney, 1992: 100; Kirkwood, 1997: 12). While a fundamental objective measures the qualitative aspects of a decision, evaluation measures provide quantitative measures for the decision. A value hierarchy combined with evaluation measures is a value model. Generally, a value model uses many quantities to measure the overall fundamental objective in the hierarchy. The evaluation measure converts a quantity from its units to a common set of units allowing the many attributes to be combined into a single measure of merit or benefit. Careful development of an attribute is required if it is to provide correct insight to the decision-maker.

Keeney identifies a conceptual part and a measurement part called a scale in measures. Desirable properties for evaluation measures are it should be measurable, understandable and operational (Keeney, 1992: 112, 116).

Keeney observes measurable attributes define objectives in more detail than the objective by itself. The attribute embodies appropriate implicit value judgements and avoids inappropriate judgements. It measures what the decision-maker is interested in and does not measure other items. Ambiguity can occur if the levels of the attribute are not well defined (Keeney, 1992: 113). The clairvoyance test should be applied to determine if the measure is ambiguous or not. The test is "if a clairvoyant were available who could foresee the future with no uncertainty, would this clairvoyant be able to unambiguously assign a score to the outcome from each alternative in a decision problem" (Kirkwood, 1997: 28)?

An understandable evaluation measure is implied by the requirements for a measurable evaluation measure. If one person assigns a level to an attribute, another should be able to interpret the level with no loss of information (Keeney, 1992: 116). If the evaluation measure is ambiguous, it will not be understandable.

Keeney defines a measure as operational if it describes possible consequences with respect to the associated objective and it provides "a sound basis for value judgements about the desirability of the various degrees to which the objective might be achieved." Besides defining a measure, other information that should be considered is where it is measured, how often it is measured, or how multiple measures aggregate over time or space. It is preferred that a measure be conditionally independent of all of the other measures in a hierarchy (Keeney, 1992: 114-115).

Kirkwood identifies four different types of scales for measuring values in value hierarchies. A scale can be either natural or constructed and can be either a direct scale or a proxy measure. Natural scales are those in general use that have a common interpretation. Constructed scales are developed specially for a particular measure. Direct scales specifically measure the quantity being examined while proxy scales are correlated with the quantity being measure, but actually measure something different then the value being quantified (Kirkwood, 1997: 24).

Keeney identified some of the advantages and disadvantages with constructed attributes or evaluation measures. Constructed attributes exactly measure what the fundamental objective is meant to address. They completely describe the objective. It is simpler to separate consequences from value judgements. Problems with constructed measures include being understandable and operational. The consequences of constructed attributes are more difficult to communicate since they do not have a common interpretation (Keeney, 1992: 118-119).

Keeney also provides an excellent discussion on proxy measures. Proxy measures reduce the number of attributes needed for a decision and simplify descriptions of the consequences. The effort to gather factual information is reduced, but the effort to specify the value model increases. Issues of fact are combined with issues of value, which results in asking technical experts to make value judgements and results in less insight (Keeney, 1992: 119-121).

Measurement Scales and Single Dimension Value Functions

Luce, Bush and Galanter identify several scale classifications (Luce, Bush and Galanter, 1963: 8-13). In order of decreasing information, scales can be absolute, ratio, interval, ordinal, and nominal scales. The difference scale, is a special case of the interval scale. Additionally each scale has an "allowable" transformation that does not change the scale classification.

Scale Type	Definition	Allowable Transformation	Example
Absolute	Units and Origin Fixed	Multiplication by Identity	Counting
Ratio	Units Arbitrary, Origin Fixed	Multiplication by Scalar	Mass (grams, pounds, etc.)
Interval	Units and Origin Arbitrary	Positive Linear (a*x + b)	Fahrenheit or Celsius
Ordinal	Only order matters	Monotonic increasing or decreasing functions	Moh's hardness scale for minerals
Nominal	Arbitrary	Any one to one	National Draft numbers or football player numbers.

Table 2: Summary of Scale types (Luce, Bush and Galanter, 1963: 8-13)

Luce, Bush and Galanter state that some scales are defined based on empirical operations. Defining scales this way "permits the subject (observer or experimenter) to compare intervals and to indicate in some way whether or not they are equal" (Luce, Bush, and Galanter, 1963: 15). By defining the scale in terms of a linear transformation, an interval scale is created.

Roberts provides examples of meaningful and meaningless statements due to scale type. He determines it is meaningful to say $f(a)=2f(b)$, where the function f transforms the quantities a and b, when the scale of f is a ratio scale. Similarly, it is also meaningful to say $f(a)/f(b) = \lambda$, where λ is a constant. These statements are meaningless, however, if the scale of f is an interval scale. Another example of a meaningful statement is to state $f(a) - f(b) > f(c) - f(d)$, where the function f transforms the quantities a, b, c and d, when the scale of f is an interval scale (Roberts, 1979: 71-74).

In decisions under certainty, three types of functions are often used to define an attribute. These are discrete functions (Clemen, 1996: 80), exponential functions (Kirkwood, 1997: 62-64; Keeney, 1992: 141-146) and piecewise linear functions

(Kirkwood, 1997: 64-68). If proper value increment questions are asked, these evaluation measures will transform a raw measurement to an interval scale (von Winterfeldt and Edwards, 1986: 209-210).

The single dimension value function converts a quantity being measured into value. Value is typically measured between 0 and 1 (Kirkwood, 1997: 61), but can be measured from 0 to 10 and 0 to 100. Which scale is used for analysis has no effect on the analysis results as long as one scale is used for all measures in the value model and if an additive value function (discussed later) is used.

Finding Alternatives and Attribute Scoring

Air Vehicles has already developed alternatives, which can be scored using the VA value model (UAV, Sustainment and Trans-Atmospheric & Space Integrating Concept Roadmaps, 1999). However, with a value model, it may be possible to improve the existing alternatives or identify new alternatives. Keeney notes, the fundamental objectives hierarchy or value hierarchy lists all that is important to a decision context. Since this is true, it is possible to use the value hierarchy to identify better alternatives. This can be accomplished by improving existing alternatives to score higher using the model or by identifying new alternatives which score better (Keeney, 1992: 201-202).

Kirkwood identifies possible methods of improving or finding new alternatives. He suggests considering each evaluation measure one at a time and identifying ways to improve the alternative in that particular area. It may be that the alternative is not attractive by improving it in a single area, but the exercise can suggest other attractive alternatives. Another approach is to improve several evaluation measures under a single value for an alternative to "maximize" a particular value. Finally, it may be possible to develop alternatives that directly balance all of the evaluation measures (Kirkwood, 1997: 49-50).

Scoring alternatives is straight forward, but can be time consuming. Technical experts consider each alternative one at a time for each attribute. In the case of multiple technical experts, a consensus should be reached about how the alternative scores in the area under consideration.

The only scores allowed are defined by the evaluation measures. Each evaluation measure converts the alternative score to value. The value scores for each attribute are then combined using value model weights and the overall value model function resulting in a single measure of merit for the overall fundamental objective being considered for the decision. Kirkwood provides an exponential function and a piecewise linear function written in Microsoft Excel Visual Basic for converting raw scores to value (Kirkwood, 1997: 78-81). He also provides detailed implementation methodology for evaluating value models in Excel (Kirkwood, 1997: 75-81).

Assessing Weights

The method of swing weights is commonly used to assess the weights for the values in a hierarchy although other methods such as pricing out and lottery weights are possible (Clemen 1996: 546-552). The swing weight method is a thought experiment where "the decision maker compares individual attributes directly by imagining (typically) hypothetical outcomes" (Clemen 1996: 547).

Kirkwood discusses the method in depth and this information on weights is based on that discussion (Kirkwood, 1997: 68-70). Each tier of values or measures in the hierarchy is considered individually. It is important to consider the ranges for measures since changes in the ranges of the measure can change the rankings of the alternatives (Kirkwood, 1997: 58-59; von Winterfeldt and Edwards, 1986: 285, 368). The decision-maker or the decision-maker's experts are asked to rank order the values or measures from least important to most important. The ranges for each value or measure are then examined one at a time. The decision-maker is asked to imagine the value or measure changing from its lowest to its highest value for each of the values or measures.

The decision-maker or the decision-maker's experts are then asked, "How much better is an increase (decrease) in value of value A to value B considering the ranges A and B can cover?" The process continues until there is one less equation then the total number of categories. The last equation needed is to sum the values for all categories to one. The result is a system of equations with the same number of equations and unknowns, which is easily solved.

For the highest tier values, this process can be complex since understanding the highest and lowest levels a value can take on is dependent on all of the values and measures below it. This can result in a large number of variables that must be considered while determining the weights (Keeney and Raifa, 1976: 125).

Multiobjective Additive Value Functions

The next step, once scoring of alternatives and assessing weights is completed, is to combine all of the scores into a single measure of merit. The most straightforward way of accomplishing this is to use an additive value function although others such as additive linear, multiplicative and multilinear are possible (von Winterfeldt and Edwards, 1986: 275-276). The additive multiobjective value function is defined as:

$$v(\mathbf{x}) = \sum_{i=1}^{n} w_i v_i(x_i) \qquad \textbf{Equation 2}$$

where **x** is the overall evaluation objective, x_i is the raw score of attribute i, v_i is the single dimension value function, and n is the total number of evaluation measures.

Keeney, Kirkwood and Clemen all discuss necessary and sufficient conditions to use an additive value function with value hierarchies (Keeney, 1992: 132-138; Kirkwood, 1997: 238-239; Clemen, 1996: 579-580). Mutual preferential independence of attributes or evaluation measures is required to use an additive value function under conditions of certainty. According to Clemen, "An attribute Y is said to [be] preferentially independent of X if preferences for specific outcomes of Y do not depend on the level of attribute X" (Clemen, 1996: 579). Mutual preferentially independent means Y is preferentially independent of X and X is preferentially independent of Y.

Clemen maintains mutual preferential independence holds "for many people and many situations, or that at least it is a reasonable approximation" (Clemen, 1996: 579). He relates this to the concept of decomposability, which is the ability to break down higher tier values into a series of lower tier values. Clemen states, "If a decision maker has done a good job of building a decomposable hierarchy, mutual preferential independence probably is a reasonable assumption. But it should never be taken for granted" (Clemen, 1996: 579). Both Clemen and Kirkwood provide formal testing procedures (Clemen, 1996: 580-582; Kirkwood, 1997: 238-239).

Fischer studied the suitability of using additive and multiplicative value and utility functions in multi-attribute utility assessments. He identifies risky and riskless functions where a decision is riskless "if the decision maker can specify with certainty the outcome which will results from each course of action under consideration" (Fischer, 1977: 297). A decision is risky "if the [decision-maker] is uncertain about the outcome of any given action, but is able to express this uncertainty in the form of a subjective probability distribution over the set of all possible outcomes" (Fischer, 1977: 299).

Fischer experimented by comparing results from small value hierarchies with holistic (direct assignment of overall-all value to outcomes by the decision-maker) results. He examined risky and riskless value functions and he examined use of additive and multiplicative value functions. Fischer found high correlations between all of the functions in his tests with a majority of the ten people he worked with. Fischer's data shows the additive value function provides a good model of decision-makers preferences, but there are some rare times it does not work. He does not recommend ignoring differences between risky and riskless decisions and additive and multiplicative value functions (Fischer, 1977: 313-314).

Ranking of Results

Kirkwood provides information on how to rank results. Once all of the alternatives are scored and the additive value function is implemented to identify the overall score for each alternative, it is a simple matter to rank order the alternatives. It is also possible to develop graphs that document the contribution made to each value in the hierarchy. The graphs provide insight on why a particular alternative scored the way it did and can be the basis for improving an alternative. Kirkwood provides implementation methods to determine the contribution each value makes to the scoring of an alternative (Kirkwood, 1996: 76-81)

Sensitivity Analysis

Sensitivity analysis on the weights can be performed to determine the weighting levels that will change the alternative rankings and can determine what the changes in policy would be. If the procedure is insensitive to meaningful variations in the weights, further discussion is not necessary. If particular weightings are sensitive, analysis of the weights can be focused on the specific alternatives affected (Kirkwood, 1997: 82-85).

Sensitivity analysis is performed by changing the weight of a single evaluation measure or a single value while holding the other weights to the same ratio as the base case. All of the weights for an evaluation measure tier or value tier must add up to 1. Hence, a particular weight is varied from 0 to 1. Kirkwood identifies the method of varying all other weights in a particular tier as follows:

> For each weight except the one that you are varying, the equation is given by the following: Multiply 1 minus the weight that is being varied by the ratio of the base case value for the weight being considered to the sum of the base case weights for all the weights except the one that is being manually varied (Kirkwood, 1997: 84).

He also provides simple examples for implementing sensitivity analysis in a Microsoft Excel spreadsheet (Kirkwood, 1997: 82-85).

Resource Allocation

A problem faced by R&D organizations is determining how to allocate scarce funds to a large number of competing projects. Kirkwood observes:

> . . . when there is a specified budget to be allocated among competing activities, then the question of how the resources not allocated to a particular activity are used becomes more important in evaluating alternatives since these resources are available to fund other activities (Kirkwood, 1997:199).

The problem is a question of identifying a group of projects or programs, which provide maximum "value" for the time, resources or dollars invested. Kirkwood identifies benefit/cost analysis and optimization methods for solving the resource allocation problem (Kirkwood, 1996: 199).

The process is to calculate the ratio of the benefit of project (determined from a value model) with the cost of funding the project. The ratio provides insight into the projects that provide the most benefit per dollar invested. By sorting the projects in ascending order based on the ratio, a funding order can be found. The cumulative benefit is then graphed against the cumulative cost. The method assumes the value and cost of a project does not change based on which project is being funded. Additionally, the number of constraints allowed by the analysis is limited to the single cost constraint. Another concern with the method is it may be possible to choose a different combination of projects, which result in an equal or higher value and more fully use the budget. In other words, an optimal portfolio is not guaranteed (Kirkwood, 1996: 200-205; Bell and Read, 1974: 36).

Bretschneider notes constrained optimization models have a set of equations containing decision variables called constraints. The model contains the objective function, constraints and decision variables. Linear Programming, integer programming and nonlinear programming are typical optimization models used in R&D decision analysis (Bretschneider, 1993: 130). Assumptions for linear programming techniques can be found in any linear programming text and are summarized in Table 3 (Winston, 1994: 53-54).

It is possible to use a linear model where the decision variables are the extent of resource commitment to a project (Bretschneider, 1993: 130) or to use integer programming where the decision is whether or not to include a particular program. Typical constraint types are budget constraints, skill availability constraints, facility availability constraints, raw material availability constraints, and program balance and/or risk balance constraints (Bretschneider, 1993: 130; Cetron, Martins, and Roepoke, 1967, 5).

Proportionality Assumption	The contribution of the objective function from each decision variable is proportional to the value of the decision variable. The contribution of each variable to the left-hand side of each constraint is proportional to the value of the variable.
Additivity Assumption	The contribution of the objective function for any variable is independent of the values of the other decision variables. The contribution of a variable to the left-hand side of each constraint is independent of the values of the variable.
Divisibility Assumption	Requires each decision variable be allowed to assume fractional values. If this does not hold, than integer programming should be used.
Certainty Assumption	Each parameter (objective function coefficient, right hand side, and technological coefficient) is known with certainty.

Table 3: Linear Programming Assumptions (Winston, 1994: 53-54)

Many types of optimization R&D portfolio selection models have been suggested (Gear, Lockett, and Pearson, 1971: 66-76). Of the wide array of possible models discussed, the linear programming approach used by Bell and Read handles optimization of scarce resources to maximize the benefit of research and development programs (Bell and Read, 1970: 35-42). The decision variables can be restricted to integer solutions only. In his 1974 article, Gear notes Bell's model has been tested, allows multiple resource constraints and allows multiple planning periods. It assumes 1) a selected project is continued until completion and 2) perfect knowledge of required resources. Additionally, it assumes one objective involved in the resource allocation problem (Gear, 1974: 199-120).

Mixed integer programs methods exist for expressing interactions between projects (Aaker and Tyebjee, 1978; Schmidt, 1993). Aaker and Tyebjee develop a model able to handle overlap in project resource utilization, technical project interdependence, and project interaction with respect to value contribution. Schmidt developed a nonlinear integer program which can handle benefit interactions, resource interactions, and outcome interactions.

Besides restricting the decision variables to integer solutions only, constraints will be required when selection of one program, (say program A), requires several other programs, (say programs B, C, and D) to be selected. At the same time, program B required to support program A might be needed to support another program (say program E). Constraints are required to allow program B to be selected if either programs A, E or both A and E are selected. If neither program A or E is selected, than program B should not be selected. Williams provides a good discussion of integer programming and logical constraints to help formulate this and other types of restrictions (Williams, 1985: 148-225).

R&D Model Characteristics and Known Limitations

Cetron, Martino and Roepcke surveyed R&D selection models and identified a number of features and ease of use considerations, which are shown in Table 4. Bretschneider and Sounder have developed criteria for determining the aptness of an R&D model. Table 5 shows the criteria originally developed by Sounder and updated by Bretschneider.

Criteria	Concept
Utility Measure	Does the method use a method to measure the utility or value of success of an R&D project (i.e. market share, profitability, military worth)
Probability of Success	Does the model explicitly measure the probability of success of each R&D project?
Orthogonality of Criteria	Are the criteria used for evaluation mutually exclusive or orthogonal?
Sensitivity	Has sensitivity of output to small changes in input been checked? A large change in output to small changes in input is not desirable.
Rejected Alternatives Retention	If a project is rejected for funding, can it be included later if funding changes?
Classification Structure	Does the method provide a structural relationship between the project and higher level organizational goals?
Time	Does the method include schedule requirements or provide scheduling outputs?
Strategies	Does the method provide a method to take into account several possible scenarios, world environments, market situations, etc.?
System Cross Support	Does the method give system development credit for support which it provides to another system development?
Technology Cross Support	Does the method give a project for advancement of technology credit for support which it provides to the advancement of other technologies?
Graphical Display	Can the results be displayed graphically allowing fast evaluation of various projects?
Flagging	Does the method identify problem areas allowing user intervention?
Optimization Criteria	What is the optimization method and what constraints are considered?
Constraints	In the review the following constraints were considered: budget, skills available, facilities available, competitor efforts, and raw materials available
Computerized	Is the method computerized?
Data Requirements	More data provides better information on the results, but is more difficult to collect. Considerations are the level of organization the data is collected at and the amount of information needed.
Manual	Can the method be applied manually or is a computer required?
Computer Program	Has the method been automated on a computer?
Running Time	How long does it take to run the model and get results?
Updating	How easy is it to update the model with new information?
Proficiency Level	What skill level is needed by the operator to run the model?
Outside Help	Does the R&D organization require outside help to use the method?

Table 4: Model Features and Ease of Use Considerations (Cetron, Martino and Ropcke, 1967: 4-5)

Realism Criterion	**Capability Criterion**
Model Includes: Multiple objective Multiple constraints Market risk Technical risk Manpower limits Facility limits Budget limits Premises uncertainty Multiple time periods Hierarchical structure Competitor effects	Model Performs: Multiple time period analysis Optimization analysis Simulation analysis Scheduling analysis
Flexibility Criterion	**Use Criterion**
Model applicable to: Applied projects Basic projects Priority decisions Termination decisions Budget allocation Project funding	Model characterized by: Familiar variables Discrete variables Computer not needed Special person not needed Special interpretations not needed Low amount of data needed Easy to obtain
Cost Criterion	**Additional Criterion**
Model has: Low set up costs Low personnel costs Low computer costs Low data collection costs	Model considers: Predictive accuracy Strategy needs Project interdependencies

Table 5: Model Evaluation Criteria (Bretschneider, 1993: 135; Sounder, 1972: B-528)

Baker and Freeland note seven limitations of benefit measurement models and resource allocation models:

1) Inadequate treatment of risk and uncertainty.
2) Inadequate treatment of multiple, often interrelated, criteria.
3) Inadequate treatment of project interrelationships with respect both to value contribution and to resource utilization.
4) No explicit recognition and incorporation of the experience and knowledge of the R and D manager,
5) The inability to recognize and treat nonmonetary aspects such as establishing and maintaining balance of R and D program; (e.g., balance between basic and applied work, between offensive and defensive activity, between product and process effort, between in-house and contracted projects, between

improvement and break-through orientation, and between high risk-high payoff and moderate or low risk-moderate payoff opportunities).

6) Perceptions held by the R&D managers that the models are unnecessarily difficult to understand and use.
7) Inadequate treatment of the time variant property of data and criteria and the associated problem of consistency in the research program and the research staff (Baker and Freeland, 1975: 1165).

Baker and Freeland's criteria identify properties R&D models should have or they will not completely cover what is important.

Literature Review Summary

This chapter has identified the dimensions of aerospace R&D and those specific to Air Vehicles' needs. It has reviewed technology selection models and identified some previous studies that use VFT. It has provided an in-depth review of value focused thinking and resource allocation models. Finally, the R&D modeling criteria and limitations of previous R&D selection models were examined.

Chapter 3: Methodology and Modeling

Introduction

The overall goal for this project is to identify the technological direction Air Vehicles should pursue to be most supportive of USAF values. Air Vehicles sets its direction by selecting, maintaining, and funding new technology programs. These programs fall under the categories of basic research, applied research, or development research. Working from the foundation laid in the literature, a methodology to evaluate Air Vehicles' R&D technology selection was developed.

The first topic covered in this chapter is an overview of developing the Air Vehicles model. Reasons for selecting value focused thinking with optimization to answer Air Vehicles' challenge and an overview of the analysis process are provided. The next topic covered is the development of the Air Vehicles' value hierarchy. The method of developing the value hierarchy is discussed followed by literature search integration, which allowed development of a notional hierarchy. The final hierarchy created by Air Vehicles' experts from the notional model is also presented.

The third topic covered is development of the Air Vehicles' value model. This topic covers considerations of measuring technological change, development of evaluation measures, aggregation of individual technology measurements using the additive value function, and weighting of values and evaluation measures. The last topics covered are modeling assumptions, applying the Air Vehicles' value model, and an exploration of how suitable the Air Vehicles' complete model is based on the literature. The latter topic checks that the model is collectively exhaustive, compares the model with criteria from previous efforts, and searches for major limitations.

Air Vehicles' Model Development Overview

Model Selection

In the literature, different types of R&D technology selection models are discussed. Essentially, Air Vehicles wants to maximize the benefit technology provides to the warfighter while minimizing the investment costs required to achieve that benefit. As reviewed in Chapter 2, there are three types of models that might be applicable for identifying benefit: comparative techniques, multidimensional scoring, and extensions of economic models (Bretschneider, 1993: 124; Baker and Freeland, 1975: 1164).

The comparative models are often inconsistent and nearly impossible to aggregate results (Bretschneider, 1993: 127-128). Because Air Vehicles has over 100 programs, these problems are magnified. It was not practical to get every program manager together in a group to perform comparisons. The difficulties in aggregating the results could prevent comparisons of the benefit versus the cost of technologies. The extensions of economic models were also dismissed, since R&D requires analysis of non-numeric concepts such as revolutionary versus evolutionary technology and programmatic risk. Converting these concepts to monetary value adds complexity to a model and possibly adds error because of the complexity.

Since R&D is multidimensional (see Table 1 in Chapter 2 for literature references), multidimensional models were deemed the most appropriate approach. Multidimensional models have been used for technology selection problems in the past (Golabi, Kirkwood, and Sicherman, 1981). Of the two types of multidimensional models discussed (value focused thinking and analytical hierarchy process), value focused thinking is the best fit. As will be shown in Chapter 4, it handles most of Baker and

Freeland's concerns by being able to treat risk, multicriteria, interrelated criteria, value contribution, inputs from experienced R&D experts, time variant data and nonmonetary aspects of R&D (Baker and Freeland, 1975: 1165). Further, value focused thinking, when properly applied, does not have the theoretical problems and limitations known to exist in the analytical hierarchy process (Belton, 1986: 10,18). It allows creative development of new alternatives (Keeney, 1994: 38-39) and does not require partial re-evaluation of all its alternatives when a new alternative is added as comparative methods do (Bretschneider, 1993: 127-128).

For resource allocation or identifying the best benefit at the lowest cost, Bretschneider identified 1) constrained optimization models, 2) emulations of organizational and human processes (simulation), or 3) Ad-hoc in nature models (Bretschneider, 1993: 124). The constrained optimization models (Kirkwood, 1997: 206-216; Bell and Read, 1974; Gear, Lockett and Pearson, 1971; Aaker and Tyebjee, 1978; Schmidt, 1993) and calculations of benefit to cost ratio are the most appropriate (Kirkwood, 1997: 199-206; Bell and Read, 1974: 36). Simulation is not practical since it is impossible to meaningfully model all of the outcomes of a single R&D program, much less hundreds of programs. This condition is further exacerbated when attempting to simulate revolutionary programs, which have limited data available on which to base a model. "Ad-hoc" models were eliminated from consideration since these models concentrate on using regression for decision making. The problem with these type of models is the inability to make new decisions not made in the past (Bretschneider, 1993: 131).

Analysis Process

The framework identifying analysis steps needed for program selection in Air Vehicles is shown in Figure 1. The first step in the study was to identify a value hierarchy for VA. The R&D literature, summarized in Table 1 on page 17, is the starting point to determine the overall fundamental objective for the decision and to determine the intermediate objectives supporting the overall objective. Since the model must represent VA's values, VA strategic planning experts and integrated concept leaders were consulted to confirm, modify, and develop value definitions. The value hierarchy was next approved by the Air Vehicles Directorate senior leaders.

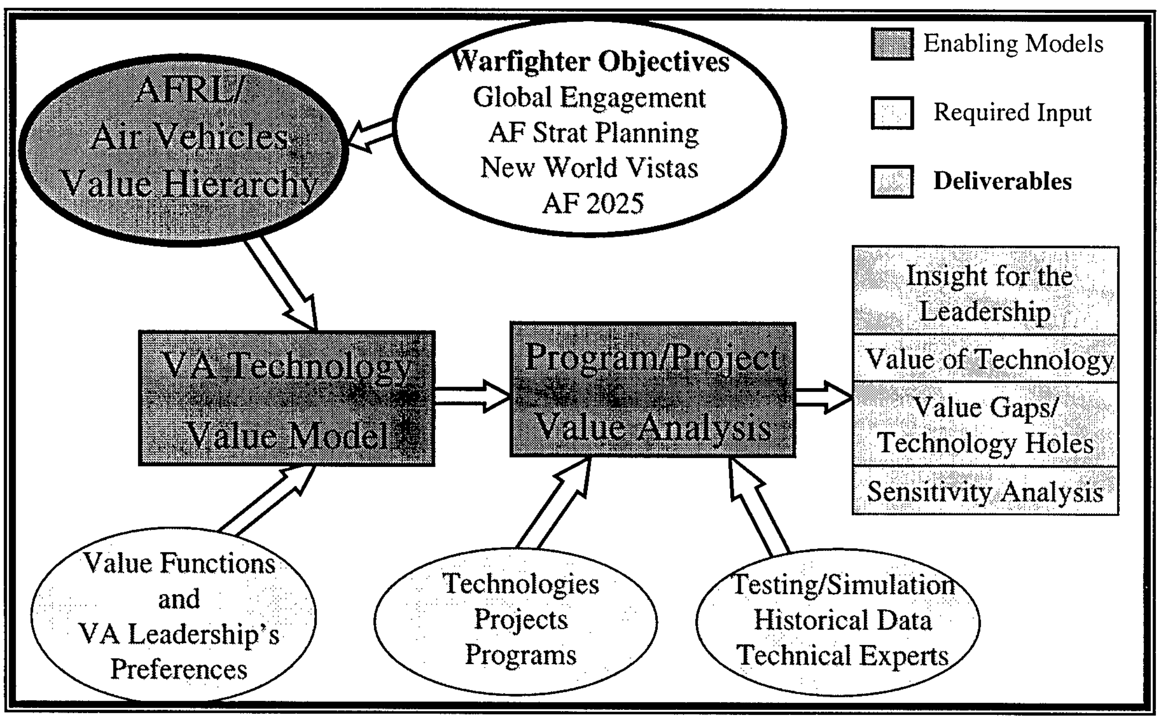


Figure 1: Study Framework

Once the value hierarchy was approved, the evaluation measures were developed. Discrete, piecewise linear and exponential scoring functions were developed. Air Vehicles' technical experts, strategic planning experts, and integrated concept leaders came to general agreement on the shape of these functions. The evaluation measures combined with the value hierarchy and weights define the value model.

After the Air Vehicles senior management approved the value model, alternatives or VA R&D programs were examined. The starting place for identifying alternatives is the list of programs identified in the AFRL/VA Strategic Plan and the Integrated Concept Leaders' roadmaps. Since Air Vehicles has over one hundred programs, a small subset was selected for analysis by the Integrated Concept Leaders, as a pilot test of the methodology. With the alternatives identified, scoring of each alternative was undertaken. Technical experts in Air Vehicles were needed to complete this task.

Finally, decision analysis was accomplished. This entails taking the alternative scores and converting each score to a value score using single dimension value functions. The additive value model was implemented to identify the overall fundamental objective score for each alternative. Verification of mutual preferential independence showed the additive value model was valid. A rank order of the alternatives was developed along with graphs showing the contribution for each value to each alternative. Sensitivity analysis was used to determine how changes in the weights changed the decision policy.

Using the VA cost for each program, the benefit to the warfighter of technology per USAF investment cost ranking was found. The overall fundamental objective for Air Vehicles of "Support the Warfighter to Achieve Air and Space Dominance" was agreed upon by the Air Vehicles' Director and was originally identified from relevant USAF doctrine (summarized in Table 1 on page 17). Finally, a simple mixed integer linear program was used to demonstrate the ability to optimize an investment strategy for VA.

Automation of the VA value model, evaluation measures, alternative scoring, and graphing of results was implemented using Micrsoft Excel. The method builds on Kirkwood's implementation concepts for Excel by making use of some of his macros. Additional macros and specialized calculation sheets were developed to simplify the calculation process.

The Search for the Air Vehicles' Value Hierarchy

The Method for Identifying the Hierarchy

Development of the Air Vehicle value hierarchy was the most difficult and important part of this effort. The question was what is important to Air Vehicles? Just asking people in Air Vehicles what is important to them would not necessarily result in a value model, since value focused thinking is a new concept to most people in Air Vehicles. While decision-makers have always used their "values" to make decisions, they have not always explicitly stated these values and/or quantified them in a systematic manner.

In the literature, two methods were identified for developing a value hierarchy. These were the "Gold" and "Silver" standards (Parnell et. al., 1998: 1338,1340). The "Gold" standard is the simplest method since it would use existing strategic USAF literature. However, while information for an Air Vehicles' model is available, no single document was available that captures all of Air Vehicles' values concerning technology. A combined standard of using existing literature and then working with experts in Air Vehicles to fill in the information gaps was the natural way to progress and was used in this analysis.

Results from the Literature

The Air Vehicles mission statement states they should "deliver the best air vehicle technologies for aerospace dominance against all threats . . ." (AFRL/VA Corporate Planning Group, 1998: 5) clearly documenting the desire to support the warfighter. However, reductions in funding to the military made it clear that cost is a major constraint for providing this benefit. Hence, the objective of this study is to select Air Vehicles' programs that maximize support to the warfighter while meeting budget constraints.

With "Support the Warfighter" identified as the overall objective, the next challenge was how to break it down, since it is not directly measurable. The question that needs to be answered next is how does the Air Force use technology to support the warfighter. Again, the literature was consulted to better understand what is important.

The *Air Force Strategic Plan* states the vision for the USAF as "Air Force people building the world's most respected Air and Space Force global power and reach for America" (Air Force Strategic Plan Volume 2: Performance Plan, Sep 1998: i). Key words in the vision statement are "global reach" and "global power." These concepts are recurring themes, which also appear in documents such as *New World Vistas, Global Engagement, and Air Force 2025. Air Force 2025* provided a good starting point for defining these words since the study was found to be "very valuable to the study director and the senior leadership of the Air Force" (Parnell et. al., 1998: 1349). It was publicly released by the former Chief of Staff of the Air Force, General Ronald R. Fogleman and the former Secretary of the Air Force, the honorable Sheila E. Widnall in 1996.

Further research of USAF strategic documents shows another concept that is important to the USAF. Examination of *New World Vistas, Air Force Strategic Plan* and *Global Engagement* identifies information superiority as one of the core competencies of the USAF. *Air Force 2025* identifies "awareness" as an important value for maintaining air and space dominance. Information superiority and "awareness" are similar concepts. Furthermore, "awareness" is required to know how to employ global power and to know where to reach out against an adversary.

The values "reach", "awareness" and "power" cannot be measured directly, so these values also need to be broken down. For each of the top three values, sub-values were identified as "gain" and "sustain." Both of these values can be identified from *AFRL/VA Strategic Plan* integrated concepts. Essentially, Air Vehicles either develops new technologies for the production of new platforms with new capabilities (i.e. gains new capability for the USAF) or improves existing platforms (i.e. sustains the existing Air Force fleet). In fact, sustainment of the USAF fleet is one of Air Vehicle's main efforts.

Improvements in awareness, reach and power are crucial to the USAF to maintain air and space dominance. However, according to *1997 Defense Technology Area Plan*, technology superiority "has been, and continues to be, a cornerstone of our national military strategy" (The Military Critical Technologies List. *1997 Defense Technology Area Plan,* 1997: Introduction). The AFRL mission is

> To Discover, Develop, Integrate, and Deliver affordable technologies for Warfighting Capabilities . . . To keep our Air Force the best in the world. (AFRL/VA Corporate Planning Group, 1998: 4).

Air Vehicles' "Core Values" state "the first essential of Aerospace Power is pre-eminence in research" (AFRL/VA Corporate Planning Group, 1998: 6). *Joint Vision 2010* states:

> This era will be one of accelerating technological change. Critical advances will have enormous impact on all military forces. Successful adaptation of new and improved technologies may provide great increases in specific capabilities. Conversely, failure to understand and adapt could lead today's militaries into premature obsolescence and greatly increase the risks that such forces will be incapable of effective operations against forces with high technology (Joint Vision 2010, 1996: 11).

The conclusion is "Technological Superiority" is a critical value for Air Vehicles.

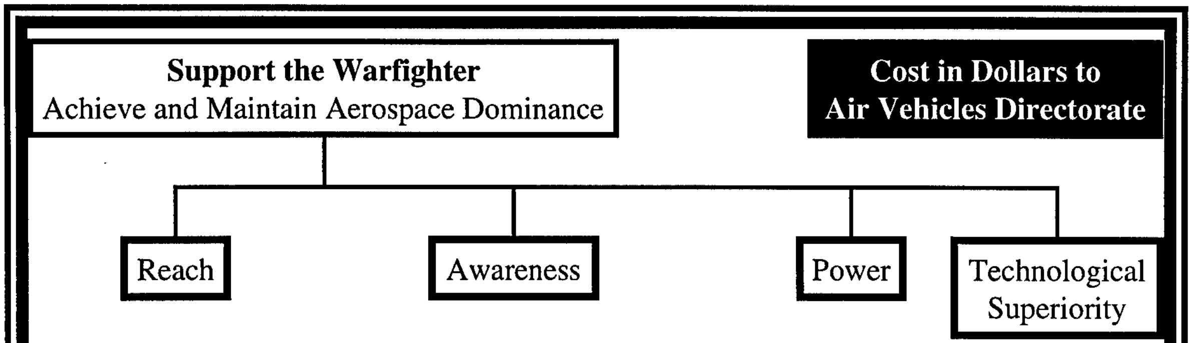
While, "Technological Superiority" is clearly important, the strategic documents examined do not specifically show how it is done. According to van Creveld,

> . . . the best military technology is not that which is "superior" in some absolute sense. Rather it is that which 'masks' or neutralizes the other side's strengths, even as it exploits his weaknesses" (van Creveld, 1989: 320).

This conclusion by van Creveld implies that technology does not dominate an enemy because of its absolute attributes. A technology must be compared with an adversary's technology to determine whether or not it dominates. With this information, an understanding of "technological superiority" as it pertains to military operations becomes possible. Further information for breaking down "technological superiority" can be found in Appendix A: USAF Strategic Documents Literature Search Results.

The Air Vehicles Hierarchy

With candidate values in hand, meetings to develop and refine the Air Vehicles Value hierarchy began in December 1998. Detailed documentation of the meetings can be found in Appendix B: Documentation of Meetings with VA. Figure 2, Figure 3, and Figure 4 show the Air Vehicles Value model with definitions for each value.



Reach	To **expand and sustain the range or scope** of influence (AFSP, AF2025, Global Engagement)
Awareness	**Knowledge or understanding of a situation** so as to enable an informed decision (NWV, Global Engagement - Information Superiority, AF2025)
Power	Ability to **affect or destroy targets** and survive (AFSP, AF2025, NWV, Global Engagement).
Technological Superiority	Technological Superiority implies a competition with other countries to **develop technology to gain advantage**. (JV2010, VA Strategic Plan, Global Engagement, 1997 Defense Technology Area Plan).

Figure 2: Top Level Value Model for Air Vehicles

Figure 2 shows the overall fundamental objective and the most important benefit Air Vehicles adds to the Air Force. Air Vehicles supports the warfighter in achieving and maintaining aerospace dominance. However, there is an investment cost associated with Air Vehicles providing this benefit. Since the benefit Air Vehicles provides to the warfighter cannot be directly measured, the overall value must be broken down, until the lower level supporting concepts are reached that can be measured. The values "reach," "awareness," "power," and "technological superiority" were accepted by the Air Vehicles Directorate as sufficiently descriptive of what is important about supporting the warfighter. Figure 2 shows the definitions for the values, which have been improved by Air Vehicles, but can be traced back to Air Force Strategic doctrine.

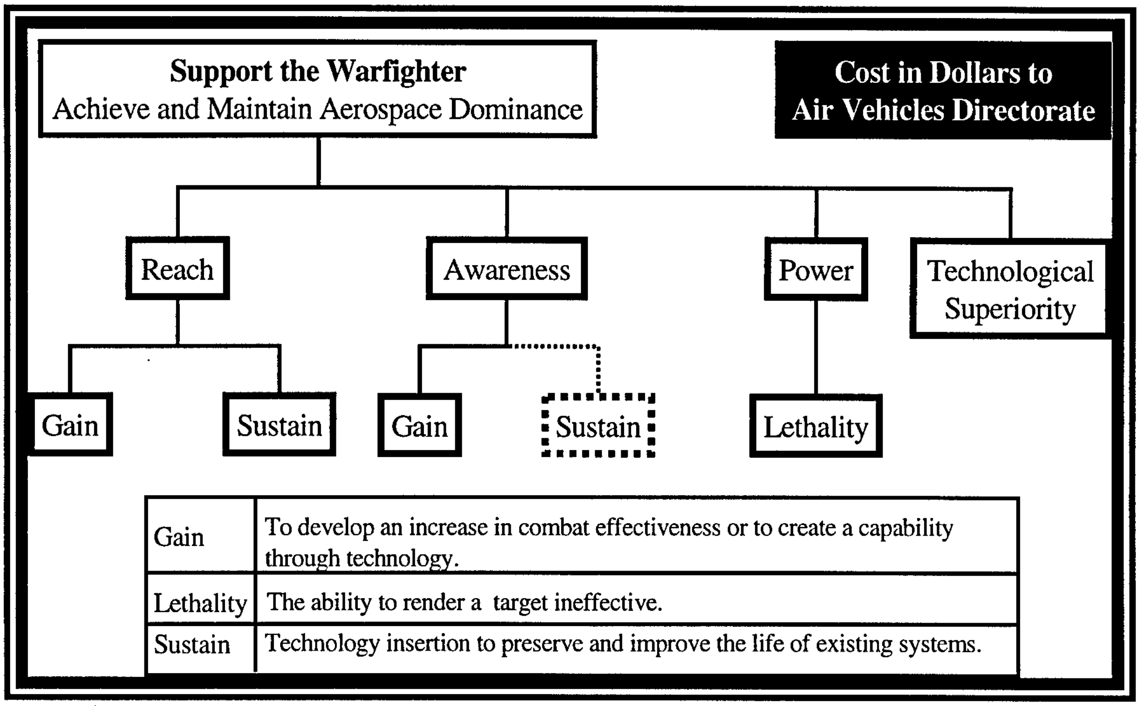


Figure 3: Value Model Breakdown of Reach, Awareness and Power

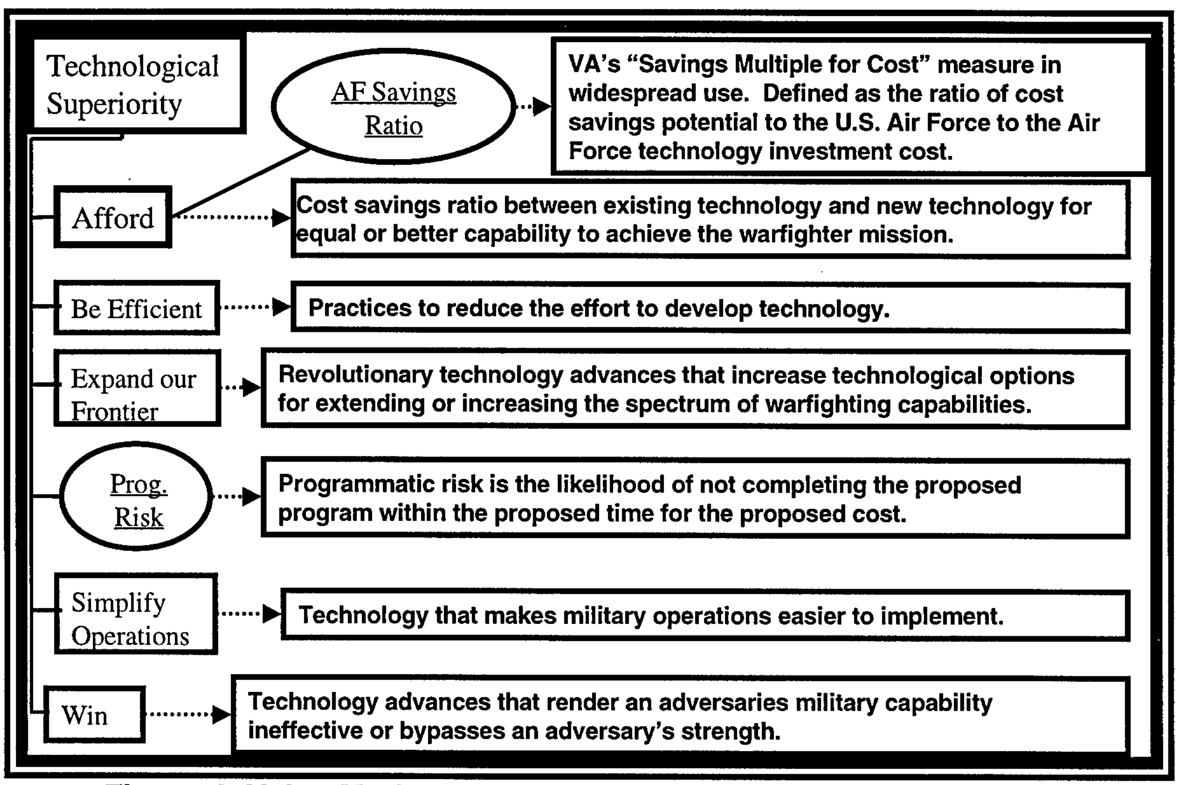


Figure 4: Value Model Breakdown of Technological Superiority

Technological superiority cannot be directly measured, either. It was therefore, further broken down, as seen in Figure 4. Considerable rearrangement took place on the values and on what was later to become evaluation measures. The definitions and values were modified to their present form from the inputs of the Air Vehicles Directorate.

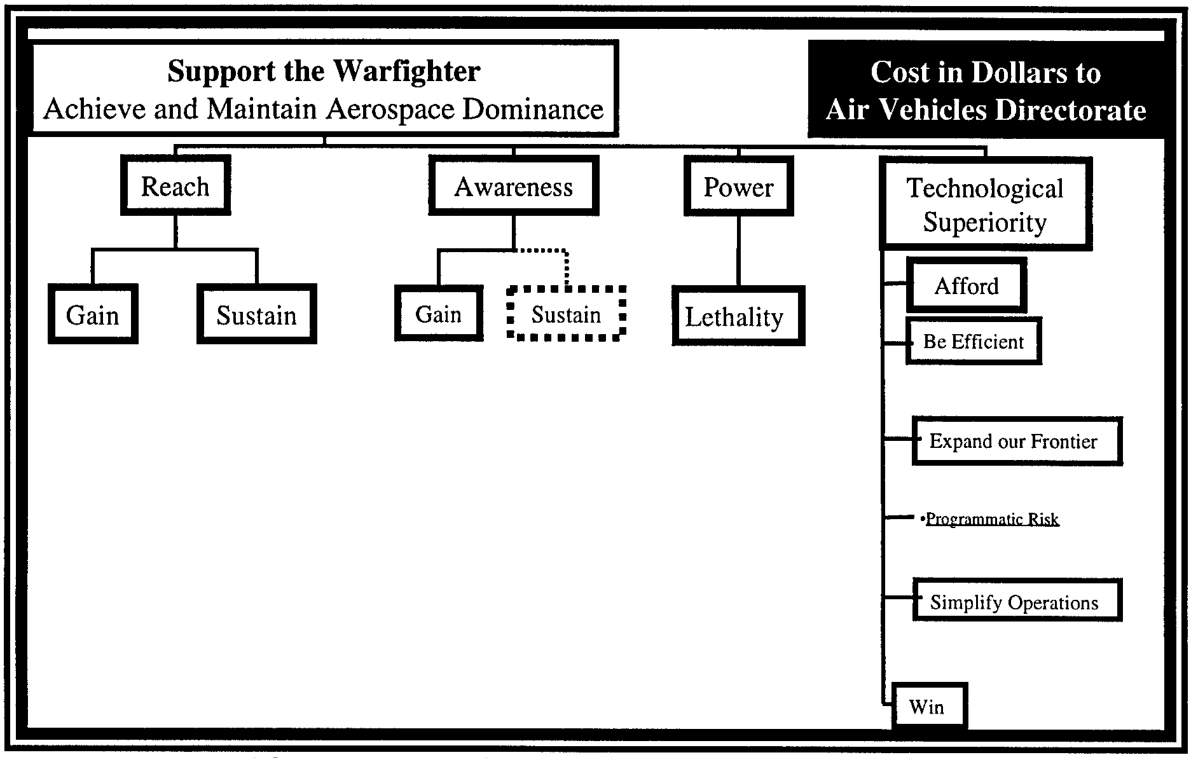


Figure 5: The Air Vehicles' Value Hierarchy

Technically, a value model should not be broken into a single value (Keeney, 1992: 78). However, this value model is also representing what is important to the AFRL at its higher levels, while it becomes specific to Air Vehicles at lower levels. Figure 5 shows the Air Vehicles' value model. The highest tiers of "Support the Warfighter" and "Reach, Awareness, Power, and Technological Superiority" are directly applicable to AFRL. The values one tier below "Reach, Awareness, Power and Technological Superiority" are specific to the ten Directorates of AFRL, but are not collectively exhaustive, except for the Air Vehicles' Directorate. For AFRL purposes, the "Cost to Air Vehicles Directorate" would be changed to "Cost to AFRL."

Developing the Air Vehicles' Value Model

Measuring Change in Support to the Warfighter due to Technology

Development of evaluation measures was the next step in the process. Early on, it was realized the evaluation measures would need to directly or indirectly measure the technological change in warfighting capability rather than a specific capability level brought about by the technology. Alexander and Mitchel developed a model for measuring technological change and in one version of their model, they allow vectors of "product" and "use variables" to change with time while holding resource input vectors constant (Alexander and Mitchel, 1985: 167-168).

The concept of measuring the difference between current state of the art and future state of the art was adopted for the Air Vehicles value model. However, measuring technological change for the warfighter was not directly measured with the value model. The model actually measures the "change in warfighter support due to technology, which is a function of the technological change brought about by Air Vehicles.

The change in warfighter support due to technology can be determined between an existing system (reference system) without the technology and a system with the proposed technology. The system without the technology is the assumed current capability while a system with the technology is assumed available at a specified date in the future. A technology program represents a potential change from a current reference system to a future new system. The difference in value between the new system and the old system quantifies the change in warfighter technological support for that evaluation measure. The deployed state of the art for an evaluation measure will be defined as the highest scoring known reference system for the objective. The word "deployed" is used because state of the art in technology may not be synonymous with the technology actual found in the USAF.

It is possible that a reference baseline system does not exist. This can happen when a revolutionary weapon system is planned for development. To use the Air Vehicles' value model, however, a reference system is required. In this situation, each evaluation measure should be examined separately to determine if any existing system is similar in that particular attribute.

Several existing systems may have to be used to define the deployed state of the art for each attribute. For example, Air Vehicles is working on an unmanned fully resuseable space vehicle. The only known example of a reuseable space vehicle in existence today is the Space Shuttle. However, the Space Shuttle is a manned system, and has a much higher payload-to-orbit capability (due to size and scale effects) than the proposed reuseable space vehicle. Comparison of the two vehicles would require scaling payload capacity and would have to subtract hardware preparation time that is specific to manned space flight. It is better to compare the new unmanned resuseable vehicle with existing expendable launch vehicles to define a reference deployed state of the art capability in technology (see Appendix H: Air Vehicles' Programs and Scoring for details). If no reference system can be found for comparison, the evaluation measure should achieve its maximum value.

Trading off Attributes in Favor of Others

A problem that arises with measuring the change warfighter technological support brings is that negative value can result. Intuitively, this happens when the new system has lower value then the reference system or the deployed state of the art for a particular evaluation measure. For example, it may be desirable to lower horsepower in an automobile to allow improvement in the fuel economy. If just a single evaluation measure was required to score a program (i.e. only horsepower mattered to the decision-maker), and it reduced capability from the current deployed state of the art, that technology would not be developed. Because the model is a multiattribute model, tradeoffs exist between the evaluation measures and the values in the model. It is possible one evaluation measure will be penalized in order to gain a much larger advantage in another evaluation measure.

While there is no theoretical reason preventing the use of negative value, value focused thinking was developed with the assumption that value is always positive. Evaluation measures that would intuitively have resulted in negative value actually scored positively. There is no problem, if the value function for each evaluation measure is calibrated for the "deployed state of the art." When a program scores below the deployed state of the art value, it can be understood that the program is decreasing capability for the warfighter. When a program scores above the deployed state of the art value, it is understood that the program is increasing capability for the warfighter.

As reviewed in Chapter 2, value functions can be measured on interval scale (Luce, Bush and Gallanter, 1963: 15; von Winterfeldt and Edwards, 1986: 209-210). Using the value function for an evaluation measure, it is possible to calculate the difference in value for a program and the deployed state of the art. Because the value for the program and the deployed state of the art are measured on the same interval scale, the difference between the two will be measured on a ratio scale. This difference is defined as the change in warfighter technological support where a value of zero represents the current deployed state of the art for that evaluation measure.

This result has three implications. First, change in warfighter technological support is being measured on a scale with an absolute zero. This means the current deployed state of the art has been estimated and quantified (within the accuracy of the evaluation measures and scoring on the programs). Second, it is possible to directly compare one program to another in how it impacts change in warfighter technological support (see (Roberts, 1979: 71-74 for a discussion on meaningful statements with ratios). Third, defining change in warfighter technological support on a ratio scale means the mathematical programming assumption of proportionality (Winston, 1994: 53-54) can be met.

The evaluation measures were developed with the aid of specially designed Excel macros and templates. The macros and the templates are documented in Appendix C: Evaluation Measure Templates and Macros. The process of developing evaluation measures follows the methods describe in Chapter 2.

Elicitation of Single Dimension Value Functions

There are infinitely many possible shapes for an evaluation measure. In all cases, the ranges and shapes of all of the evaluation functions were developed with the help of Air Vehicles leaders and technical experts. The types of evaluation measures used were discrete, exponential, piecewise linear or combinations of exponential functions (piecewise exponential).

An evaluation measure with categories is a discrete measure with a discrete function. A special case of a discrete function is a binary function. In this situation, an alternative either receives all of the value or none of the value for the function.

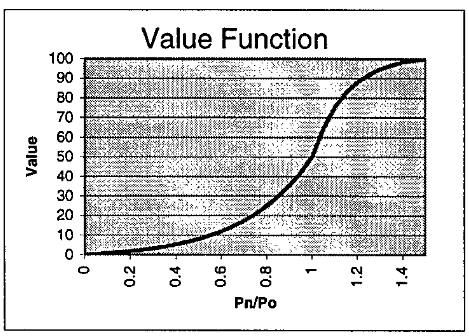
Determination of whether a value function should be an exponential function, a piecewise linear function, or some other function required input from the Air Vehicles' experts. For this project, an exponential function was the first choice function. This is because of its flexibility to model diminishing returns on value for convex curves or the ability to show only marginal gains in value until maximum value for concave curves is achieve.

Questions were asked to gain an understanding of the shape of the curve. If the exponential curve was clearly not correct, a piecewise linear curve was tried. If additional questions showed a location in the value function of large increase or decrease followed by little change in the value, an S-curve was considered (see Appendix D: S-Curves as a Value Measure for details). If the resulting function was an asymmetrical S-curve, multiple exponential curves were combined to develop the value function.

An example of an evaluation measure can be found in Figure 6. "Availability" is an evaluation measure under "Reach" under "Gain." The discussion for this evaluation measure with Air Vehicles first considered the definition. The definition needed to include "a single system which prevents the aircraft from performing its mission" in the definition. Modern aircraft are typically available 60%-65% of the time. The measure is P_{AN}/P_{A0}, which is the ratio of the probability of being available for the new system versus the probability of being available for the old system.

The range of the ratio was set to never go higher than 1.5, which is an increase in availability for the new system. A value of 0 is the worst the new system can be available, which is not available at all. This allows for an increase up to 100% in most situations and for decreasing availability in the case of a new weapon system performing a new mission. The measure assumes time between failure and time to repair is considered in determining the probability of availability. This evaluation measure is mutually exclusive with Regeneration because it does not cover repair of battle damage or the time to replenish consumeables on the weapon system.

The evaluation measure function shown in Figure 6 describes the function from a P_{AN}/P_{A0} from 0 to 1. The equation that describes P_{AN}/P_{A0} from 1 to 1.5 is shown in Figure 7. The only difference between Figure 6 and Figure 7 is that "Sustain Availability" will never be decreased by adding on new technology, while "Gain Availability" has the potential of decreasing in favor of other attributes.



Evaluation Measure: Gain Availability

Range Units: Unitless

Definition: Pn/Po where:

Pn is the probability the weapon system is availabile with the proposed new technology

Po is the probability the weapon system is available without the proposed technology.

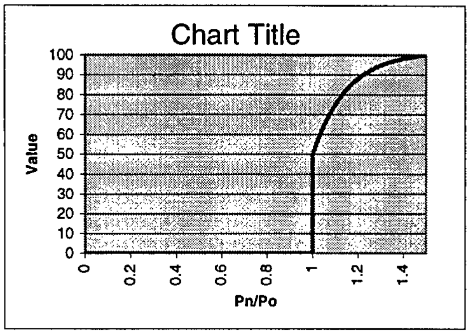
Availability is the probability the weapon system can complete its normal combat mission on demand. A weapon system is not available when mission critical equipment fails.

Comments: This measure combines both the time between failures or the reliability of the system with the time to repair the system. This alternative results in no-change when Pn=Po.

V(X) = A-B*exp(-X/R)

A	B	R	X	Value	Value Function Range	
-1.95	-1.95	-0.3048	0.00	0.0	Lower	0
Find R			0.80	25.0	Set Value	25
			1.00	50.0	Upper	50

Figure 6: Gain Availability Evaluation Measure



Evaluation Measure: Sustain Availability

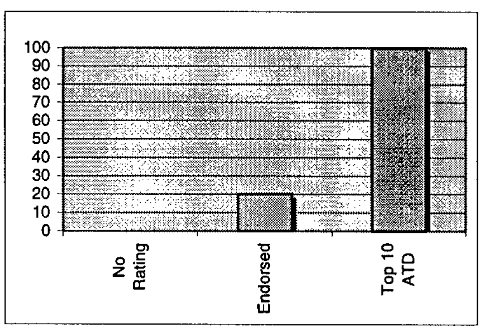
Range Units: Unitless
Definition: Pn/Po where:
Pn is the probability the weapon system is availabile with the proposed new technology
Po is the probability the weapon system is available without the proposed technology.
Availability is the probability the weapon system can complete its normal combat mission on demand. A weapon system is not available when mission critical equipment fails.
Comments: This measure combines both the time between failures or the reliability of the system with the time to repair the system. The availability of a weapon system will never be intentionally decreased. This alternative results in no-change when Pn=Po.

V(X) = A-B*exp(-X/R)

A	B	R	X	Value	Value Function Range	
101.95	36785.25	0.15238	1.00	50.0	Lower	50
Find R			1.10	75.0	Set Value	75
			1.50	100.0	Upper	100

Figure 7: Sustain Availability Evaluation Measure

An example of a constructed evaluation measure can be seen in Figure 8. This evaluation measure was developed to show the importance of how outside customers rate Air Vehicles' programs. Making the "Top 10 ATD" or top 10 advanced technology development list provides the most value. An "endorsement" from a System Program Office or a Major Command is also valuable, but is far less important than being in "Top 10 ATD." This change in value between the two shows the tremendous importance of being in the "Top 10 ATD" group.



ReScale

Range Units: Categories as defined
Definition: The rating of the program given by the appropriate agency.
Comments: A program in the Top 10 ATD's has tremendous importance. Endorsement by a SPO or MAJCOM is good, but far less useful.

Evaluation Measure: Be Efficient: User Rating

Abreviation	Category	Value	Category Definition
X1	No Rating	0	Not rated.
X2	Endorsed	20	Written endorsement by MAJCOM or SPO.
X3	Top 10 ATD	100	In the MAJCOM's top 10 Advanced Technology Development List

Figure 8: User Rating under Technological Superiority under Be Efficient

Appendix F: Air Vehicles' Evaluation Measures, shows all of the evaluation measures used in the Air Vehicles value model. Definitions for each evaluation measure are provided along with comments, mathematical representations of the functions and graphical representations of the functions. Figure 9 shows the entire Air Vehicles value model.

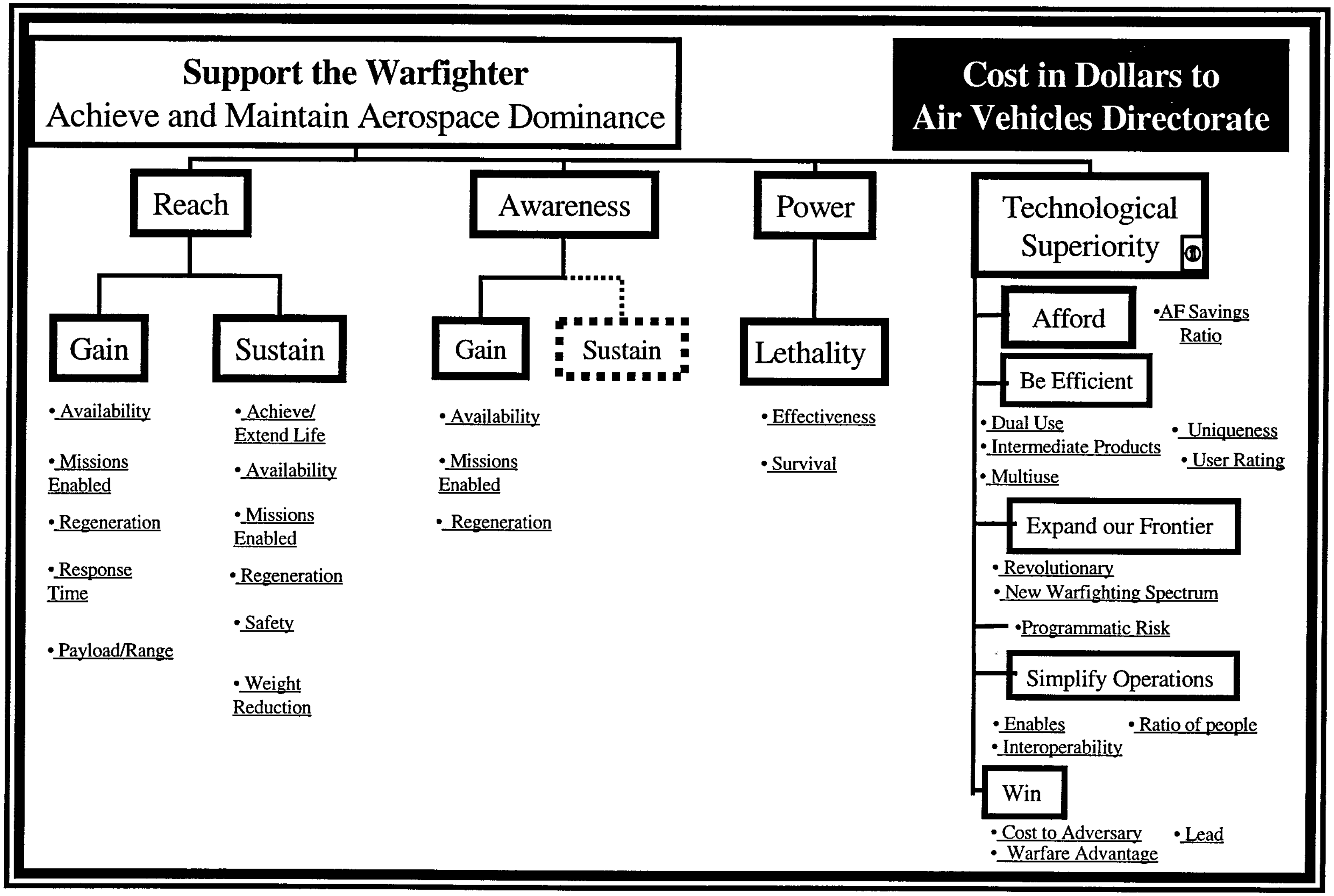


Figure 9: Air Vehicles Value Model

Using the Additive Value Function

From the literature, it was determined that a majority of small value hierarchies under certainty can use the simple additive value function for combining multiple single dimension value functions into an overall figure of merit with no loss in accuracy (Clemen, 1996: 579; Fischer, 1977: 299). However, in a minority of cases, the additive value function cannot be used because mutual preferential independence does not hold. To be certain mutual preferential independence holds, a test was conducted with Air Vehicles. The meetings were held with the Integrated Concept Leaders and the Strategic Integrated Product Team Leader.

A matrix with every evaluation measure in the value model in the columns and every evaluation measure in the rows was developed. The measures in the rows were set at three arbitrary low, medium and high levels. Each evaluation measure in the columns was incremented from an arbitrary low level to an arbitrary high level. The arbitrary levels were chosen not to be at the lowest or highest point of the evaluation measure. Air Vehicles was asked to compare each measurement in each row at a fixed value level with each evaluation measure in the columns. The purpose was to determine if they would always prefer the highest level to the lowest level for each evaluation measure, regardless of how the fixed measure was set.

The team reported they would not change their preferences for any of the other evaluation measures based on any particular measure being fixed at a particular level. This result combined with the literature search result that given mutual preferential independence, additive value functions give up very little accuracy, supported the additive value function choice for the Air Vehicles' value model.

Weighting of Values using a Hypothetical Example

The method of swing weights (Kirkwood, 1997: 68-70) described in Chapter 2: Assessing Weights on page 29 was modified for this thesis. The major problem with the method, outlined from the literature, is the requirement for a decision-maker to consider the ranges of all of the values and evaluations measures under the two values being compared (Keeney and Raifa, 1976: 125). The value model for Air Vehicles is complex and contains 31 evaluation measures. It is nearly impossible to consider the ranges for 5-10 evaluation measures simultaneously while assessing how much more important one value is to another.

A different process was employed. The concept is to ask how much value is gained "swinging" from the lowest to highest in one evaluation measure compared to "swinging" from the lowest to highest in another evaluation measure across two different value model columns. When a decision-maker provides a ratio of the importance, the relationship between the highest value above each evaluation measure will be established.

To understand how this happens, the concept of local weights and global weights must be discussed. A method for defining local weights was defined in Chapter 2. Essentially, a group of values or evaluation measures is considered under a single higher level value. The decision-maker is asked to rank order the values/evaluation measures and then is asked questions requiring him to compare two at a time. The decision-maker will be asked as many comparison questions as there are values/evaluation measures at that tier minus one. The last equation is that all weights must sum to one. What results is a set of simultaneous equations that are easily solved.

Global weights combine all of the local weights at the highest tiers of the value model down to the lowest tier to develop an overall weight for each evaluation measure. Figure 10 shows a sample value model with local weights determined from a hypothetical decision-maker. The global weight for M1 was found by multiplying all of the local weights at higher tier levels by the local weight of M1. That is, the global weight for M1 is (0.25)(0.4)(1)= 0.1. The value "VT" has a weight of one, since it has no other value at the same tier level.

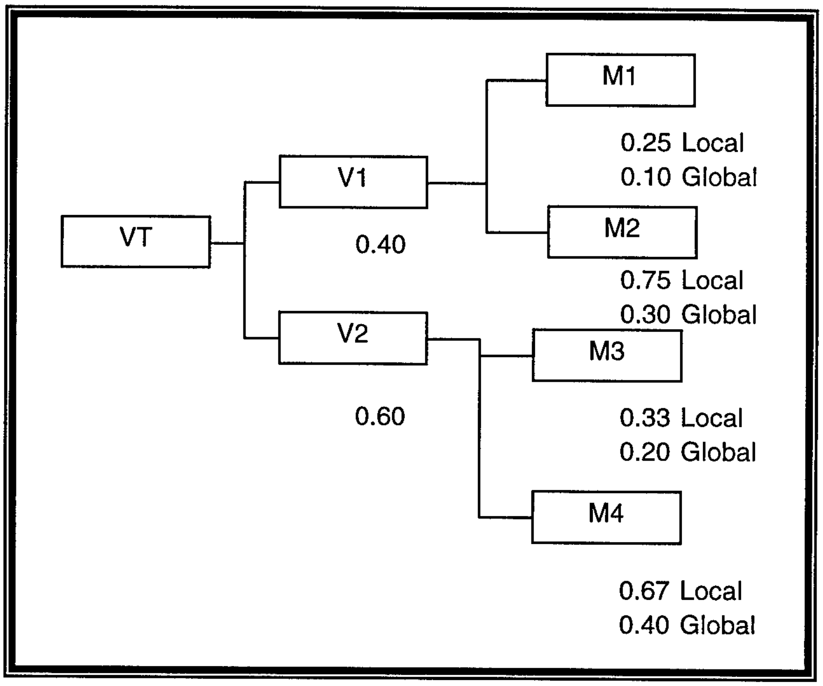


Figure 10: Difference between Global and Local Weights

Similar to the swing weight method, the decision-maker is asked to rank order the evaluation measures before any information is elicited. The ability for weights to change based on the evaluation measure range is still a factor in this method. In Figure 10, M2 would be more important than M1 and M4 would be more important than M3. Next, the decision-maker is asked to compare two evaluation measures (considering the ranges they cover) between two values. For example, the decision-maker could be asked, "How much more important is M2 to M3?" In this case, the decision-maker would have answered 1½ times as important. The relationship refers to the global weights of M2 and M3.

Next, the standard method of swing weights is employed to find the local weights for M1, M2, M3, and M4. For this example, it will be assumed the decision-maker believes M2 to be three times more important than M1 and M4 to be twice as important as M3. The equations for finding the local weights are:

$$\begin{aligned} W_{M4} &= 2W_{M3} \\ W_{M2} &= 3W_{M1} \\ W_{M1} + W_{M2} &= 1 \\ W_{M3} + W_{M4} &= 1 \end{aligned}$$ **Equation 3**

with the an equal number of unknowns and equations, the local weights can be easily solved to find $W_{M1} = 0.25$, $W_{M2} = 0.75$, $W_{M3} = 0.33$, and $W_{M4} = 0.67$. The variable "W" represents the weight for the subscripted evaluation measure or value as shown in Figure 10.

Next, the decision-maker is asked to compare evaluation measure M2 with M3 to set the relationship between V1 and V2. The result is the decision-maker never has to consider more than two evaluation measures for every value model relationship he is asked to find. It will be assumed the decision-maker believes M2 to be 1.5 times more important than M3. This relationship does not compare local weights like was done with Equation 3, but compares global weights. Therefore, a slightly different set of equations must be solved for as follows:

$$\begin{aligned} W_{M2}W_{V1} &= 1.5(W_{M3}W_{V2}) \\ W_{V1} + W_{V2} &= 1 \end{aligned}$$ **Equation 4**

The first equation defines the relationship "elicited" from the decision-maker in terms of local weights. The second equation is the standard requirement that all local weights must sum to one. Solving the simultaneous equation using the answers from Equation 3 results in $W_{V1} = 0.4$ and $W_{V2} = 0.6$.

In the "elicited relationship for measures between values" equation, the weight for value "VT" Figure 10 does not appear in the equation. Although the weight for this value is one, it would not have mattered if it had been any other positive number less than one (zero renders calculation of weight irrelevant). This is because both V1 and V2 are subvalues to VT. When comparing the global weights between V1 and V2 using evaluation measures M2 and M3, the weight for VT would appear on both sides of the equation. This value's weight and any value above VT can be "ignored" since it will always cancel out of the equation relating the two global weights.

Air Vehicles' Weights

For Air Vehicles, the weights were elicited from both the Directorate Senior Leadership and from the Integrated Concept Leaders. The Directorate Senior Leadership provided weights for the values, using the new method discussed in the previous section while the swing weights method was used to query the Integrated Concept Leaders. Table 6 documents the weights elicited from Air Vehicles while Appendix G: Air Vehicles' Weight Calculations shows the details for the calculations.

The Directorate Senior Leadership was asked several questions in an attempt to gain consistent answers. The senior leader was first asked to rank order the evaluation measures to determine the most important measure for each value. Then, only the most important measures were compared. This is important because it allowed the decision-maker to compare something he was most familiar with and deals with often. Another concern would be to not compare the highest ranking evaluation measure with the lowest level in another value since this would inflate the decision-maker's answers. Careful attention was paid to explaining what the ranges of the evaluation measures being compared were. Besides changing the ultimate weights in the model, it was important the decision-makers were considering the same evaluation measure as was documented in the value model.

Support the Warfighter	Local Weights			Global Weights
Reach	0.284			
Gain		0.211		
Availability			0.200	0.0120
Response Time			0.200	0.0120
Missions Enabled			0.200	0.0120
Regeneration			0.200	0.0120
Payload-Range			0.200	0.0120
Sustain		0.789		
Safety			0.202	0.0453
Achieve/Extend Life			0.179	0.0400
Availability			0.179	0.0400
Regeneration			0.179	0.0400
Weight Reduction			0.143	0.0320
Missions Enabled			0.119	0.0267
Awareness	0.040			
Gain		1.000		
Availability			0.333	0.0133
Missions Enabled			0.333	0.0133
Regeneration			0.333	0.0133
Power	0.092			
Lethality		1.000		
Effectiveness			0.565	0.0520
Survival			0.435	0.0400
Technological Superiority	0.584			
Afford		0.046		
AF Savings Ratio			1.000	0.0267
Be Efficient		0.240		
User Rating			0.260	0.0363
Multiuse			0.195	0.0273
Uniqueness			0.234	0.0327
Intermediate Projects			0.182	0.0254
Dual Use			0.130	0.0182
Expand Our Frontier		0.274		
New Warfighting Spectrum			0.500	0.0800
Revolutionary			0.500	0.0800
Programmatic Risk		0.009		0.0053
Simplify Operations		0.093		
Enables			0.333	0.0182
Interoperability			0.333	0.0182
Ratio of People			0.333	0.0182
Win		0.338		
Warfare Advantage			0.405	0.0800
Lead			0.324	0.0640
Cost to Adversary			0.270	0.0533

Table 6: Weights for the Air Vehicles Value Model

Modeling Assumptions

Specific to R&D and Air Vehicles

Biondi and Galli stated assumptions that allow technology to be quantified. Their first premise that development of technology is not completely random is critical here. If development of technology is random, than all attempts to model technology are doomed. Another premise they propose is that technology can be quantified and that it is possible to identify "higher-quality configurations." Again, this premise is fundamental to this work.

The difference in current technology or deployed state of the art is compared with the potential deployed state of the art in many of the evaluation measures. It is assumed that the alternatives chosen to represent the current technological deployed state of the art are in fact the deployed state of the art. Failure to adhere to this assumption will inflate the value of new technology, which will cause erroneous results.

The programs or alternatives are assumed to represent a typical sample of programs in Air Vehicles. Seven programs were analyzed in this effort. Air Vehicles has stated there are 100-200 programs in various stages of work. The Integrated Concept Leaders at Air Vehicles were specifically asked to identify programs they thought would represent Air Vehicles' program portfolio that would be diverse enough to test the model.

Levels of technical risk are assumed to correlate with R&D categories of basic research, applied research, and development research. In order of highest risk to lowest risk, basic research ranks highest, applied research is lower, and development research is lowest. As such, technical risk is predefined and assumed constant for any program in a particular category. Technical risk is held constant when programmatic risk is varied.

Specific to the Value Model and the Resource Allocation Models

Many raw scores of attributes were measured using ratios, percentage change, or a simple difference between deployed state of the art and the new proposed deployed state of the art. This aggregation allows mission dependent information to be cancelled from the measurement and results in a manageable number of evaluation measures in the value model.

The programs or alternatives in the initial study are assumed to not interact. For example, the value of Program A and Program B might together have higher or lower value than the sum of the values of the two programs. One method to address this would be to evaluate a new program consisting of the two programs combined. This method is imperfect at best, and further work is needed to relax the assumption.

In reality, Air Vehicles does not fund their programs all at once and up front. Since total funding requirements for Air Vehicles' programs were provided, it is assumed these numbers represented the present value of all future yearly funding required to complete the program. Yearly cash flow constraints are easily added to the mathematical optimization programs used in this analysis.

Yearly funding profiles for the programs scored were not available at the time analysis was being completed. It is assumed that the programs are funded as a lump sum dollar amount. Clearly, this is not true in reality, and the models being used could be improved to consider periodic funding for the programs.

Any alternative that scores beyond the highest value for an evaluation measure receives the maximum value of 100 for that measure. Similarly, any alternative that scores below the lowest value for an evaluation measure receives the lowest value of zero for that evaluation measure. This prevents an alternative from being misrepresented in the value model and prevents biasing of the results. If the decision-maker ever feels an alternative should score outside of these boundaries, the evaluation measure should be rescaled accordingly.

Using the Air Vehicles Value Model

Alternatives

The starting point for identification of alternatives or technology programs is the Air Vehicle's Strategic plan and the Integrated Concept Leaders' roadmaps, which list programs under each integrated concept. From these technologies, Air Vehicles provided a subset of programs for analysis (see Figure 7). The programs were chosen so all higher tier values would score (thereby testing the model) and so each of Air Vehicles' three Integrated Concepts would have programs scored. The "Scoring Areas" show values where each program contributed. All programs except "Composite Repair of Aircraft" scored under "Reach" under "Gain". Three programs contributed under "Reach" under "Sustain," one program contributed under "Awareness," and four programs brought improvement to "Power." All scoring information came from the Air Vehicles' program managers or someone they designated as knowledgeable about their program.

All of the scoring functions were implemented in Excel. Air Vehicles also provided their investment costs required to perform each program. Elicited scores and descriptions of each program can be found in Appendix H: Air Vehicles' Programs and Scoring.

		Scoring Areas				Integrated Concepts		
Alternative/Information	Program	Reach/Gain	Reach/Sustain	Awareness	Power	UAV	Sustainment	Space
Weapons Bay Noise Suppression	**A**	X	X		X		X	
Composite Repair of Aircraft Strctures	**B**		X				X	
ITAC	**C**	X			X	X		
SITE-M	**D**	X			X	X		
Actuation Health-Monitoring Systems (HMS)	**E**	X	X	X				X
Space-Based System-of-systems Advanced Dv Demo & Validation	**F**	X						X
MTV	**G**	X			X	X		

Table 7: Programs Scored Using the Air Vehicles' Value Model

Besides identifying technology programs, it was also necessary to identify baseline warfighter scores or the current deployed state of the art for the proposed technology program. The purpose of this was to allow identification of the change from the current deployed state of the art in technology to the new proposed deployed state of the art. Scoring the change in technology allowed quantification of the value of technology.

A hypothetical "no change" alternative was determined. This alternative was the one that results in no improvement in value between an existing reference system and the new technology system. The no change alternative provides insight to the decision-maker about whether or not a program actually improves the warfighter's capability and whether or not it should be pursued. It also represents the deployed state of the art. At the highest level of the hierarchy, it shows the deployed state of the art for the warfighter as defined by Air Vehicles.

Program Evaluation

Program evaluation is the process of taking the raw scores for each program and converting them to an overall value using the value model. The process is to convert the raw scores provided by Air Vehicles into value using the single dimensional value functions for each attribute. Using an additive value function, the value functions were "rolled up" into a single measure of benefit to the warfighter. This process was completed for every alternative under consideration. The alternatives were then ranked according to their overall value. Graphs were developed showing how each alternative contributes in different areas to the overall value.

Because Air Vehicles supplied the expected cost for each alternative, the benefit to cost ratio was calculated for each alternative. The ratio allows determination of the largest "bang for the buck." The result was a prioritized list identifying the alternatives that provide the most benefit per cost. It represents the first cut at developing a portfolio of programs that optimize the benefit of the programs while meeting budgetary constraints. However, the portfolio is not guaranteed to be optimal. Therefore, a simple mixed integer program was developed to maximize the benefit to the warfighter while meeting a target budget.

Sensitivity Analysis

The weights for each evaluation measure and value were varied while holding the other measures at a constant ratio. From Kirkwood's discussion reviewed in Chapter 2, the following equation was developed for varying weights:

$$w_k = (1 - w_j)\left(\frac{w_k^0}{\sum_{\substack{i=1 \\ i \neq j}}^{k} w_i^0}\right) \qquad \text{for all } w_k \text{ where } k \neq j \qquad \textbf{Equation 5}$$

where w is defined as a local weight in a tier of the value model, k is the index to the weight to be kept at a constant ratio, j is the index to the weight being varied, and w^0 is the baseline weight for the weight being kept at constant ratio. The results were graphed showing changes in which programs are most valuable depending on weights. The analysis will quantify how robust the decision analysis results are.

Scoring Lessons Learned

In most cases, the program managers who were scoring were able to estimate overall ratios, but found it difficult to estimate a value for a system with the technology and a value for one without the technology. The best method to overcome this would be to develop or make use of existing simulation software to better estimate these parameters. Scoring the evaluation measures under Reach was difficult and the evaluation measures under Power were even more difficult.

In fact, under Power, the Program Managers reported they were guessing at the values for the measures. They knew that one program should score higher than another, but they did not feel confident in quantifying an actual scoring level. It might help to change the name of the "Effectiveness" to "Target Survival" since the evaluation measure is really using the probability of the target surviving. Additionally, it might help to change the name of "Survival" to "Platform Pk" since this evaluation measure considers the probability of killing a friendly unit, rather than the actual survival of the unit. The concepts are the complements of what is specified by the evaluation measure name, but considerable confusion resulted in attempting to explain these concepts.

Scoring using the Air Vehicles' value model required 10 hours for the seven programs scored. The scoring was completed with four program managers, since some manage more than one program. Scoring in small groups is important because it allows the program managers to communicate details about their program. These details are useful for the analyst to help develop insights in the results. The program managers of the programs were the best people to score their programs, although some tool to help them estimate specific probabilities would be very helpful and might decrease the time for scoring.

Suitability of the Air Vehicles' Model

Three questions can be asked about the Air Vehicles' model as to its usefulness. First, does the model represent all that is important (collectively exhaustive) about aerospace R&D? Second, is this model comparable to what has been done before? Third, are there any problems with the model limiting its capability to evaluate Air Vehicles' R&D? Clearly, other specific questions can be asked such as: 1) is the model doing what it was intended to do (verification), 2) is the model accurate for its intended use (validation), and 3) should the model be used by Air Vehicles (accreditation) (DoD Directive 5009.59, 1994). However, verification, validation and accreditation (VV&A) requires independent third party involvement, at least to some degree, to eliminate bias (Defense Modeling and Simulation Office, 1996: 2-11– 2-12). Hence, only the first three questions will be considered.

Table 8 summarizes how the Air Vehicles' value model covers dimensions of R&D identified in Table 1 of Chapter 2 and provides the information needed to answer the first question. Nearly every dimension was covered either directly or indirectly by Air Vehicles' values with the exception of training and educating people. Training and education of people, one result of basic research (Martin, 1996: 346) was not part of the value model at Air Vehicles' request. It belongs to a separate analysis effort, which would concentrate on what is important about developing Air Force R&D people.

R&D Dimension	Measurment
Aerospace Specific Measurements	All measures of "Gain," "Sustain" and "Lethality."
Contribute to Society	"Support the Warfighter" Defense of society is a contribution to it.
Evolutionary versus Revolutionary	"Expand our Frontier" and maximizing applicable "Gain," "Sustain" and "Lethality" metrics.
Improve Capability -Theoretical - Empirical - Methodological	Indirectly measured by how it contributes to a weapons system in "Gain," "Sustain" and "Lethality."
Performance versus Technical	Performance parameters are measured while technical parameters are not measured. Technical parameters are the means of accomplishing the performance parameters.
Programs	The Air Vehicles' value model scores programs.
Qualitative and Quantitative - Quantitative-objective - Quantitative-subjective - Qualitative-subjective	Values, discrete evaluation measures, and continuous evaluation measures were used in the value model and can be categorized by these dimensions.
Risk	Programmatic Risk measured, but this is a limited way of accomplishing the task. Value focused thinking uncertainty methods would improve this.
Scientific Knowledge	Measured indirectly by how it improves performance or decreases cost.
Technological Change	All measures of "Gain," "Sustain" and "Lethality" compare a reference system with the proposed new system. Several measures under Technological Change show this, also. This parameter is measured indirectly as "change in warfighter technological support."
Technological Trajectories - Cost Reduction - Incidence of Capitol Cost - Space Time Dimension of goods and services - Incidence of Specific Resource Consumption - Lifetime - Size/scale effects	Measured as follows: - Cost Reduction: "Afford" - Incidence of Capitol Cost: Indirectly – "Afford" - Space Time Dimension: Indirectly through "Gain," "Sustain" and "Lethality" - Resource Consumption: Payload/Range, Regeneration and Availability - Lifetime: "Achieve/Extend Life" - Size/scale effects: Indirectly – "Afford"
Train and Educate	Not measured – out of scope of model.
Military Specific - U.S. Air Force Strategic Planning - U.S. Air Force Doctrine - Historical Analysis of War	Measured by "Be Efficient," "Simplify Operations," and "Win"

Table 8: Dimensions covered by Air Vehicles Value Model

The other area that is covered in a limited way is risk. This area could be improved in the future using probabilistic methods available to Value-Focused Thinking (Kirkwood, 1997: Chapter 7). Probabilistic analysis was not implemented in the Air Vehicles' model due to lack of needed resources.

The conclusion of this survey using the literature is that the Air Vehicles' value model is collectively exhaustive in that it covers what is important to the Air Force warfighter. The question of whether or not the value model was collectively exhaustive was also asked of the Integrated Concept Leaders, the Strategic Integrated Process Team members, and the senior management of Air Vehicles. They have all agreed that the model is collectively exhaustive, to the best of their knowledge. In the future, it is recommended the model be shown to relevant Major Commands (MAJCOMs) in the USAF to determine if they agree.

The second question of whether the Air Vehicles' model is as good as previous models can be addressed using the data in Table 9. It identifies characteristics of the Air Vehicles value model and optimization capabilities as documented by Cetron, Martino, and Ropcke; Bretschneider and Sounder. The Air Vehicles model again covers almost all areas identified or is flexible enough that the missing capabilities could be added to the model. The model's weaknesses are directly related to its complexity. Because R&D is multidimensional, it would be difficult to simplify the model while maintaining accuracy in the results.

R&D Model Characteristic	Explanation
- Utility Measure - Orthogonality of Criteria - Sensitivity - Rejected Alternatives Retention - Classification Structure - Graphical Display - Computerized - Computer Program - Multiple objective - Hierarchical Structure - Basic/Applied Research - Priority Decisions - Low set up and computer Costs - Budget Limits - Termination Decisions - Competitor Effects - Optimization Analysis - Strategy Needs - Quick computer run time	The Air Vehicles value model with optimization has these characteristics. Note: Competitor effects for the warfighter can be defined as an adversary's predicted reaction to new technology. Optimization analysis is simplified in this model.
Probability of Success, Market Risk, Technical Risk, Premises uncertainty	Market risk and premises risk is not applicable. Probability of success and technical risk are capture by "Programmatic Risk" measure. Technical risk is assumed constant.
- Manpower and Facility Limits - Multiple Time Periods - Project Interdependencies - Strategies or future scenario analysis - Improved User friendliness	The Air Vehicles value model with optimization could have these options added on.
- Some variables not familiar - Requires a computer - Requires an analyst - Some special interpretation needed - Not capable of simulation or scheduling analysis - Requires large amounts of data and extensive time of personnel.	The Air Vehicles value model with optimization has these weaknesses.

Table 9: Characteristics of the Air Vehicles Model compared to R&D Model Features in the Literature

The third question of whether or not the model is too limited to properly describe R&D issues can be determined using Baker and Freeland's criteria (Baker and Freeland, 1975: 1165). They identified seven limitations of benefit measurement models and resource allocation models. The first consideration deals with risk and uncertainty. Value focused thinking with optimization allows in-depth treatment of the concepts, but the effort was beyond the scope of this effort (see Kirkwood, 1997: Chapter 7 for example). Baker and Freeland's concern on treatment of multiple and interrelated criteria is difficult to handle with value focused thinking, since mutually exclusive values and evaluation measures are needed (Keeney, 1992: 78). However, the builders of the Air Vehicles' model felt the values and evaluation measures were mutually exclusive and covered what is important to Air Vehicles. The builders were the analyst team for this project, the Air Vehicles' Integrated Concept Leaders, and the Strategic Integrated Concept Leaders. Optimization models can also be used to address interrelated criteria (Aaker and Tyebjee, 1978; Schmidt, 1993), although these methods were not needed in this effort.

Baker and Freeland's issue of maintaining balance between nonmonetary aspects of R&D was addressed by value focused thinking with optimization and is partially taken care of by the Air Vehicles' value model. This is possible simply in the identification of the values and the evaluation measures, which came from Air Vehicles. Golabi, Kirkwood, and Sicherman went further and used a clever mixed integer program combined with decision-maker interactions to balance constraints (Golabi, Kirkwood, and Sicherman, 1981: 176), but that kind of effort was, again, beyond the available resources.

The use of value focused thinking with Air Vehicles' should overcome Baker and Freeland's issue that models do not take advantage of R&D experts' experience and knowledge since it uses extensive expert inputs. For examples of how expert knowledge is used, see Parnell et. al., 1998; Golabi, Kirkwood, and Sicherman, 1981. The concern brought up by Baker and Freeland that R&D models are complex will not be dispelled by using this type of model as value focused thinking can result in complex formulations. For examples of how complex a model can become, see Parnell et. al., 1998; Golabi, Kirkwood, and Sicherman, 1981. Baker and Freeland's last issue, identifying problems of treatment of time variant data and criteria, is handled in this analysis by using quantitative-subjective and qualitative-subjective measures (Werner and Sounder, 1997: 34-37) with discrete evaluation measures (Clemen, 1996: 80).

Methodology and Modeling Summary

Reasons for selecting value focused thinking to select technology for Air Vehicles were presented. Next, the Air Vehicles' value model was developed and presented. Finally, a subset of Air Vehicles' programs was presented, program evaluation methods were discussed and the suitability of the model was explored.

Chapter 4: Results and Analysis

Introduction

With the Air Vehicles' value and optimization models discussed and developed, analysis is performed. First, the Air Vehicles' Value model is applied. This allows ranking of programs and determination of value gaps or identification of where programs do not score highly. Next, sensitivity analysis is performed and several topics are examined. First, how stable the value model is with changes in weights is examined. Second, a possible way of quantifying how technologist and operators in the USAF value technology was proposed. Next, the importance of Technological Superiority to Air Vehicles is discussed. Additionally, what the different Integrated Concepts value about making gains in new technology is looked at. Finally, some critical uncertain variables requiring further study are identified.

In the final section of the Chapter, optimization techniques are applied to maximize Air Vehicles' support for the warfighter for various target budgets. In preparation for optimization, the change in warfighter support due to technology is quantified and examples of meaningful statements using the results are provided. Using budget constraints, programs are optimized with an "all or nothing" funding assumption or with an "allowance of partial funding" assumption.

Value of Air Vehicles Technology

Ranking of a subset of Air Vehicles' Programs

The Air Vehicles' value model was used to analyze the benefit to the warfighter of seven technology programs currently in progress or planned in the near future. Table 10 shows the overall value scores calculated for the programs in rank order and it shows hypothetical "programs" which document the highest possible score, the lowest possible score, and the "No Change" alternative. "Benefit" is the score each program received for supporting the warfighter. The "Program Coding" is an arbitrary label for each program that simplifies references.

Air Vehicles' Program	Benefit	Ranking	Program Coding
Space-Based System-of-Systems Advanced Development Demo & Validation	48	1	F
Actuation Health-Monitoring Systems (HMS)	46	2	E
MTV	45	3	G
ITAC	43	4	C
SITE-M	42	5	D
Weapons Bay Noise Suppression	34	6	A
Composite Repair of Aircraft Structures	22	7	B
No Change	10	N/A	N/A

Table 10: Overall Scores and Relative Rankings for Seven Air Vehicles' Programs

The program that provides the most benefit to the warfighter (using the value model) was determined to be the "Space-Based System-of-Systems Advanced Development Demonstration and Validation." All of the programs were better than the "No Change" alternative, which indicates they are all making improvements over the current deployed state of the art. Hence, this result shows that the analyzed programs have the potential of making a substantial contribution to the warfighter.

Identifying Technological Gaps using the Value Model

The results from the value model can be used to determine if there are values not covered by the programs. With an exhaustive list of programs, if a value consistently scores poorly, identification of the poorly scoring values is the first step to fixing the problem. If a value is missed or consistently scores poorly, programs can be modified to perform better or new programs can be formulated to meet the shortfall. Chapter 2 listed some methods of creatively generating new programs.

Due to the small sample size of Air Vehicles programs scored, an analysis of value gaps can only be illustrated. It will be demonstrated by reviewing the programs in a few areas and observing shortfalls. A complete set of graphical results for the analyzed Air Vehicles' programs can be found in Appendix I: Graphical Sub-value Contribution to each Value and can be found in the Excel file "Ranking Graphs.xls." A review of hundreds of programs requires some development of automated tools to speed up the process.

The structure of the value model makes it is possible to determine the amount of value contributed by sub-values that are linked to a higher tier value. Figure 11 shows the contribution made by each of the seven programs scored for Air Vehicles along with the "No Change" hypothetical program for comparison. Any program that does not contribute at least as much value as the "No Change" program is not improving the deployed state of the art for Air Vehicles, although it might be funded for safety or cost reasons. Clearly, all of the programs in the notional set are advancing technology for the warfighter at least some amount.

To begin the analysis, the programs can be visually compared with each other and with the "Hypothetical Best Case" program to see what area is scoring lower than desired. For example, all of the programs score under "Reach," but none of the programs come close to the "Hypothetical Best Case." To find out why this is true, the next value in the value model should be examined.

In this case, Reach is divided into "Gain" and "Sustain." Figure 12 shows the contributions each program makes to "Gain" and "Sustain" under Reach. Clearly, some of the "Gain" programs score quite high (for example consider Space Based System-of-Systems Advanced Dv Demo & Validation). However, under sustain, all of the programs scored much lower than the possible "Hypothetical Best Case."

Figure 13 shows each program's contribution made to "Sustain." Out of the seven programs analyzed, three show contributions to "Sustain." Visual inspection of Figure 13 shows that no programs scored in "Missions Enabled," "Safety," or "Weight Reduction." Additionally, the programs did not score extremely high in "Achieve/Extend Life." If it were found that none of the over 100 Air Vehicles' programs scored in these areas, it would become important to create or modify programs to score in the areas. Otherwise, not all of Air Vehicles' values would be achieved. If the decision-makers felt after analysis that these values were not important after all, then they should be dropped from the value model and the section of the model should be reworked as needed.

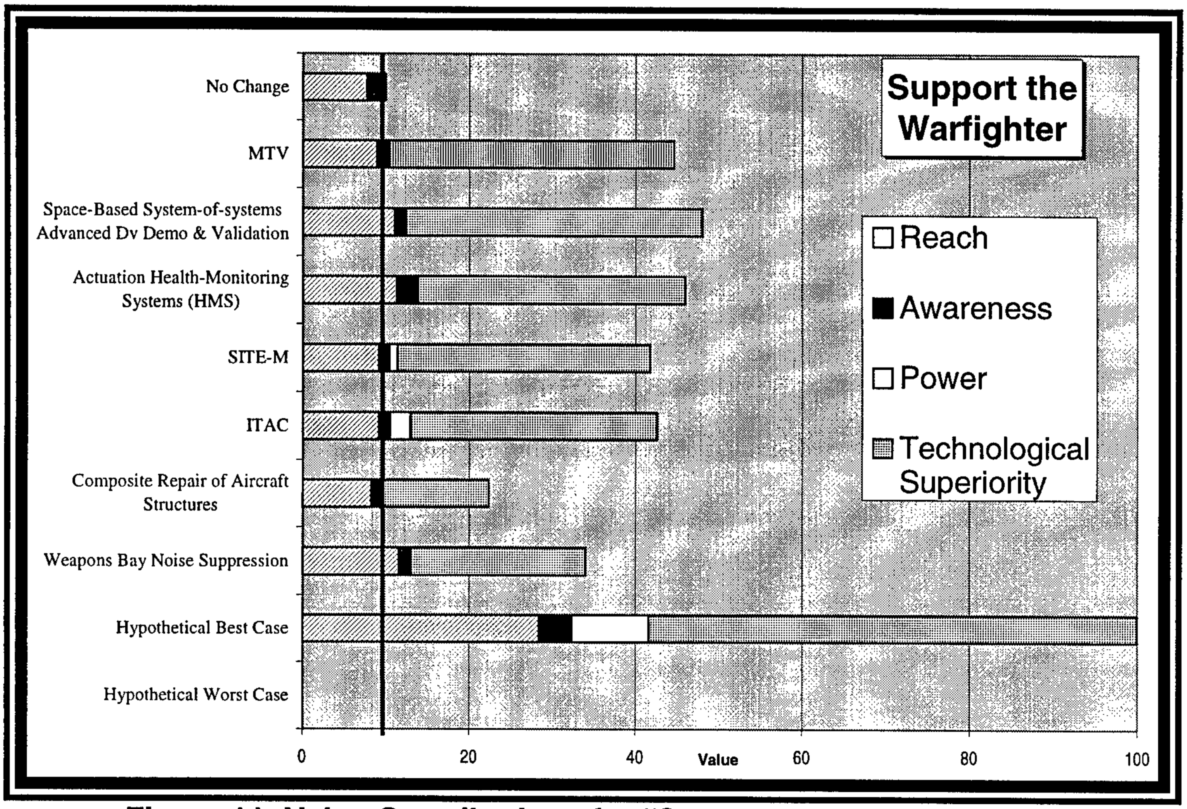


Figure 11: Value Contributions for "Support the Warfighter"

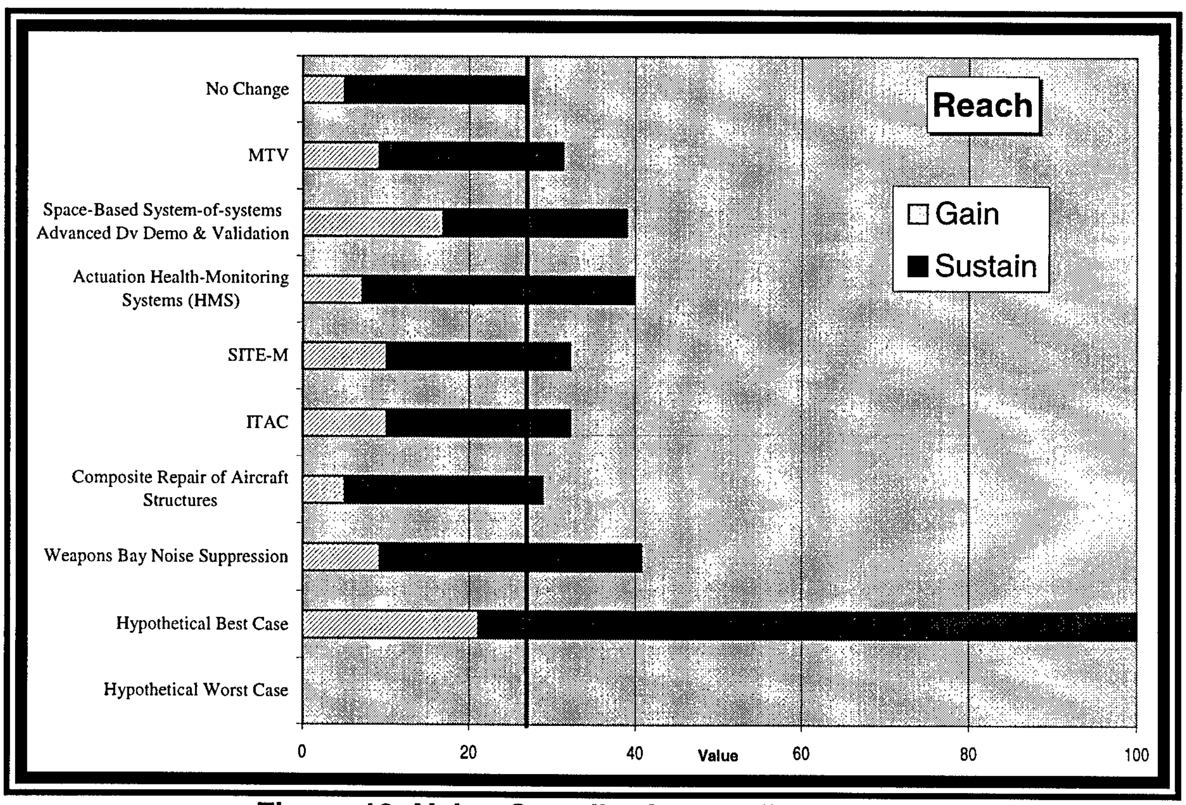


Figure 12: Value Contributions to "Reach"

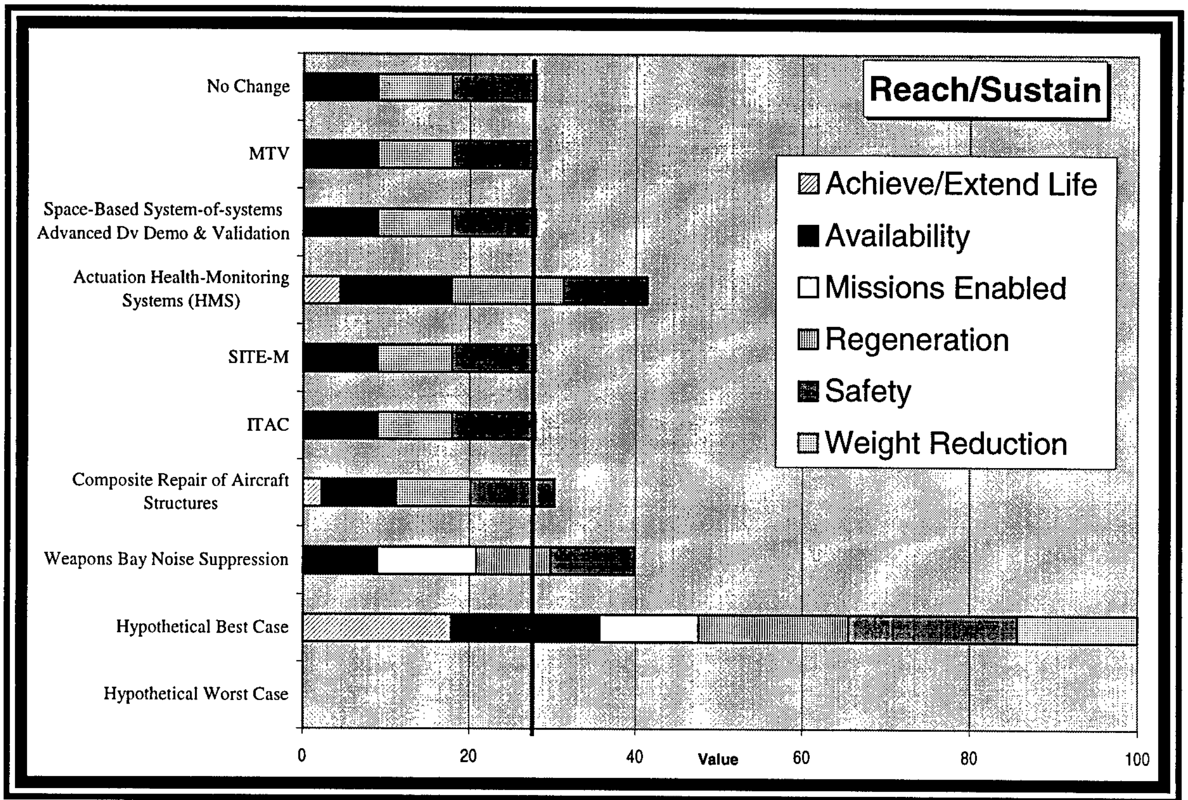


Figure 13: Value Contributions to "Sustain"

Sensitivity of the Air Vehicles' Value Model

Sensitivity analysis was accomplished on all of the weights for the values and evaluation measures. The graphical results can be found in Appendix J: Sensitivity Analysis of all Values and Evaluation Measures and can be found electronically in the Excel file called "Sensitivity Analysis.xls." In the discussion that follows, all graphs use the key shown in Figure 14. Variation in weights was calculated for each program score for Air Vehicles and graphed. "Set Weight" represents the baseline weight selected by Air Vehicles for the value or evaluation measure under examination. This value allows comparison of changes to weights with the baseline. The "No Change" alternative is graphed as a reference. Any program scoring lower than the "No Change" line is not improving the deployed state of the art in technology for the warfighter.

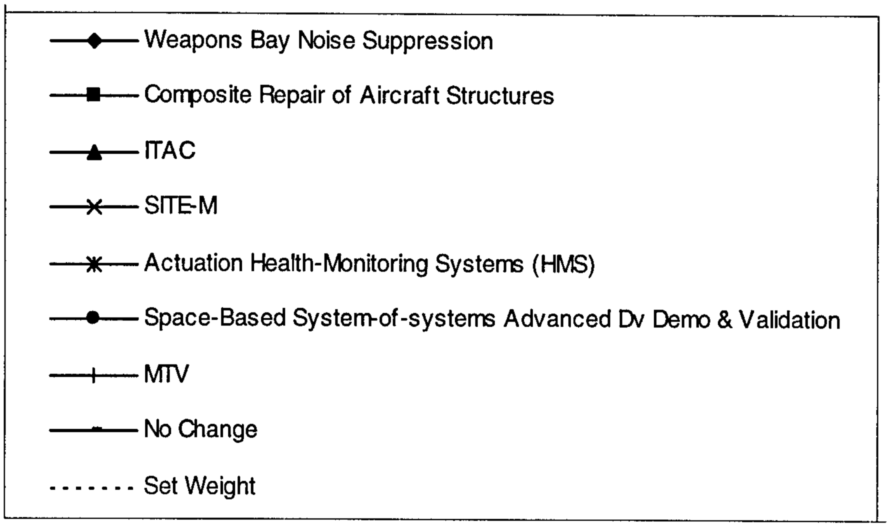


Figure 14: Sensitivity Analysis Key

Analysis of "Support the Warfighter"

Figure 15 shows the results of varying the weight for "Reach" from its lowest possible value to its highest possible value. If the weight is lowered from its baseline value, there is no change in the ranking of the alternatives until an approximate weight of 0.15 is reached. When this happens, the MTV program changes position with the Actuation Health Monitoring Program. Other then this, no other changes take place.

If the weight is increased from its baseline value, the "Weapons Bay Noise Suppression" program becomes more important, and at a weight of 0.6, it scores better than "SITE-M," "MTV", and "ITAC." As the current weight for "Reach" is 0.28, the importance of "Reach" would have to double or be reduced by nearly half before any ranking changes take place. The conclusion is a major policy shift would be needed in Air Vehicles before the programs would change their ranks.

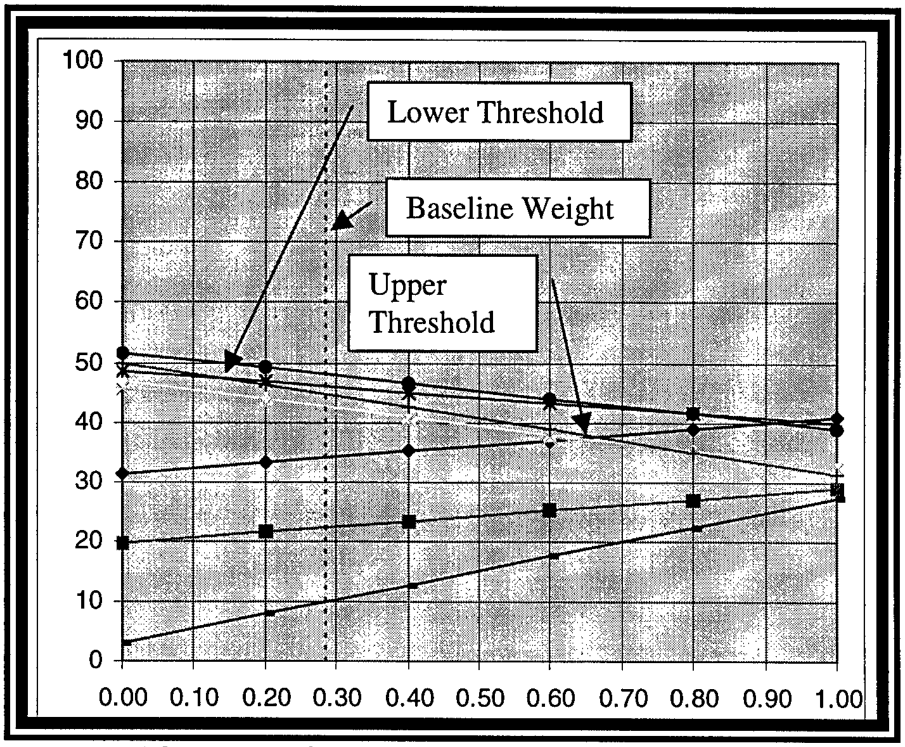


Figure 15: Sensitivity of Weight for Reach

Table 11 shows the thresholds where changing the weight of the top tier values results in a change in the ranks of the scored programs. The discussion that follows examines where changes in the rankings of the programs change to determine how the ranks change based on the weights for the top tiered evaluation measures. The purpose of this is to determine how sensitive Air Vehicles' value model is to the weight. If large changes take place for small changes in the weights, the model would be extremely sensitive and Air Vehicles would have to be extremely accurate in determining the weights. If the opposite is true, then there would be room for errors in subjective judgement, which would increase the confidence in the modeling results.

Value	Weight	Lower Threshold	Percent Decrease	Upper Threshold	Percent Increase
Reach	0.28	0.15	46%	0.65	57%
Awareness	0.04	0	100%	0.1	60%
Power	0.09	0.02	78%	0.15	40%
Technological Superiority	0.58	0.43	26%	0.73	21%

Table 11: Approximate Weight changes that first re-rank Programs (Note – Weights do not add up to one due to round off)

"Awareness" has no lower threshold where the programs change their ranks, but would have to be increased 60% before programs would change their rankings. Only "Actuation Health Monitoring System" scored under "awareness." The threshold represents the point where the program becomes the most valuable program in the programs scored for Air Vehicles. Because Air Vehicles is not the primary Directorate for developing "Awareness" in AFRL, it is highly unlikely this value would increase drastically in weight.

"Power" has a lower threshold of 0.02 for weight where "ITAC" and "SITE-M" ranked fourth and fifth respectively, change places. Starting at the upper threshold of 0.15, "MTV," "Actuation Health Monitoring Systems," and finally "Space Based System of Systems Advanced Development Demonstration and Validation" programs become overwhelmed by the importance being placed on "Power." Because Air Vehicles is not the primary Directorate in AFRL for developing aerospace power, it is unlikely this value would ever be weighted so heavily.

"Technological Superiority" has a lower threshold of 0.43, where "MTV" and "ITAC" ranked third and forth, respectively change places. A the upper threshold of 0.73 for weight, "Actuation Health Monitoring" and "MTV" ranked second and third change places. At nearly the same weight, "ITAC" and "SITE-M," ranked fourth and fifth respectively, change places.

Overall, if the programs do not change ranks over a wide range of changes in the weights for the Air Vehicles' value model. Air Vehicles does not have to perfectly estimate the weights for the value model. Further, in the weight ranges documented in Table 11, at no time did the top ranked program "Space Based System of Systems Advanced Development Demonstration and Validation" ever change positions. Hence, it can be confidently stated that this program provides the most value to the warfighter of any of the programs scored.

Analysis of Extremes of Technological Superiority

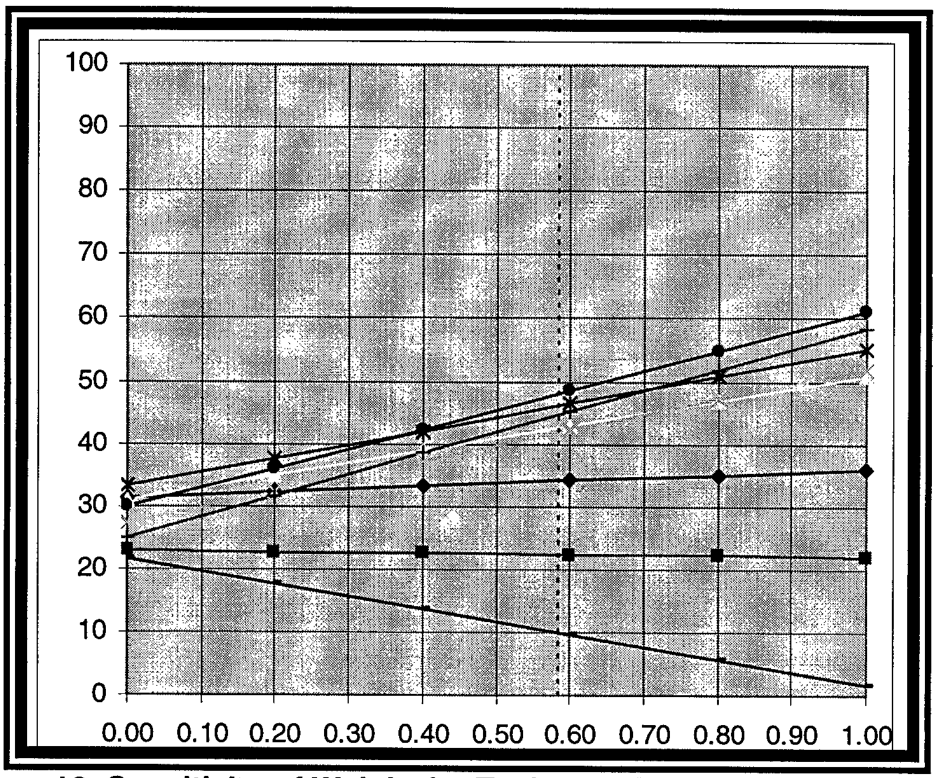


Figure 16: Sensitivity of Weight for Technological Superiority

Technological Superiority, besides being the highest weighted value, shows tremendous importance to the Air Vehicles' Directorate. Figure 16 shows how varying the weight of Technological Superiority changes the rankings and overall scores of the programs scored. For low weights, the ability to distinguish between the different programs becomes more and more difficult. As the weight increases, the programs diverge significantly and the scores increase dramatically.

Analysis of Gain versus Sustain under Reach

The senior leadership of Air Vehicles believe that starting about 2002, Air Vehicles will be increasing its emphasis on gaining new capabilities rather than sustaining old ones. There is clear reason to believe the weights for "Gain" and "Sustain" will be changing. Sensitivity analysis of this quantity can provide some insights on what this might mean.

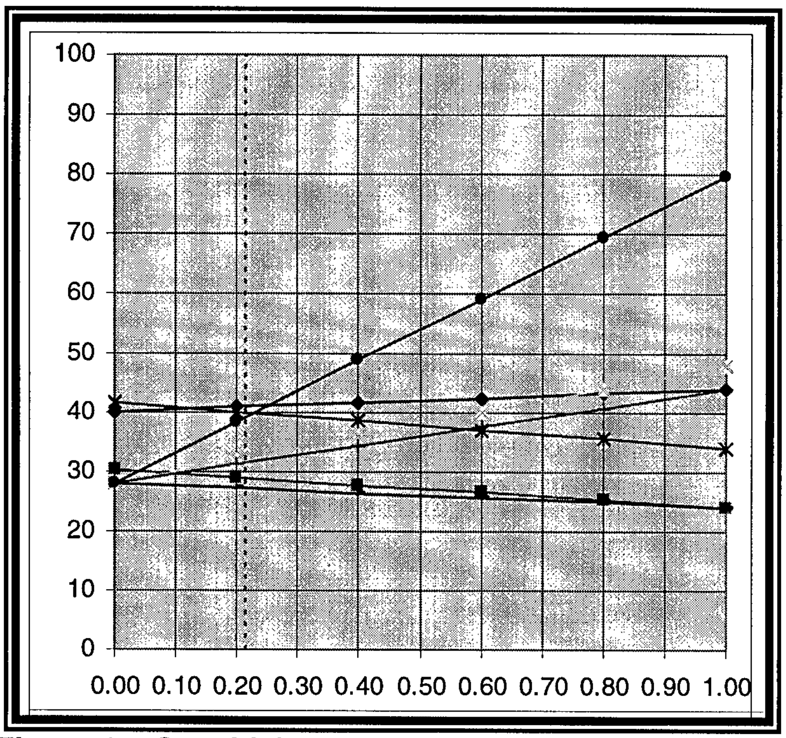


Figure 17: Sensitivity of Weight on Gain under Reach

As the weight of "Gain" under "Reach" increases, the "Space Based System-of-Systems Advanced Demonstration and Validation" program will increase in performance. The analysis shows most of the other programs improving in importance. However, the "Composite Repair of Aircraft" program and the "Actuation Health Monitoring System" will tend to decrease. This is because the "Composite Repair of Aircraft" program does not score under "Gain" and the "Actuation Health Monitoring System" scores higher under "Sustain" than it does under "Gain." Future programs should attempt to maximize "Gain" and any scoring in "Sustain" will help, but will not be as important as it is currently.

Space versus UAV and Sustainment Efforts under Reach/Gain

In meetings with the Integrated Concept Leaders, there was disagreement on what the weights should be for the evaluation measures under Reach/Gain. The best program in all cases was "Space Based System of Systems Advanced Development Demonstration and Validation." This program received all of the possible value in all categories except "Payload-Range". For more information on why, see Appendix H: Air Vehicles' Programs and Scoring. The "Composite Repair of Aircraft" program always decreased in value with increasing weight on any evaluation measure under "Gain" since it did not score under "Gain."

Table 12 summarizes the trends for each evaluation measure when the weight for that particular measure is increased. The Space programs improved in "Availability" and "Regeneration." The UAV programs scored improved in "Missions Enabled" and "Response Time." The Sustainment programs did not do well under Gain, although the "Weapons Bay Noise Suppression" program did show improvements in "Missions Enabled."

Program	Availability	Missions Enabled	Regeneration	Response Time	Payload-Reach
Weapons Bay Noise Suppression (Sustainment)	Little Change	Increase	Little Change	Decrease	Decrease
Composite Repair of Aircraft Structures (Sustainment)	Decrease	Decrease	Decrease	Decrease	Decrease
ITAC (UAV)	Little Change	Increase	Little Change	Decrease	Decrease (Nonzero Score)
SITE-M (UAV)	Decrease	Increase	Little Change	Increase	Decrease
Actuation health-Monitoring Systems (Space)	Increase	Decrease	Increase	Decrease	Decrease
Space-Based System-of-Systems Advanced Development Demonstration and Validation (Space)	Increase	Increase	Increase	Increase	Decrease
MTV (UAV)	Increase	Decrease	Increase	Increase	Decrease (Nonzero Score)

Table 12: Scored Air Vehicle Program Trends under Reach/Gain Evaluation Measures

Critical Uncertainties

During scoring of the programs, some of the evaluation measures were difficult to estimate scores. The Air Vehicles' experts admitted they were guessing the evaluation measures for "Survival" under Power/Lethality. However, they felt the "SITE-M" program bounded the scores for the other programs and were certain which programs improved "Survival." Another evaluation measure that drew much discussion was the "Revolutionary" metric under Technological Superiority/Expand our Frontier. The group suggested the definition was not quite correct. They felt "Revolutionary" should apply to changing the paradigm of the warfighter, not changing the paradigm of Air Vehicles'.

The other place for uncertainty was "Programmatic Risk." The experts felt a medium level of "Programmatic Risk" should be closer to a 75-25 split rather than a 50-50 split. This difference in opinion seems to be more related to risk aversion (Kirkwood, 1997: 136). Some people are risk adverse in that they are willing to do most anything to avoid it. Others are risk seeking in that they are willing to gamble with the odds against them when the possible rewards are high. This difference in opinion on how to define "Programmatic Risk" may be a manifestation of different risk attitudes in Air Vehicles and should be addressed directly.

With these concerns in mind, the scores in the affected programs for each area were changed to see if the overall ranks would change for the programs. The "Survival" scores for "Weapons Bay Noise Suppression,", "ITAC," and "MTV" were set to the same value as the "SITE-M" program. The ranks did not change, although the scores did change slightly. Similarly, the "Programmatic Risk" scores were changed. However, the global weight for this evaluation measure is a magnitude and a half less than all of the other evaluation measures, which means this evaluation measure currently has no effect.

Varying "Revolutionary" did cause a major change in the ranks of the programs. Table 13 shows the results of making the changes. The conclusion from this analysis is "Revolutionary" is a prime candidate for further study and might actually be better analyzed using uncertainty.

Program	Original Ranking	New Ranking
Weapons Bay Noise Suppression *	6	6
Composite Repair of Aircraft Structures *	7	7
ITAC *	1	4
SITE-M *	2	5
Actuation health-Monitoring Systems	4	2
Space-Based System-of-Systems Advanced Development Demonstration and Validation	3	1
MTV	5	3

Table 13: Change in Ranks by Changing "Revolutionary" for Programs Marked with "*"

The Cost of Creating Change in Warfighter Technological Support

Measuring the Change in Warfighter Support for a Program

It would be incorrect to conclude that Air Vehicles should only fund the programs resulting in the greatest benefit to the warfighter, since the benefit achieved comes at a price. "Change in warfighter technological support" is defined as the difference between a program score and the "No Change" alternative score. A program that provides large benefits for small investment costs is preferred to one that provides large benefits for large investment costs.

One approach for determining the best benefit to the warfighter for a particular investment cost is to calculate the benefit to cost ratio (Kirkwood, 1997: 200-206; Bell and Read, 1974: 36). Table 14 shows the programs re-ranked from the highest to the lowest benefit per cost ratio. The best programs are those that provide large jumps in benefit at the smallest possible cost. In the Air Vehicles' subset of programs, it is clear that all of the programs provide varying amounts of benefit, but some require larger investments for the benefit attained than others.

Alternative	Cost (Millions of Dollars)	Warfighter Benefit	Benefit/ Cost	Program Code Letter	Change in warfighter Technological Support
SITE-M	2	41.73	20.86	D	31.78
Actuation Health-Monitoring Systems (HMS)	4	46.00	11.50	E	36.05
Weapons Bay Noise Suppression	7	34.00	4.86	A	24.05
ITAC	11	42.62	3.87	C	32.67
Composite Repair of Aircraft Structures	6	22.36	3.73	B	12.41
Space-Based System-of-systems Advanced Development Demo & Validation	25	48.03	1.92	F	38.07
MTV	25	44.58	1.78	G	34.63

Table 14: Air Vehicles' Programs Ranked from highest to lowest Benefit to Cost Ratio

However, the "Strategic Position" in the Air Vehicles' strategic states Air Vehicles will "deliver the best air vehicle technologies for aerospace dominance against all threats . . ." Using the benefit to cost ratio to rank the programs is flawed because the decision-maker cannot be certain if the proposed programs are actually improving the deployed state of the art or not. Additionally, the benefit to cost ratio method using "Warfighter Benefit" in Table 14, measures the best *programs* for aerospace rather than the best *technologies* for aerospace. While technological change cannot be directly measured from the Air Vehicles' value model, what can be measured is the change in warfighting technological support, which was discussed in Chapter 3. This quantity compared with cost can be found in Figure 18.

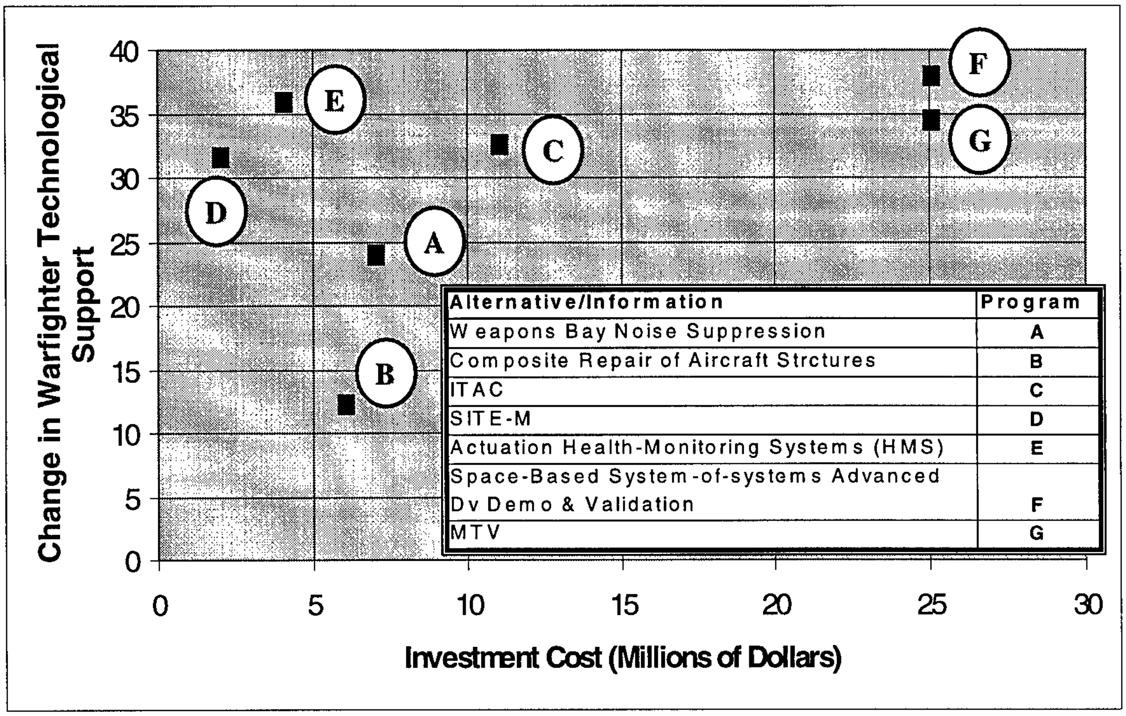


Figure 18: The Change in Warfighter Benefit versus the Cost

A new parameter, called change in warfighter technological intensity is defined as the ratio of change in warfighting technological support to investment cost. Some observations about this variable are in Appendix K: Intensity of Change in Warfighter Support due to Technology . Table 15 shows the Air Vehicles' programs scored in descending order of change in warfighter technological intensity.

In Chapter 3, the change in warfighting technological support was found to be measured on a ratio scale. Consequently, using the values in Table 15, it is possible to make statements like "the 'Weapons Bay Noise Suppression' program (score of 24.05) provides nearly twice the change in warfighting technological support that the 'Composite Repair of Aircraft Structures' program (score of 12.41) provides." Similarly, it can be stated that "the 'Space-Based System-of-Systems Advanced Development Demo & Validation' (score of 38.07) is expected to provide over three times the technological advancement in Air Force warfighting that the 'Composite Repair of Aircraft Structures' program (score of 12.41) provides."

Alternative	Cost (C_i) (Millions of Dollars)	Change in Warfighter Technological Support (T_i)	Change in Warfighter Technological Intensity	Program Code Letter
SITE-M	2	31.78	15.89	D
Actuation Health-Monitoring Systems (HMS)	4	36.05	9.01	E
Weapons Bay Noise Suppression	7	24.05	3.44	A
ITAC	11	32.67	2.97	C
Composite Repair of Aircraft Structures	6	12.41	2.07	B
Space-Based System-of-Systems Advanced Development Demo & Validation	25	38.07	1.52	F
MTV	25	34.63	1.39	G

Table 15: Change in Warfighter Technological Support of Air Vehicles' Programs Ranked from highest to lowest Technological Intensity

The total change in warfighter technological support can be compared with the total investment cost using the change in warfighter technological intensity for ranking purposes. The result is shown in Figure 19. The decision-maker can use this method to find a good solution of what programs should be funded. The decision-maker can choose the funding level for the portfolio and then can determine impacts the technology will have on improving the deployed state of the art. As the funding increases, the program at the chosen funding level and the programs at lower funding levels become part of the overall portfolio of programs.

In using the method, however, the decision-maker should realize that the result has many limitations. First, the portfolio does not have to be optimal (Kirkwood, 1996: 200-205; Bell and Read, 1974: 36). Second, there is no insight provided on possible portfolio combinations between the plotted points. Third, the method can only use a single constraint (cost in this case) and assumes that the programs do not interact (Kirkwood, 1997: 206). To be guaranteed of an optimal portfolio of programs, linear or integer programming techniques are required. This topic will be examined next.

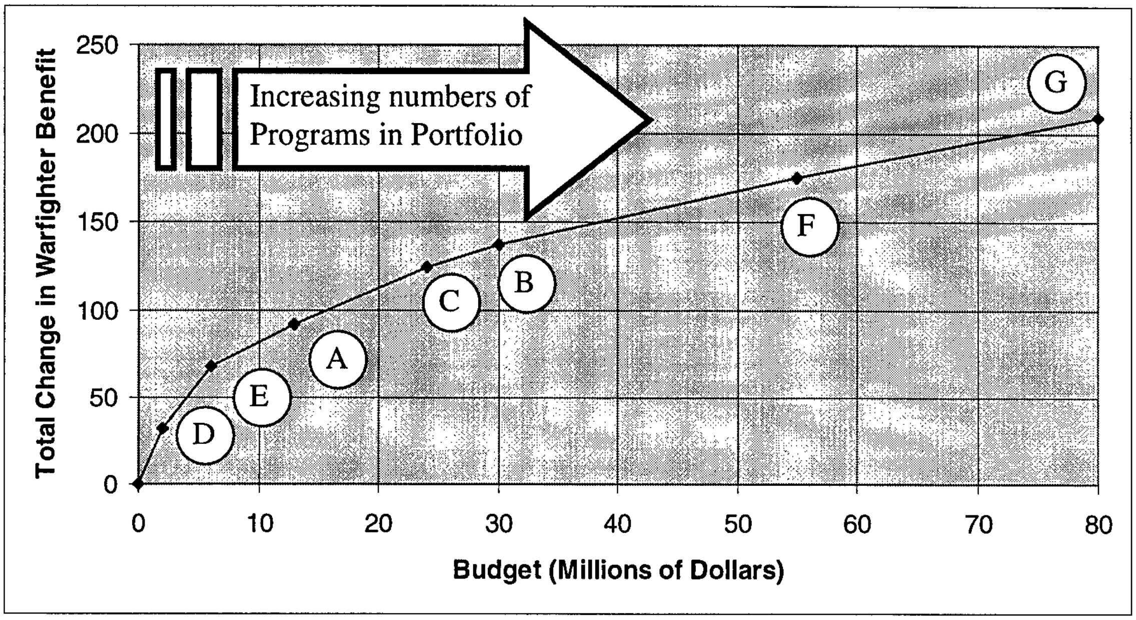


Figure 19: Total Change in Warfighter Technological Support versus Cumulative Cost Results

The Change in Warfighter Support due to Technology versus Program Cost Assuming "All or Nothing" Funding

Comparing technological change with investment cost allowed the development of a possibly sub-optimal portfolio of programs. The first policy type examined for optimization is the case where a program is either fully funded or dropped from the planned portfolio. To determine the optimal solution, the following binary or 0-1 math program was developed:

Let x_i = the fraction of program i that is funded.

Let T_i = the change in warfigher technological support to be created because of implementation of program i.

Let C_i = the investment cost of implementing program i (in millions of dollars).

Let B = the available funding for a portfolio of programs.

Let $i \in \{A,B,C,D,E,F,G\}$ which are the programs to be optimized.

$$\text{Maximize Technological Change} = \sum_i T_i x_i$$

Such That

$$\sum_i C_i x_i \leq B$$

$$x_i \in \{0,1\} \quad \text{for all } i$$

The values for Change in Warfighter Support due to Technology (T_i) and the investment cost (C_i) are taken from Table 15. The available budget, B, was parameterized to vary from no dollars to \$80 million in increments of \$1 million. The \$80 million figure was chosen since this is the minimum investment required funding for all seven of the Air Vehicles' programs scored in the study.

Figure 20 shows the optimized change in warfighter technological support that can be created versus all investment cost up to the point where all programs are funded. It also shows the change in warfighter technological support versus cost calculated using the benefit to cost ratio. In this situation, the benefit to cost ratio method turned out to be optimal at the points calculated. The 0-1 math calculations show combinations of programs can be specified that provide optimum portfolio policies at intermediate points not found by the benefit to cost ratio method.

Figure 21 shows the optimized portfolio of programs that provides the most change in warfighter technological support for investments between \$60 million and \$80 million. A change of \$1 million dollars difference in funding can make a substantial difference in which programs are funded. For example, a drop in funding from \$74 million to $73 million results in "Weapons Bay Noise Reduction" program not being funded in favor of "Composite Repair of Aircraft Structures." Another drop of $1 million dollars results in "ITAC" being dropped in favor of funding both "Weapons Bay Noise Reduction" and "Composite Repair of Aircraft Structures." In the next section, the assumption of "all or nothing" funding is relaxed, allowing consideration of partially funding programs.

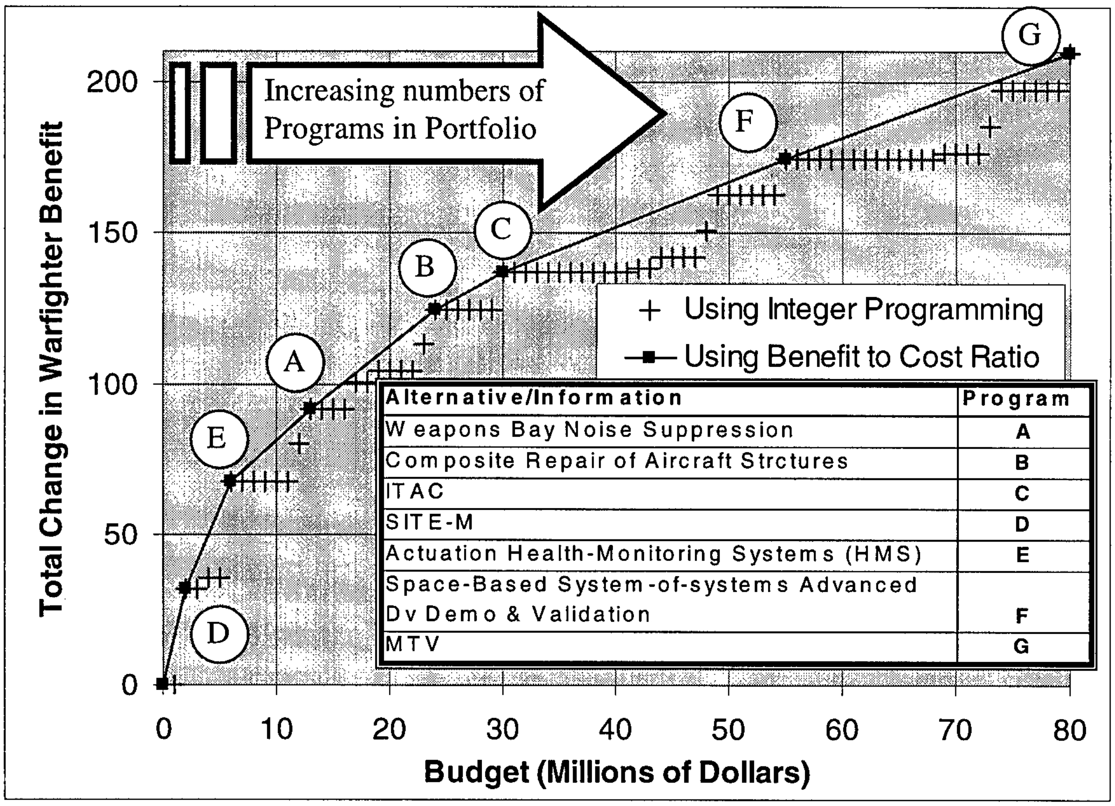


Figure 20: Optimized Change in Warfighter Technological Support versus Investment Cost using 0-1 Math Program

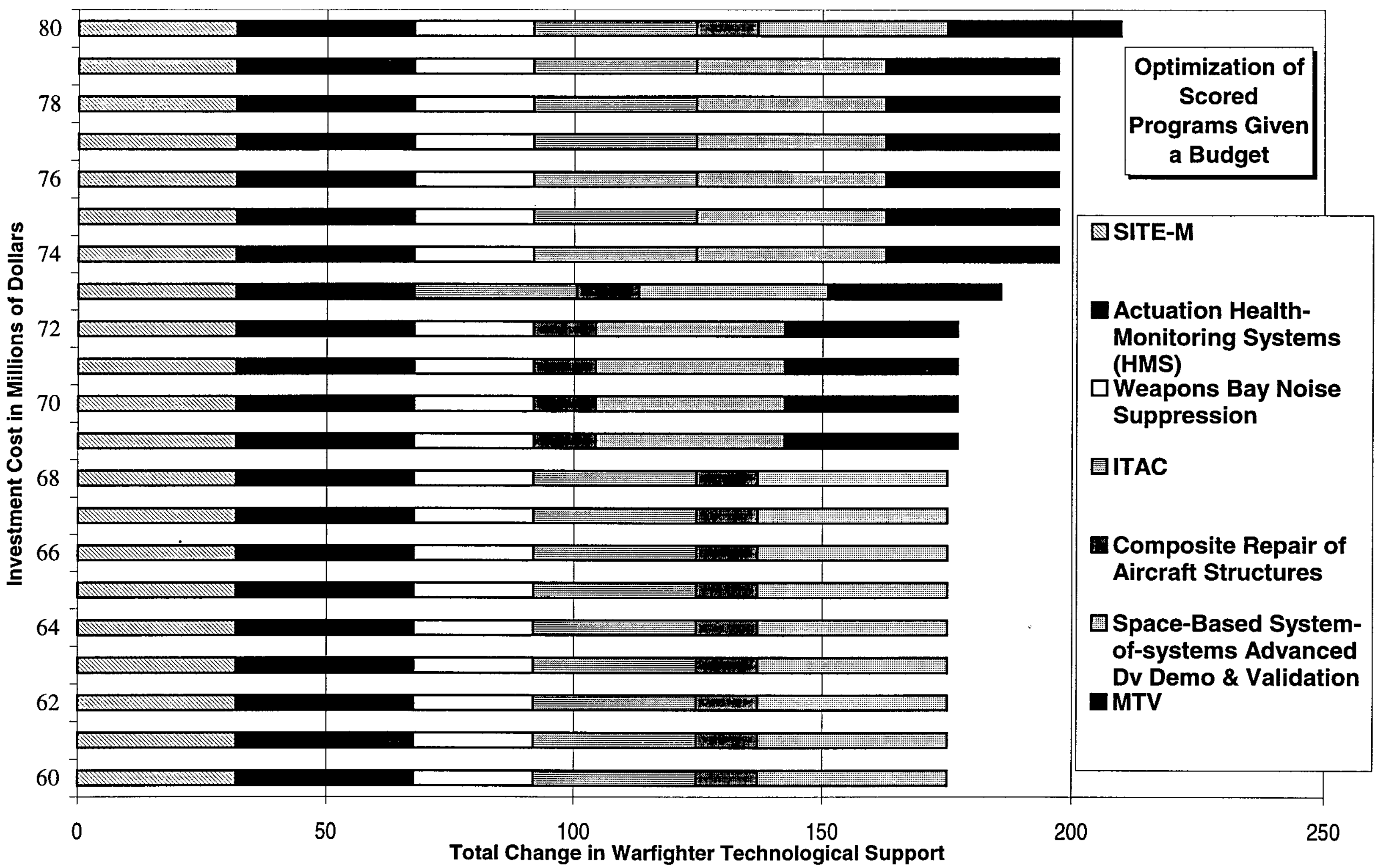


Figure 21: Portfolio Mix of Programs for various Investment Costs by Cutting Programs

Change in Warfighter Technological Support versus Program Cost Assumes Partial Funding of Programs

By relaxing the integer (all or nothing) requirement, partial funding can be considered. The linear programming implementation for calculating change in warfighter technological support, is shown below:

Let x_i = the fraction of program i that is funded.
Let T_i = the technological change to be created because of implementation of program i.
Let C_i = the investment cost of implementing program i (in millions of dollars).
Let B = the available funding to fund a portfolio of programs.
Let $i \in \{A, B, C, D, E, F, G\}$ which are the programs to be optimized.
Let L_i = the lower fraction of funding allowed for program i.

$$\text{Maximize Technological Change} = \sum_i T_i x_i$$

Such That

$$\sum_i C_i x_i \le B$$

$$L_i \le x_i \le 1 \quad \text{for all } i$$

The value L_i is the lower bound that program i can drop to and still improve the deployed state of the art in technology. This formulation assumes that both investment cost and change in warfighter technological support can be reduced linearly until the lower bound L_i is reached. Specifying L_i results in the hard constraint that program i must be funded at least to the level of L_i.

Two cases of the linear program were run. First, a case where $L_i = 0$ was run to determine the maximum possible change in warfighter technological support for various budget levels. Then, the following arbitrary values for L were set:

$L_A = 0.75$, $L_B = 0$, $L_C = 0$, $L_D = 0.75$, $L_E = 0.75$, $L_F = 0$, $L_G = 0.95$.

Figure 22 shows the optimal change in warfighter technological support for various budgets for both partial funding cases and the "all or nothing" funding profile shown in the last section. Table 16 shows the percent funding for the Air Vehicles' programs for various funding levels. The result shows the "No Minimum Required" funding profile provides the most total change in warfighter benefit at a particular budget level. In general, this is the best and most desired funding profile that is possible. However, it is impossible to achieve this profile since R&D programs cannot be funded below certain levels and still gain any useful results.

The "Minimum Required Partial Funding" profile shows the penalties paid by being forced to fund some of the projects at a relatively high level. The profile stops at $34 million because below $34 million it is impossible to meet all of the funding requirements (the linear program is infeasible below $34 million). The "All or Nothing Funding" profile shows the profile for the programs if the assumption is they must be 100% funded or not funded at all. With this in mind, it appears there may be times when a partial funding policy with positive lower funding limits and the "All or Nothing" funding policy each provide more benefit than the other. This is shown by the fact that some of the "All or Nothing" results are higher than the equivalent "Minimum Partial Funding" results. The reverse also takes place showing that partial funding is sometimes the better policy for maximizing change to warfighter support due to technology.

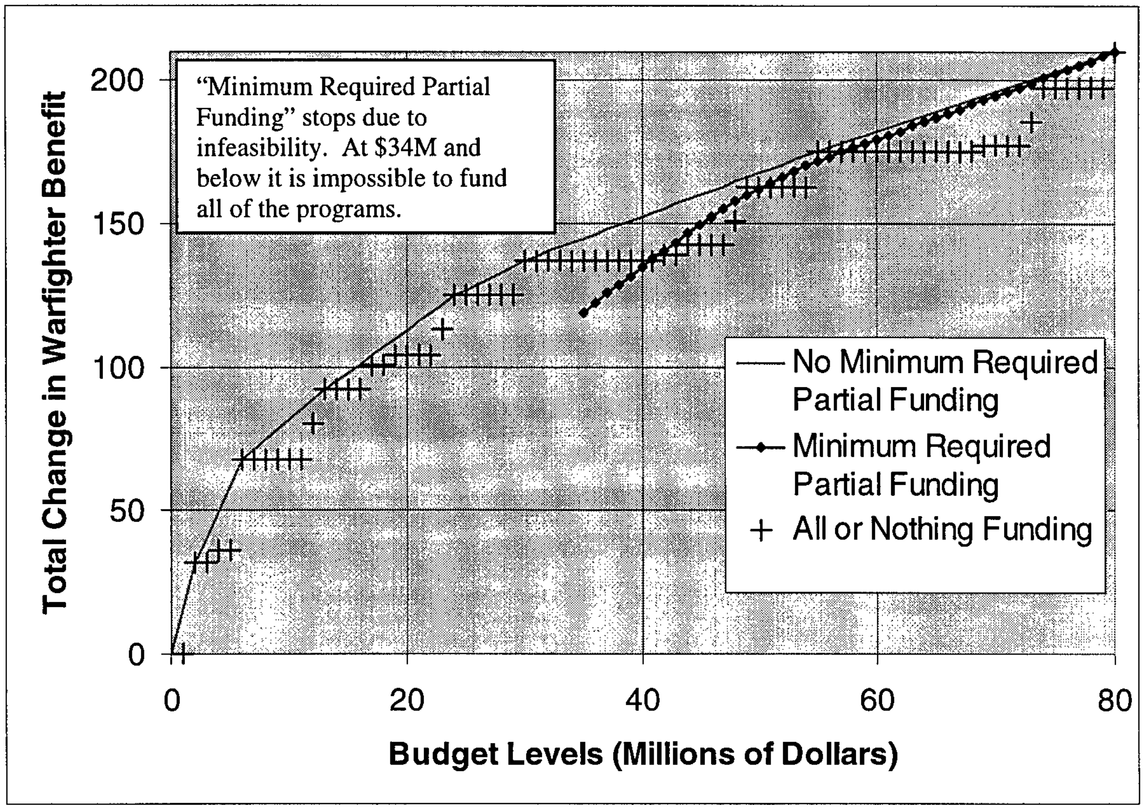


Figure 22: Optimized Change in Warfighter Technological Support versus Investment Costs using Linear Programming

		Program						
Budget (Millions of Dollars)	Change in Warfighter Tech. Benefit	D	E	A	C	B	F	G
35	119	100%	100%	75%	0%	0%	0%	95%
36	122	100%	100%	89%	0%	0%	0%	95%
37	126	100%	100%	100%	2%	0%	0%	95%
38	128	100%	100%	100%	11%	0%	0%	95%
39	131	100%	100%	100%	20%	0%	0%	95%
40	134	100%	100%	100%	30%	0%	0%	95%
41	137	100%	100%	100%	39%	0%	0%	95%
42	140	100%	100%	100%	48%	0%	0%	95%
43	143	100%	100%	100%	57%	0%	0%	95%
44	146	100%	100%	100%	66%	0%	0%	95%
45	149	100%	100%	100%	75%	0%	0%	95%
46	152	100%	100%	100%	84%	0%	0%	95%
47	155	100%	100%	100%	93%	0%	0%	95%
48	158	100%	100%	100%	100%	4%	0%	95%
49	160	100%	100%	100%	100%	21%	0%	95%
50	162	100%	100%	100%	100%	38%	0%	95%
51	164	100%	100%	100%	100%	54%	0%	95%
52	166	100%	100%	100%	100%	71%	0%	95%
53	168	100%	100%	100%	100%	88%	0%	95%
54	170	100%	100%	100%	100%	100%	1%	95%
55	172	100%	100%	100%	100%	100%	5%	95%
56	173	100%	100%	100%	100%	100%	9%	95%
57	175	100%	100%	100%	100%	100%	13%	95%
58	176	100%	100%	100%	100%	100%	17%	95%
59	178	100%	100%	100%	100%	100%	21%	95%
60	179	100%	100%	100%	100%	100%	25%	95%
61	181	100%	100%	100%	100%	100%	29%	95%
62	182	100%	100%	100%	100%	100%	33%	95%
63	184	100%	100%	100%	100%	100%	37%	95%
64	185	100%	100%	100%	100%	100%	41%	95%
65	187	100%	100%	100%	100%	100%	45%	95%
66	189	100%	100%	100%	100%	100%	49%	95%
67	190	100%	100%	100%	100%	100%	53%	95%
68	192	100%	100%	100%	100%	100%	57%	95%
69	193	100%	100%	100%	100%	100%	61%	95%
70	195	100%	100%	100%	100%	100%	65%	95%
71	196	100%	100%	100%	100%	100%	69%	95%
72	198	100%	100%	100%	100%	100%	73%	95%
73	199	100%	100%	100%	100%	100%	77%	95%
74	201	100%	100%	100%	100%	100%	81%	95%
75	202	100%	100%	100%	100%	100%	85%	95%
76	204	100%	100%	100%	100%	100%	89%	95%
77	205	100%	100%	100%	100%	100%	93%	95%
78	207	100%	100%	100%	100%	100%	97%	95%
79	208	100%	100%	100%	100%	100%	100%	96%
80	210	100%	100%	100%	100%	100%	100%	100%

Table 16: Percent Funding Profile for Minimum Partial Funding

Other Costs Besides Investment Dollars

There are other types of constraints, that are likely to be important to Air Vehicles other than the investment dollar amounts. According to the literature, typical constraint types are budget constraints, skill availability constraints, facility availability constraints, raw material availability constraints, and program balance and/or risk balance constraints (Bretschneider, 1993: 130; Cetron, Martins, and Roepoke, 1967, 5). The constraints are examined for how they might be added to the "all or nothing" funding math analysis or the integer math program, although similar types of constraints can be added to the partial funding math analysis.

One type of constraint is the need to balance programs among several groups. An example is to constrain the analysis such that a minimum number of Integrated Concepts or basic/applied/development programs are funded. For example, in the integer programming example, if there is a requirement to have at least one of each Integrated Concept program funded, the following constraints would be added:

$$\begin{aligned} x_A + x_B &\geq 1 \\ x_C + x_D + x_G &\geq 1 \\ x_E + x_E &\geq 1 \end{aligned}$$

Equation 6

Another type of constraint could deal with resources. If the variable C (originally investment cost) is redefined to be the amount of resource j required to complete program i or $C_{i,j}$, then any number of resources could be accounted for by the model (with in the limits of computational power). In this case, j would be defined as a resource type, which would range from one to the total number of resources being considered. Resources could consist of budget constraints, skill availability constraints, facility availability constraints, and raw material availability constraints. The variable B would also be changed to have the subscript j, and the constraint would look like:

$$\sum_{i} C_{i,j} x_i \leq B_j \qquad \textbf{Equation 7}$$

The variable B_j would now represent the maximum amount of resource type j that is available, overall. There would be a total of j equations formed by this constraint.

It is also possible to add constraints so the program has multiperiods for resources and funding. A variable k could be defined to be the period (fiscal year say) a particular resource is to be provided for. Then, the following type of constraint could be added:

$$\sum_{i} C_{i,k} x_i \leq B_k \qquad \textbf{Equation 8}$$

Another example of a possible constraint occurs if funding of one program requires another program or a set of programs to be funded. For example, if program G requires programs A, B, C, and D (this is not true in reality), then the following constraint would be formed:

$$4x_G - x_A - x_B - x_C - x_D \leq 0 \qquad \textbf{Equation 9}$$

This constraint requires programs A, B, C and D to be funded if program G is funded. If program G is not funded, programs A, B, C or D can be funded in any combination, with no effect on program G.

The constraints identified can be combined together in the model. It is also possible to formulate other constraints that may be unique to Air Vehicles. More information is available in the literature (Bell and Read, 1974; Gear, 1974).

Summary

The Air Vehicles model was applied to analyze seven of Air Vehicles' programs. The programs were ranked by the benefit they provide to the warfighter. Change in warfighter technological support was calculated for each program and used to identify the impact the programs have to the deployed state of the art, to compare programs with each other, and used in mathematical optimization programs. It was found integer and linear programming techniques can be used together to determine when to cut programs and when to scale back programs for various budgets.

Analysis with the Air Vehicles Value model demonstrated the ability to find values not covered in a portfolio of programs, although with a small sampling of programs, the results are not conclusive. Sensitivity analysis showed the Air Vehicles' value model does not have large changes in the alternatives for small changes in weights. Further, a method for comparing technologists' and operators' views of the value of technology was proposed. Finally, some evaluation measures were identified to be uncertain and should be studied in the future.

Chapter 5: Findings and Conclusions

Introduction

In Chapter 1, it was stated that R&D organizations have to justify their expenditures or risk being dismantled. Dismantling of an R&D organization is a serious business, which could have ramifications far into the future, depending on the organization's responsibilities. To prevent this, an organization has to change and adapt to a constantly changing world. Information is critical to adapting, but information has to be organized to be useful. This thesis has provided one way of organizing and then understanding what the information means.

The objective for this work was to answer this question:

> "What direction in technology R&D should the Air Vehicle Directorate take to be most consistent with Air Force values?"

This single question, which is easily identified, is not simple to answer. The question began a research effort requiring extensive literature search, development of a methodology with a model and analysis to provide an answer.

This study began with a literature search to identify the dimensions of Aerospace R&D in the literature. Next, technology selection models were examined. Of the large number of models, Value-Focused Thinking was selected, due to its theoretically sound foundations and because of its unique ability to allow "out of the box" thinking. Optimization models were also selected because they allow development of "best" program portfolios. The literature search was wrapped up by examining characteristics of past technology selection models to understand their strengths and weaknesses.

The study next considered a methodology. It began by setting up an overall framework for the study and resulted in a model. It was learned that Air Vehicles' primary mission is to support the USAF warfighter with dominant technology. Besides developing improvements that provide the warfighter an advantage on the battlefield, Air Vehicles' also has to be technologically superior to any adversary the United States might face today or in the future. These concepts are what is important to Air Vehicles. In the process, concepts like "deployed state of the art" were quantified and issues peculiar to R&D such as trading off technological attributes were identified. Methods of measuring change in warfighter technological support were developed. Most importantly, the development of the Air Vehicles' model took place with the Air Vehicles' managers and technical experts.

Analysis of program results identified what programs provided the most benefit to the warfighter and those that provided less. A method for identifying values not scoring in the alternatives was demonstrated. In the process of understanding this, however, it was realized that change in warfighter technological support could now be measured and used to draw conclusions. Optimization methods were used to show the best method of minimizing the impacts of budget constraints. Finally, analysis of the value model showed the model was stable over a range of weights on the values. A model was proposed to explain how operators in the USAF might see the value of technology and to show how Air Vehicles' sees technology.

Conclusions

It is possible to identify dimensions of R&D and aerospace from the literature. From these results, a value model was developed that Air Vehicles was able to provide inputs to modify and improve the model. The model was used to identify the change in support to the warfighter due to technology and optimization was applied to maximize the support to the warfighter for various budget constraints. The model was found relatively insensitive to fluctuations in the weights. Use of the R&D literature showed the model was adequate for the job of selecting technology, although more work could be done in the area of uncertainty. The model was used successfully to analyze sever programs for Air Vehicles.

Recommendations

It is recommended Air Vehicles should implement this method for selecting programs. In the process, Air Vehicles should verify, validate and accredit the model. With the value model developed, Air Vehicles can score their programs, with their technical experts, and determine the value of their programs. From there, it is recommended that the integer programming techniques and/or the linear programming techniques be used to identify the best portfolio of programs. Additionally, Air Vehicles should implement other modeling techniques that would help them to better estimate the scores for the value model.

Future Research

This effort should be expanded to the other Directorates of AFRL and should be developed for AFRL overall use. Originally AFRL requested this effort, and this study was completed as a first step toward helping AFRL. One approach to completing this for AFRL would be to approach the other nine Directorates and add their values to the Air Vehicles hierarchy. Undoubtedly, the hierarchy will change, especially at the lower levels. The hierarchy should be built in a modular fashion. Representatives from each Directorate would be needed to represent their Directorate and to identify resources from their Directorate to develop the model. Next, evaluation measures would have to be determined for the other Directorates. Then, AFRL would be requested to weight the upper levels, while the Directorates would have to weight the lowest levels in the value model. Finally, programs could be scored.

The dimensions of R&D should be explored more thoroughly. While extensive literature searching allowed identification of these dimensions in the first place, it is realized there are other sources available that could enrich the concepts. Further, it would be interesting to examine other fields of R&D such as propulsion.

To allow development of more creative alternatives, aeronautical experts need to get together and develop a structured approach to explore what has not yet been done. One structured approach might be to develop a means hierarchy for the Air Vehicles' value model. Another idea is to develop a value model to identify what is important about the technical aspects of aeronautics. This type of model might answer the question "what is possible to develop in the field of aeronautics." Alternatives identified could be used in the Air Vehicles value model to determine the value to the warfighter. This exploration would also have to identify possible military applications for the concepts.

The Air Vehicles' value model should be improved to cover uncertainty. It was determined that identifying what revolutionary a technology is can be difficult. Along with revolutionary, another variable that should be revisited for uncertainty is programmatic risk. Although this was weighted extremely low, the result could change in the future.

Methods of more accurately predicting change in warfighter technological support should be examined. With the variable defined, there may be other theoretical considerations of how it might be applied, measured or derived. The concept of technological intensity might also be explored. It would be extremely helpful if a way could be found to more quickly measure this quantify for technology.

The use of alternative future scenarios could easily be applied to Air Vehicles. In finding out weights from the Air Vehicles senior decision-makers, it was learned that the importance of Sustain was expected to diminish around 2002 while Gain would increase (under Reach). This is a clear indication that alternative futures should be examined, or at least the time horizon being examined directly changes the weights on the value model.

The Excel models for implementing the Air Vehicles model can be somewhat awkward. Specifically, adding new alternatives can be difficult. Any person who develops a model in Excel for value models and math programming should first examine this one to see where improvements might be made. Documentation for the implementation can be found in the Appendices.

The assumptions made that programs do not interact should be relaxed. This assumption is convenient for the analyst, but is not true, in practice. In the literature, models were identified that could overcome this limitation. More research is needed.

The Air Vehicles Value Model should be used to score a much larger number of programs, if not all of them, in Air Vehicles. The programs should be analyzed to determine where value gaps are or where higher scoring programs are needed. Analysis might turn up missing values in the value model, or may help Air Vehicles create alternatives that better support the warfighter.

Another possible area for future work would be to consider the time value of technology, which would be similar in concept to the time value of money. As the time increases to complete a project, the value of the technology will tend to decrease. That is, other technology being developed will tend to degrade the importance originally attached to the program. This is a possible area for future research.

Summary

The model developed for Air Vehicles provides a method to answer the question of how Air Vehicles should select technologies to be most consistent with Air Force values. The model was developed with the expert help of Air Vehicles and by using documents in the literature. The model was demonstrated by scoring seven of Air Vehicles' programs. This work sets the foundation for further work with Air Force Research Laboratory and its nine other Directorates.

Appendix A: USAF Strategic Documents Literature Search Results

The purpose of this Literature Search was to determine if correlation existed between proposed Air Vehicle Values of "Awareness, Reach and Power" and with various Air Force Strategic Planning Documents. Correlation was determined qualitatively based on the definitions of various Air Force Strategic Planning Concepts and the proposed definitions of "Awareness, Reach and Power." The conclusions from correlating the documents can be found in Table 17, while a summary of the correlations can be found in Table 18. Documents examined include Air Force Basic Doctrine, Joint Vision 2010, Air Force 2025, Global Engagement, Air Force Strategic Plan, New World Vistas, and the Air Vehicles Strategic Plan (Draft Working Copy #3). Comparisons of Principles of War defined in Air Force Basic Doctrine was done for the purpose of showing coverage by the four values. Reasons behind correlations are subject to individual interpretation and experience.

A second purpose was to identify a fourth value of the same tier as the other proposed values because it was believed the three values by themselves were not exhaustive in detailing what was important in technology for achieving air and space dominance or supporting the USAF warfighter. This was done by elimination. When the Strategic Planning Documents examined had concepts not covered by "Awareness, Reach and Power," these concepts were placed in the "Technology Leadership" column. After examining the documents, the concepts were combined into like groups. Three groups were found: a group with technology values, a group dealing with Air Force people, and a group of constraints that limit the technology programs chosen for development. The groups were named "Technological Superiority", "Air Force People" and "Constraints", respectively.

The "Technological Superiority" concept was identified as the fourth value. "Air Force People" was determined to bring up questions beyond the scope of this study. The "Constraints" are noted for future reference in the AFIT Thesis Effort.

Technology Leadership	Definitions
Technological Superiority	"Technology is perhaps best understood as an abstract system of knowledge, an attitude towards life and a method for solving its problems"(van Crevald, 1989: 1). It is a competition with other countries to develop technology to gain advantage.
Be Efficient	Management practices known to reduce the effort to develop technology.
Deter	Technology that discourages an adversary from acting because of doubt or fear.
Domestically Unduplicated	Technology being developed commercially or expected to be developed commercially should not be built by Military Laboratories.
Exploit Adversary's Technology Gaps	Rapid advances in technology that provides asymmetrical counters to our adversary's military strengths.
Feasible Technology	Technology capable of being developed within the time horizon at acceptable cost with available resources or with resources that can be developed.
Maintain Technological Superiority	Advances that render portions or all of an adversaries capability obsolete and prevents an adversaries from making our military capabilities obsolete.
Multiuse	An alternative that can support many integrated thrusts or projects is better than one that does not.
Prevent Exploitation	Technology that prevents adversaries from making rapid advances in technology that provide asymmetrical counters to US military strengths.
Simplify Operations	Technology that automates operations which simplifies military operations and falls under the Simplicity Principle of War.
Air Force People - Talented - Dedicated - Trained - Knowledgeable	Talented Air Force people and contractors are the force behind our ability to win technological superiority. However, the question of what is important to train, equip, and take care of our people is a separate question from what technology we should develop. The issue is beyond the scope of this study.
Scope Alternatives to Air Vehicle Technologies	There are many possible ways to win technological superiority, increase awareness, increase reach and increase power for the Air Force. This study is limited to Air Vehicles Options. This concept is a constraint.
Scope Alternatives to Integrated Concepts	Many possibilities exist to apply Air Vehicles Technologies. The VA Director has identified specific Integrated Concepts that will be supported by his Directorate. This sets direction and constrains technology directions.
Affordable Technology	The technology must be with in the budget of Air Vehicles.

Table 17: Technology Leadership Values in USAF Strategic Planning Documents

Document or Concept/Value	Reach	Awareness	Power	Technology Leadership
Air Force Basic Doctrine				
Unity of Command : Principle of War		X	X	
Objective : Principle of War		X		
Offensive : Principle of War		X	X	
Mass : Principle of War	X	X	X	
Maneuver : Principle of War	X	X	X	
Economy of Force : Principle of War		X	X	
Security : Principle of War		X	X	
Surprise : Principle of War	X	X	X	
Simplicity : Principle of War				X
Global Engagement				
Rapid Global Mobility : Core Competency	X			
Precision Engagement : Core Competency	X	X	X	
Global Attack : Core Competency	X		X	
Air and Space Superiority : Core Competency	X	X	X	
Information Superiority : Core Competency		X		
Agile Combat Support : Core Competency	X	X		
Joint Vision 2010				
Dominant Maneuver : Operational Concept	X	X	X	
Precision Engagement : Operational Concept	X	X	X	
Full-Dimensional Protection : Operational Concept	X	X	X	
Focused Logistics : Operational Concept	X	X		
Defend against asymmetrical counters to US military strengths or Technology Gap Exploitation				X
Maintain Technological Superiority	X	X	X	X
Incremental Advancement	X	X	X	
Air Force 2025				X
Reach	X			
Awareness		X		
Power			X	
Air Force Strategic Plan				
Strategic Agility	X	X	X	X
Overseas Presence	X			X
Power Projection	X			
Decisive Force			X	
Air Force Vision Statement	X	X	X	X
Air Force Core Competencies	X	X	X	X
VA Strategic Plan Draft # 3				
Air Vehicles Strategic Position				
Aircraft Sustainment	X		X	
Space Superiority/Global Presence	X			X
UAV formally called "Precision Strike Technology"	X		X	X
Innovative Core Technology	X	X	X	X
Pre-eminence in Research : Core Value	X	X	X	X
Talented and Dedicated People				X
New World Vistas				
Global Awareness		X		
Dynamic Planning and Execution Control			X	
Mobility	X		X	
Projection of Lethal and Sublethal Power			X	
Space Operations		X	X	
People				X
Affordability				X
Survivability			X	
Speed	X			
Range	X			
Lethality			X	
Flexibility				X
VA Proposed Value Definitions	X	X	X	
Other Ideas				
Technological Know-How				X
Relevance				X
Exploit Technology Gaps of Adversaries				X

Table 18: Summary of Correlations between USAF Strategic Documents and Reach, Awareness, Power, and Technological Superiority

Table 19: Detailed Qualitative Correlations between USAF Strategic Documents and Reach, Awareness, Power, and Technological Superiority

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Air Force Basic Doctrine						*Air Force Basic Doctrine. On Line. Internet. Available from http://www.hqafdc.maxwell.af.mil/, Sep 97.*
Unity of Command : Principle of War	All efforts for every objective should be under one responsible commander. This means "all efforts should be directed and coordinated toward a common objective. Air and space power's theater wide perspective calls for unity of command to gain the most efficient application."		Communication of the commander's orders is needed.	Coordination of efforts increases the combat power of a force. The coordinated act of influencing targets assumes command and control.		(Air Force Basic Doctrine, Sep 97: 12)
Objective : Principle of War	"The principle of objective is concerned with directing military operations toward a defined and attainable objective that contributes to strategic, operational, or tactical aims. In application, this principle refers to unity of effort. Success in military operations demands that all efforts be directed toward the achievement of common aims. In a broad sense, this principle holds that political and military goals should be complementary and clearly articulated."		To choose an objective, the commander must have knowledge or understanding of the war scenario to make an informed decision.			(Air Force Basic Doctrine, Sep 97: 13)

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Offensive : Principle of War	"The principle of the offensive holds that offensive action, or initiative, provides the means for joint forces to dictate battle-space operations. Once seized, the initiative should be retained and fully exploited."		Implies knowledge of enemy positions	The potential to employ offensive actions. If power is too small, the offensive will fail.		(Air Force Basic Doctrine, Sep 97: 14)
Mass : Principle of War	"The principle of mass calls for concentrating combat power at a decisive time and place. Concentration of military power is a fundamental consideration in all military operations. At the operational level, this principle suggests that superior, concentrated combat power is used to achieve decisive results."	The commander must be able to bring forces to the decisive point and sustain operations at that point.	The commander needs knowledge of where and when the decisive time and place is. This is awareness.	Massing units which employ power allows greater force than single units alone. Massed units allow the offensive principle and the security principle to succeed. Too much mass is not economy of force.		(Air Force Basic Doctrine, Sep 97: 15)
Maneuver : Principle of War	"The principle of maneuver calls for action to place the enemy in a position of disadvantage through the flexible application of combat power. Air and space power's ability to conduct maneuver is not only a product of its speed and range, but also flows from its flexibility and versatility during the planning and execution of operations."	Reach is needed for Maneuver to take place	Understanding of a potential opportunity is needed allow the decision to perform maneuver to take place.	Enhances power since the enemy can be placed at a disadvantage.		(Air Force Basic Doctrine, Sep 97: 17)

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Economy of Force : Principle of War	"The economy of force principle calls for the rational use of force by selecting the best mix of combat power. To ensure overwhelming combat power is available, minimal combat power should be devoted to secondary objectives. At the operational level, this requires minimum effort be made towards secondary objectives that do not support the larger operational or strategic objectives."		The commander must be knowledgeable of enemy positions and intentions to apply this principle.	This is the efficient use of combat power. Too much power is overkill and too little power will fail to achieve the objective.		(Air Force Basic Doctrine, Sep 97: 18)
Security : Principle of War	"The principle of security requires that friendly forces and their operations be protected from enemy action that could provide the enemy with unexpected advantage."		Knowledge of enemy intentions and positions is needed to be secure. This is because it is impossible to protect against all enemy actions.	An application of power		(Air Force Basic Doctrine, Sep 97: 18)
Surprise : Principle of War	"Surprise leverages the security principle by attacking at a time, place, or in a manner for which the enemy is not prepared. The speed and range of air and space forces, coupled with their flexibility and versatility, allow air forces to achieve surprise more readily than surface forces."	The commander must be able to influence the enemy and sustain the operation for surprise to be possible.	Knowledge of enemy actions and intent allows the commander to formulate alternatives that are unexpected by the enemy.	With surprise, power is enhanced		(Air Force Basic Doctrine, Sep 97: 18)

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Simplicity : Principle of War	"The final principle, simplicity, calls for avoiding unnecessary complexity in organizing, preparing, planning, and conducting military operations. This ensures that guidance, plans, and orders are as simple and direct as the objective will allow."				Technology can be used to simplify operations by automating tasks which are operationally complex.	(Air Force Basic Doctrine, Sep 97: 21)
Global Engagement						Global Engagement: A Vision for the 21 st Century Air Force, 1996
Rapid Global Mobility : Core Competency	"Rapid Global Mobility provides the nation its global reach and underpins its role as a global power. The ability to move rapidly to any spot on the globe ensures that tomorrow, just as today, the nation can respond quickly and decisively to unexpected challenges to its interests."	Similar definition to Reach				
Precision Engagement : Core Competency	"Joint Vision 2010 defines Precision Engagement as the capability "that enables our forces to locate the objective or target, provide responsive command and control, generate the desired effect, assess our level of success, and retain the flexibility to re-engage with precision when required." The Air Force's core competency of Precision Engagement is grounded in the Joint definition. Its essence lies in the ability to apply selective force against specific targets and achieve discrete and discriminate effects. The nation needs the precise application of military capability to meet policy objectives. The Air Force's Precision Engagement core competency provides the nation with reliable precision,	The application of power at an extended range is reach (i.e. getting to the decisive point)	Locate the target, assess our level of success is awareness. Providing responsive command and control is information related which is communication of an informed decision.	Generate the desired effect and reengaging is application of power.		

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
	an ability to deliver what is needed for the desired effect, but with minimal risk and collateral damage."					
Global Attack : Core Competency	"The ability of the Air Force to attack rapidly anywhere on the globe at any time is unique. The military utility of air power, particularly its speed, range, and flexibility prompted creation of the Air Force as a separate Service following World War II."	Speed and range are different levels of reach. Rapid attack is synonymous with speed.		Flexibility is the ability to apply power to all kinds of targets. Types of targets might be different levels of power. Numbers of targets might also be levels of power.		

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Air and Space Superiority : Core Competency	"Superiority in air and space - control over what moves through air and space - delivers a fundamental benefit to the Joint Force. It prevents adversaries from interfering with operations of air, space or surface forces, and assures freedom of action and movement. The control of air and space is a critical enabler for the Joint Force because it allows all U.S. forces freedom from attack and freedom to attack. With Air and Space Superiority, the Joint Force can dominate enemy operations in all dimensions - land, sea, air and space."	Control implies the ability to reach the object being controlled so power can be exercised over the object.	Control also implies knowledge of what is being controlled.	"Control over what moves in the air and space" implies application of power to enforce our will.		
Information Superiority : Core Competency	"In no other area is the pace and extent of technological change as great as in the realm of information. The volume of information in joint warfare is already growing rapidly. The ability of the future Joint Team to achieve dominant battlefield awareness will depend heavily on the ability of the Air Force's air- and space-based assets to provide global awareness, intelligence, communications, weather and navigation support. While Information Superiority is not the Air Force's sole domain, it is, and will remain, an Air Force core competency. The strategic perspective and the flexibility gained from operating in the air-space continuum make airmen uniquely suited for information operations. "		Information superiority is the means of achieving awareness.			

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Agile Combat Support : Core Competency	"Agile Combat Support is recognized as a core competency for its central role in enabling air and space power to contribute to the objectives of a Joint Force Commander. Effective combat support operations allow combat commanders to improve the responsiveness, deployability, and sustainability of their forces. The efficiency and flexibility of Agile Combat Support will substitute responsiveness for massive deployed inventories. "	The ability to reach enables this capability. The turn around time and speed of the weapon system matter here. Actual delivery of material requires reach.	Locations of current logistic groups moving to resupply is needed to allow rerouting. This is awareness. Fusion of information, track and shift assets even while enroute, and delivery of tailored packages at the correct point requires awareness.			
Joint Vision 2010						Joint Vision 2010, 1996.
Dominant Maneuver : Operational Concept	"Dominant maneuver will be the multidimensional application of information, engagement, and mobility capabilities to position and employ widely dispersed joint air, land, sea, and space forces to accomplish the assigned operational tasks. Dominant maneuver will allow our forces to gain a decisive advantage by controlling the breadth, depth, and height of the battlespace."	Related to engagement and mobility capabilities	Awareness deals with information. Positioning and employment of dispersed and diverse forces is awareness. Information allows an informed decision.	Engagement and control of air, surface, space, and subsurface forces is the employment of power.		*(Joint Vision 2010, 1996: 20)*

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Precision Engagement : Operational Concept	"Precision engagement will consist of a system of systems that enables our forces to locate the objective or target, provide responsive command and control, generate the desired effect, assess our level of success, and retain the flexibility to reengage with precision when required. Even from extended ranges, precision engagement will allow us to shape the battlespace, enhancing the protection of our forces."	The application of power at an extended range is reach (i.e. getting to the decisive point)	Locate the target, assess our level of success is awareness. Providing responsive command and control is information related which is communication of an informed decision.	Generate the desired effect and reengaging is application of power.		*(Joint Vision 2010, 1996: 21)*
Full-Dimensional Protection : Operational Concept	"The primary prerequisite for full-dimensional protection will be control of the battlespace to ensure our forces can maintain freedom of action during deployment, maneuver and engagement, while providing multi-layered defenses for our forces and facilities at all levels. Full-dimensional protection will enable the effective employment of our forces while degrading opportunities for the enemy. It will be essential, in most cases, for gaining and maintaining the initiative required to execute decisive operations. The concept will be proactive, incorporating both offensive and defensive actions that may extend well into areas of enemy operations."	Extending into enemy areas of operation is using reach.	Knowing where to attack in enemy territory is use of information which is awareness.	Offensive and defensive actions taken to control the battlespace is an application of power.		*(Joint Vision 2010, 1996: 22)*

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Focused Logistics : Operational Concept	"Focused logistics will be the fusion of information, logistics, and transportation technologies to provide rapid crisis response, to track and shift assets even while enroute, and to deliver tailored logistics packages and sustainment directly at the strategic, operational, and tactical level of operations. It will be fully adaptive to the needs of our increasingly dispersed and mobile forces, providing support in hours or days versus weeks. Focused logistics will enable joint forces of the future to be more mobile, versatile, and projectable from anywhere in the world. "	Actual delivery of material requires reach.	Locations of current logistic groups moving to resupply is needed to allow rerouting. This is awareness. Fusion of information, track and shift assets even while enroute, and delivery of tailored packages at the correct point requires awareness.			*(Joint Vision 2010, 1996: 23)*
Defend against asymmetrical counters to US military strengths or Technology Gap Exploitation	"Our most vexing future adversary may be one who can use technology to make rapid improvements in its military capabilities that provide asymmetrical counters to US military strengths, including information technologies."				It is impossible for America to build technology to meet every contingency. An adversary can exploit gaps in America's technological armor and overcome our advantage. This might create surprise.	*(Joint Vision 2010, 1996: 10-11)*

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Maintain Technological Superiority	"This era will be one of accelerating technological change. Critical advances will have enormous impact on all military forces. Successful adaptation of new and improved technologies may provide great increases in specific capabilities. Conversely, failure to understand and adapt could lead today's militaries into premature obsolescence and greatly increase the risks that such forces will be incapable of effective operations against forces with high technology."	Increases capability by improving weapon systems	Increases capability by improving weapon systems	Increases capability by improving weapon systems	Failure to adapt means "premature obsolescence" making forces ineffective.	*(Joint Vision 2010, 1996: 11)*
Incremental Advancement	"Long-range precision capability, combined with a wide range of delivery systems, is emerging as a key factor in future warfare. Technological advances will continue the trend toward improved precision. Global positioning systems, high-energy research, electromagnetic technology, and enhanced stand-off capabilities will provide increased accuracy and a wider range of delivery options. These capabilities will increase the combat power available for use against selected objectives, resulting in enhanced economy of force and a higher tempo of operations."	"Long Range precision capability" is reach.	Precision is a measure of the level of awareness.	"wide range of delivery systems" are diverse applications of power. Increased tempo increases power. Economy of force is not applying too much power.		*(Global Engagement, Unknown Date: 11)*

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Air Force 2025					An issue with this study is that while out of the box thinking is clearly evident through out the study, the study is poorly anchored to reality. It is difficult to determine if the systems proposed by 2025 are feasible.	Jackson, Jack A., Brian L. Jones, and Lee J. Lehmkuhl. An Operational Analysis for 2025. Air University Press, 1996. On-line. Internet, 1996. Available from http://www.au.af.mil/au/2025.
Reach	"Ability to move to expand the range or scope of influence or effect, and to sustain this influence or effect by maintaining and replenishing."	In Depth Definition				Jackson, Jack A., Brian L. Jones, and Lee J. Lehmkuhl. An Operational Analysis for 2025 (Air University Press, 1996), 13.

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Awareness	"Knowledge, understanding, or cognizance of some thing or situation through alertness in observing, detecting, and identifying, so as to enable, direct, and communicate an informed decision."		In Depth Definition. The 2025 Analysis brought out the concept of Awareness in important in understanding the application of Global Reach and Global Power in the Air Force Vision Statement. This hidden value is implied by the Vision Statement though not explicitly noted.			Jackson, Jack A., Brian L. Jones, and Lee J. Lehmkuhl. An Operational Analysis for 2025 (Air University Press, 1996), 13.
Power	"Ability to overtly or covertly affect, control, manipulate, deny, exploit, or destroy targets, including forces, people, equipment, and information, and the ability to survive while affecting targets."			In Depth Definition		Jackson, Jack A., Brian L. Jones, and Lee J. Lehmkuhl. An Operational Analysis for 2025 (Air University Press, 1996), 13.
Air Force Strategic Plan						

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Strategic Agility	"Strategic agility is the timely concentration, employment, and sustainment of US military power anywhere at our own initiative, at a speed and tempo our adversaries cannot match. It requires the US military to conduct a variety of missions across the full range of military operations."	Employment and sustainment are concepts of reach. Employing military power anywhere is reach. Speed and tempo are possible measures of reach.	While awareness is not specifically mentioned, it is implied by the concept of "across the full range of military operations." Since the full range of military operations covers information warfare, awareness is implied.	Timely concentration is a method of employing power. Speed and tempo are possible measures of power.	The concept of "speed and tempo our adversaries cannot match" is not completely covered by Reach, Awareness and Power. Specifically, the concept of "adversaries cannot match" is not implied by the other values. This could happen due to superior Operational implementation or due to superior technological capabilities.	(Air Force Strategic Plan Volume 1 : The Future Security Environment, 1998 :21-22)
Overseas Presence	"Overseas presence is the visible posture of US forces and infrastructure positioned forward or in key regions. Some forces are permanently stationed overseas to promote security and stability, prevent conflict, substantiate our allied commitments, and ensure continued access."	Overseas presence is prepositioned reach.			Deterrence to adversaries is a reason to station troops overseas. Superior Technology could deter adversaries, also.	(Air Force Strategic Plan Volume 1 : The Future Security Environment, 1998 :22)

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Power Projection	". . .power projection aims for unconstrained global reach. It is the ability to deploy and sustain rapidly and effectively US forces in and from multiple, dispersed locations. It provides our national leaders with more options for responding to potential crises, and is accomplished in concert with our permanent forward presence."	An in depth definition of the concept of reach.				(Air Force Strategic Plan Volume 1 : The Future Security Environment, 1998 :22)
Decisive Force	"decisive force is the commitment of sufficient military power to overwhelm all armed resistance in order to establish new military conditions and achieve political objectives."			Decisive force and the principle of war of economy force are closely linked. Economy of force using the right amount of force at the decisive point and time.		(Air Force Strategic Plan Volume 1 : The Future Security Environment, 1998 :22)
Air Force Vision Statement	"AIR FORCE VISION STATEMENT: Air Force people building the world's most respected Air and Space Force global power and reach for America."	Global reach and reach are synonymous	Implied. The U.S. must know where to reach and when to reach before employing power.	Global Power and power are synonymous	Air Force People.	(Air Force Strategic Plan Volume 2 : Performance Plan, Sep 1998 :i)

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Air Force Core Competencies	"AIR FORCE CORE COMPETENCIES: Our Nation's Air Force develops, trains, sustains and integrates the elements of air and space power to produce: · Air and Space Superiority · Global Attack · Rapid Global Mobility · Precision Engagement · Information Superiority · Agile Combat Support"	Develop and sustains is captured in the concept of gain and maintain.	Develop and sustains is captured in the concept of gain and maintain.	Develop and sustains is captured in the concept of gain and maintain.	Trains and integrates elements of air and space power is part of the Core Competencies. It is part of Air Vehicles in their Strategic Plan, also.	(Air Force Strategic Plan Volume 2 : Performance Plan, Sep 1998 :i)
VA Strategic Plan Draft # 3						
Air Vehicles Strategic Position	"The AFRL Air Vehicles Directorate will deliver the best air vehicle technologies for aerospace dominance against all threats by developing, integrating, and transitioning:"					(Air Force Research Laboratory Air Vehicles Directorate 2010: Strategic Business Plan, Working Draft #3, 21 Sep 98, 5)
Aircraft Sustainment	"Provide technology insertion which enables the fleet to meet evolving warfighter needs."	The concept of "Maintain" under this overarching value will be defined to cover these advances in technology.		The concept of "Maintain" under this overarching value will be defined to cover these advances in technology.		(Air Force Research Laboratory Air Vehicles Directorate 2010: Strategic Business Plan, Working Draft #3, 21 Sep 98, 15)

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Space Superiority/Global Presence	"To provide affordable, quick reaction, trans-atmospheric and space capability."	" . . .quick reaction" is the reach value. Tran-atmosheric is the means VA has chosen to maximize this value.			Two missions are implied: Trans-atmospheric or missions on the Earth and missions into space. The affordable concept must also be accounted for in a model.	(Air Force Research Laboratory Air Vehicles Directorate 2010: Strategic Business Plan, Working Draft #3, 21 Sep 98, 16)
UAV formally called "Precision Strike Technology"	"To provide technologies for affordable, flexible, and survivable aerospace vehicles to defeat time critical and time-sensitive ground and air targets, using a light, lean, and lethal combat force."	Time sensitive or time critical targets is reach.		Survivable forces are more powerful than non-survivable forces. "Light, lean and lethal combat force" are types of power.	Affordable is mentioned. Flexible implies capable of diverse missions.	(Air Force Research Laboratory Air Vehicles Directorate 2010: Strategic Business Plan, Working Draft #3, 21 Sep 98, 17)

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Innovative Core Technology	"To create and nurture innovative research into breakthrough technologies which enable revolutionary warfighter capabilities."	If the value above is considered correct based on the AF Vision, 2025 study, and the clear links to other AF strategic documents, then "breakthrough" technologies should generate alternatives that improve this value.	If the value above is considered correct based on the AF Vision, 2025 study, and the clear links to other AF strategic documents, then "breakthrough" technologies should generate alternatives that improve this value.	If the value above is considered correct based on the AF Vision, 2025 study, and the clear links to other AF strategic documents, then "breakthrough" technologies should generate alternatives that improve this value.	"Breakthrough technologies" is not well defined. Why are breakthrough technologies important? Is it because we must keep up with other countries? Is it because we must prevent other countries from exploiting gaps in our technologies?	(Air Force Research Laboratory Air Vehicles Directorate 2010: Strategic Business Plan, Working Draft #3, 21 Sep 98, 18)
Pre-eminence in Research : Core Value	"We believe the first essential of Aerospace Power is pre-eminence in research."	Improves	Improves	Improves	Pre-eminence appears to be another name for Technological Superiority	(Air Force Research Laboratory Air Vehicles Directorate 2010: Strategic Business Plan, Working Draft #3, 21 Sep 98, 6)
Talented and Dedicated People	"We further believe that the first essential of pre-eminence in research is talented and dedicated people working together."				Talented or competent people and dedicated people	(Air Force Research Laboratory Air Vehicles Directorate 2010: Strategic Business Plan, Working Draft #3, 21 Sep 98, 6)

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
New World Vistas						*New World Vistas Air and Space Power for the 21st Century Summary Volume. Washington, D.C.: USAF Scientific Advisory Board, 1995. On-line. Internet, 1995. Available from http://web.fie.com/fedix/vista.html.*
Global Awareness	"Global awareness means that the Air Force can use affordable means to derive appropriate information about one or more places of interest after a delay which is short enough to satisfy operational needs."		Similar to Proposed definition. A "place of interest" is the situation in the propose value. Affordable means is a constraint. "Derive appropriate information" is knowledge or understanding.			*New World Vistas: Summary Volume.*
Dynamic Planning and Execution Control	"Dynamic Planning and Execution Control exploits the information derived through Global Awareness. It is not possible to increase the tempo of operations without increasing the tempo of planning."			Command and Control is to be handled under Power.		*New World Vistas: Summary Volume.*

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Mobility	"Mobility can be the limiting factor in operations. Airlift is also in demand during peacetime for humanitarian operations. Humanitarian operations bring special problems to the Air Force, because they may require airlift aircraft and people to enter regions of high danger. It may not be possible to provide external protection for airlifters or external response to attack. The safety of mobility operations will be increased greatly by Global Awareness and by Dynamic Planning and Execution Control. The Air Force airlift system will be integrated into both systems. Today, it is technologically possible to track shipments and aircraft in real time at reasonable cost. New commercial satellite systems, such as Iridium, can be used to enhance that capability at lower cost and higher reliability."	Mobility and its uses are a form of reach in action.		*New World Vistas defines the concept of survivability here and attributes improvements in the attribute by using Global Awareness capabilities. While argument is possible about where the survivable attribute belongs, there is no doubt is a value.*		*New World Vistas: Summary Volume.*

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Projection of Lethal and Sublethal Power	"The Air Force understands well the issues associated with projecting power from airborne platforms. The subject of Precision Guided Munitions (PGMs) and their benefits needs no elaboration. We do, however, present ideas for making PGMs more effective. We will discuss power projection methods and devices which are different from those now in use. The Global Awareness and Dynamic Control capabilities will enable power projection capabilities not now possible in both existing and new platforms. Many of the fundamental tasks presented to the Air Force will not change much during the next decade. Added to the traditional air-to-air and air-to- ground missions, however, will be the countering and destroying of weapons of mass destruction and operations in urban areas. It is likely, too, that the availability of low cost SAM's will establish a premium for the their efficient destruction."			Destruction or neutralization of targets requires "no elaboration." No mention of being survivable is discussed here. However, this is handled in previous definitions.		*New World Vistas: Summary Volume.*
Space Operations	"Space operations will become increasingly important to the successful completion of most missions in the 21st century.[35] The essential role of Space in Global Awareness and Dynamic Planning and Execution Control was discussed, and, in particular, the value of distributed satellites was addressed. The interaction between military and commercial space applications has not begun to evolve. It is time, now, for the Air Force to define its relationship with commercial and		Use of space for Awareness is an efficient alternative for achieving high levels of Awareness.	Use of Space for Dynamic Planning and Execution Control will be considered part of Power.		*New World Vistas: Summary Volume.*

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
	international space organizations."					
People	"New World Vistas looks decades into the future. We predict increasing dependence on autonomous weapons and information systems. During the entire period, we see people as central to Air Force operations. Therefore, the design of systems must include the "human system" as an integral part. Increased tempo of operations and reduced Force size will demand that people interact with weapons systems more efficiently than ever before. Science and technology can assist the process of human interaction with the machine of the future. Improved and specialized training can assist the process of interacting with the machine of the present."				Training is critical for development and use of advance technology.	*New World Vistas: Summary Volume.*
Future War	"Technologies supporting warfare seem to be undergoing a revolutionary change. Some perceive the most vital asset for modern warfare is information. Nevertheless, information is a necessary, but not sufficient condition for victory. The timely dispersion of force around the globe and precision delivery of lethal or non-lethal weapons will remain an					*New World Vistas: Aircraft and Propulsion Volume*

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
	essential contributor to the final victory."					
Affordability	"AFFORDABILITY means reduced cost of the weapon or weapon system from conception and development through the life of the system(life cycle cost)."				Affordability is a constraint on military weapon systems.	*New World Vistas: Aircraft and Propulsion Volume*
Survivability	"SURVIVABILITY provides the ability to operate successfully in high threat environments."			Part of the definitions of Power.		*New World Vistas: Aircraft and Propulsion Volume*
Speed	"SPEED enables the system to respond rapidly to a military need and enhances survivability."	An attribute of Reach.				*New World Vistas: Aircraft and Propulsion Volume*
Range	"RANGE provides the ability to reach trouble spots anywhere on the battlefield or on the globe with minimal support from tankers or bases."	An attribute of Reach.				*New World Vistas: Aircraft and Propulsion Volume*
Lethality	"LETHALITY enables the system to deliver weapons of destruction efficiently and to kill on the first try."			A descriptor of Power.		*New World Vistas: Aircraft and Propulsion Volume*
Flexibility	"FLEXIBILITY is the ability to accomplish a variety of missions or carry a variety of payloads to meet differing requirements."				Able to accomplish a variety of missions.	*New World Vistas: Aircraft and Propulsion Volume*

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
VA Proposed Value Definitions		To expand and sustain the range or scope of influence.	Knowledge or understanding of a situation so as to enable an informed decision.	Ability to affect or destroy targets and survive.		
Other Ideas						
Technological Know-How	The knowledge and skill to do technology right.				Someone has to know how to build the weapon systems employed by the warfighter. These people are unique in the United States and possibly the world because they power the innovative process.	
Relevance	Pertinent critical technology areas that potentially allow aerospace dominance				Many technologies can be used to improve awareness, reach and power. Air vehicles works on only one technology area of the many that are possible.	

Document or Concept/Value	Definition	Reach	Awareness	Power	Technology Leadership	Full Reference
Exploit Technology Gaps of Adversaries	Joint Vision 2010 identifies the need to protect our forces against asymmetrical counters to our technology. An adversary has the same problem if we exploit asymmetrical counters to his technology.				An adversary cannot protect every technology gap which leaves room for the U.S. to counter specific technologies.	

Appendix B: Documentation of Meetings with VA

VA-AFIT Value Hierarchy Meeting Highlights/4 Dec 98

AFRL/VA: Al Boudreau, Lt Col Richard Docken, Dick Colclough, Dr. David Moorehouse, Jim Pruner, Brian Van Vliet, Dr. Yvette Weber
AFIT/ENS: Capt Winthrop, LTC Kloeber, Dr. Deckro

Subject: Value Hierarchy, 1st two tiers.
Comments: Definitely support the top level of "Support the Warfighter"
Change Technology Race to Technological Superiority

Subject: 2nd Tier under Reach Awareness and Power
Comments: Affordability is missing – Possible Locations:
1. Same level as Gain and Sustain
2. Below Gain for Reach, Awareness and Power
3. Part of Technological Superiority

General agreement that Gain and Sustain belong and are good terms to use.

Subject: Tiers below Technological Superiority
Comments: Technology for its own sake is not included or is not fully covered.

Subject: Measures for Reach
Comments: Change Speed to Response time. Need to include survivability in hierarchy.

Subject: Open Action Items

Done	Capt Winthrop will modify the AFRL/VA model to incorporate affordability.
	AFIT/ENS and VA to identify elements of "innovation for its own sake."
Done	AFIT/ENS to e-mail meeting materials no later than Monday, 7 Dec 98.
	Dr. Moorhouse plans to e-mail briefing material of previous ROI work through Mr. Colclough.
	Capt Winthrop will examine additional Air Force Strategic documents to glean values.
	AFIT/ENS set up meeting with VA Division Chiefs to confirm values and definitions.
Done	AFIT/ENS set up meeting with VA to confirm values and definitions –> 1500 Tuesday, 8 Dec. '98.

VA-AFIT Value Hierarchy Meeting Highlights/8 Dec 98

AFRL/VA: Al Boudreau, Dick Colclough, Lt Col Richard Docken, Jim Pruner, Brian Van Vliet, Dr. Mike Zeigler
AFIT/ENS: Capt Winthrop, LTC Kloeber, Dr. Deckro

Subject: Review of Reach, Awareness, Power, Technological Superiority Definitions
Comments: Acceptable as written.

Subject: Afford under Reach, Awareness, and Power or under Gain and Sustain
Comments: Technically, Afford could be under Gain and Sustain. Under Reach, Awareness, and Power because of the political importance of the value and because it allows calculation of lifecycle cost. If broken out, this is not possible.

Subject: Definition of Afford
Comment: Afford needs to emphasize a reduction in cost. Definition reworded for better flow.

Subject: Definitions of Gain, Sustain, and Afford
Comments: There are other ways of gaining reach besides technology. "Through technology" added to reflect that we are considering technology. The order of the three values changed to alphabetical which also coincides with emphasizing Afford.

Subject: Measures of Afford
Comments: Afford can be broken down into O&S, Development and Acquisition cost changes for the Air Force. However, the relationships are complex for the three measures. VA uses Return on Investment (ROI) which is defined several ways by VA. Attendees recommend using ROI as a composite measure.

Subject: Gain under Reach - Measures
Comments: Changed from suggested into Response Time, Reliability, Weight, and L/D. Definitions need to emphasize the change in the attribute pertaining to the system, not the technology. Lifetime is a Sustain measure, not Gain.

Subject: Sustain under Reach – Measures
Comments: Lifetime is more than just hours added to useful life. It also means fixing existing systems to meet expected life. Number of new capabilities is wrong. It is more the quality of the capabilities being added. Mission flexibility is needed here. One sustainment program fixed an operational problem, decreased operational cost, increased the reliability, and resulted in small decreases in weight.

Subject: Open Action Items

	Capt Winthrop will modify the AFRL/VA model to incorporate Gain Measures for Reach.
	Capt Winthrop will modify the AFRL/VA model to incorporate Sustain Measures for Reach.

	AFIT/ENS and VA to identify elements of "innovation for its own sake."
	Dr. Moorhouse plans to e-mail briefing material of previous ROI work through Mr. Colclough.
	Capt Winthrop will examine additional Air Force Strategic documents to glean values.
	AFIT/ENS set up meeting with VA Division Chiefs to confirm values and definitions.
Done	AFIT/ENS set up follow on meeting with VA-> 0900 Monday, 14 Dec. '98.

VA-AFIT Value Hierarchy Meeting Highlights/14 Dec 98

AFRL/VA: Dick Colclough, Lt Col Richard Docken, Brian Van Vliet, Yvette Weber, Dr. Mike Zeigler
AFIT/ENS: Capt Winthrop, Dr. Deckro

Subject: Afford under Reach, Awareness, and Power
Comment: Definition accepted.

Subject: L/D Measure
Comment: Change L/D to ΔL/D.

Subject: Be Flexible
Comment: Removed from model since it is described by reliability and missions enabled (new measure). Missions enabled should be added to both Gain and Sustain under Reach.

Subject: Safety
Comment: Safety is an issue, which is difficult to measure. Safety can be flight critical or mission critical. Measuring safety needs work. It may be a binary measure.

Subject: Measures under Awareness Gain and Sustain
Comment: VA believes the same measures under Reach fit under Awareness. The problem is how to deal with double counting. One suggestion was to redefine Reach to look at getting to the theatre while Awareness looks at in theatre. Survivable and loiter time are possible measures that were suggested. It may be that Air Vehicles does not do anything under Awareness and Power.

Subject: Measures under Reach
Comment: The measures and definitions for Gain and Sustain under Reach are acceptable now. These definitions are baseline.

Subject: Open Action Items

Done	Capt Winthrop will modify the AFRL/VA model to incorporate Gain Measures for Reach.
Done	Capt Winthrop will modify the AFRL/VA model to incorporate Sustain Measures for Reach.
	AFIT/ENS and VA to identify elements of "innovation for its own sake."
	Dr. Moorhouse plans to e-mail briefing material of previous ROI work through Mr. Colclough.
	Capt Winthrop will examine additional Air Force Strategic documents to glean values.
	AFIT/ENS set up meeting with VA Division Chiefs to confirm values and definitions.
Done	AFIT/ENS set up follow on meeting with VA–> 0900 Monday, 14 Dec. '98.

VA-AFIT Value Hierarchy Meeting Highlights/17 Dec 98

AFRL/VA: Al Boudreau, Dick Colclough, Lt Col Richard Docken, Dr. Moorhouse, Yvette Weber
AFIT/ENS: Capt Winthrop

Subject: Simplify Operations
Comment: Removed "automate" from the definition since there are other ways technology can be used to simplify operations. It is also possible to use technology to make operations more complex. Operations can be simplified by the use of automation, decreasing people required to perform an operation, or interoperability.

Subject: Mask and Prevent Masking
Comment: The concepts covered by these words are difficult to understand at first. However, after explaining the concept, everyone agreed the concepts made sense and were important to the model. Possible words to replace mask are bypass and overcome. Examples of masking or unmasking also help. Examples include electronic warfare, using radar in WWII by England to overcome air advantage by Germans, the threat of nuclear terrorism in a briefcase and using UAV's to detect the weapons, etc. These concepts may be part of the "Neutralize" value.

Subject: Feasible is acceptably defined

Subject: Be Efficient
Comment: Originally had "known" and "Management" in the definition. The practices do not have to be known practices and management does not fit in the definition at all.

Subject: Expand our Frontier
Comment: It took some time to get this concept across. The concern is "Expand our Frontier" has connotations about evolutionary technology and was supposed to cover revolutionary technology. The word scope was confusing in the definition. Scope was replaced with spectrum where spectrum means an increase in the technological base allowing fighting to take place in previously unknown realms. Examples are the birth of airpower, information dominance, and space. The definition was reworded somewhat and the word revolutionary was entered into the definition to eliminate connotations of the phrase being evolutionary, also.

Subject: Deter
Comment: Definition acceptable as written except that cost was added to doubt and fear as reasons to discourage an adversary.

Subject: Neutralize
Comment: Propose changing "obsolete" to "ineffective."

Subject: Measures under "Feasible"

Comment: "Number of Advances" changed to "Number of Technological Challenges." The definition was improved. Unfortunately, Technological Challenges are not all of the same difficulty level. After discussion, it was suggested "Resources Required." The definition for this needs to be worked on and checked with VA.

Subject: Measures under "Be Feasible"
Comment: The measures suggested were acceptable to the group. The "Uniqueness" measure can have VA teaming up with more than just industry. VA partners with other Government agencies, also. The definition needs to be altered, slightly.

Subject: Open Action Items

Done	AFIT/ENS and VA to identify elements of "innovation for its own sake."
	Dr. Moorhouse plans to e-mail briefing material of previous ROI work through Mr. Colclough.
	Capt Winthrop will examine additional Air Force Strategic documents to glean values.
	AFIT/ENS set up meeting with VA Division Chiefs to confirm values and definitions.
	Capt Winthrop will define "Resources Required" under Feasible
Done	Capt Winthrop will modify definition of Uniqueness to include partnering with Gov't agencies.
Done	Capt Winthrop will work on improving definitions and words for "mask" and "prevent masking" concepts.
	Capt Winthrop needs to discuss adding cost under Feasible as a measure with LTC Kloeber.
	Prepare for next meeting on 21 Dec 0900. Send E-mail to those who cannot attend.

VA-AFIT Value Hierarchy Meeting Highlights/21 Dec 98

AFRL/VA: Dick Colclough, Lt Col Richard Docken, Dr. Moorhouse, Jim Pruner, Rikki Peters
AFIT/ENS: Capt Winthrop

Subject: Counteract, Prevent Counteraction, Neutralize
Comment: The VA group could not easily distinguish between the three values. It is so difficult to distinguish that VA recommends combining these concepts into one value. Further, deter seems to fit as part of these concepts. VA recommends simplification of the model.

Subject: Simplify Operations
Comment: The value is acceptable and the measures are accepted.

Subject: Proposed Measure for advantage level for technology
Comment: A possible measure measuring the advantage of technology on the battlefield would have decapitate, deter, neutralize and enhance as levels. Decapitate means to make an action of an adversary unthinkable or impossible because American technology is so powerful. Deter would keep its former meaning of technology that discourages an adversary from acting because of doubt, fear or cost. Neutralize would keep its former meaning of technology advances that render some or all of an adversaries military capability ineffective and cannot be countered at the completion of the advance. Enhance is an improvement to our forces technology giving us an advantage over an adversary.

Subject: Open Action Items

	Dr. Moorhouse plans to e-mail briefing material of previous ROI work through Mr. Colclough.
	Capt Winthrop will examine additional Air Force Strategic documents to glean values.
	AFIT/ENS set up meeting with VA Division Chiefs to confirm values and definitions.
OBE	Capt Winthrop will define "Resources Required" under Feasible
Done	Capt Winthrop needs to discuss adding cost under Feasible as a measure with LTC Kloeber.
Done	Capt Winthrop to combine deter, neutralize, counteract, and prevent counteraction into one value.
Done	Capt Winthrop to request standard program proposal form.
OBE	Capt Winthrop to E-mail latest briefing out for comments over Christmas
Done	Prepare for meeting in first week in January.

VA-AFIT Value Hierarchy Meeting Highlights/7 Jan 99

AFRL/VA: Lt Col Richard Docken, Mike Ziegler
AFIT/ENS: Capt Winthrop, Dr. Dick Deckro, LTC Jack Kloeber

Subject: Reusability and recoverability measures under Power Gain and Sustain
Comments: Reusability and recoverability appear similar. The difference is reusability is time before the entire system must be overhauled and recoverability is the turn around time in between missions. Suggestions for measures are turn around time, mission capable rate, and sortie generation rate.

Subject: Detectability, countermeasures and vulnerability under survive under Power/Gain and Sustain
Comments: These concepts are essentially right. However, the wrong words are being used. Better words are vulnerability, susceptibility, and detectability. Participants recommended talking with SURVIAC to find documents that discuss these concepts.

Subject: Add Lethality to Power under Gain and Sustain
Comments: Lethality may not be what VA does, but should be added as an opener for future discussion.

Subject: Changes in Technological Superiority are acceptable
Comments: The word adversary is used a lot in the model. Adversary needs definition. This should not be a large problem since VA has documentation that tells us who the adversary is. Another issue here is the type of war being fought. Nuclear weapons are not overwhelming in all possible types of war (conventional, nuclear, irregular).

Subject: Advantage Categories
Comments: The categories make sense as written. This category is likely to be a source of controversy during scoring.

Subject: Expand our Frontier and Simplify Operations
Comments: These definitions overlap somewhat. Specifically, the concept of enabling technology that simplifies operations and "Potential for New warfighting capability" are difficult to tell apart in some situations.

Subject: Open Action Items

OBE	Dr. Moorhouse plans to e-mail briefing material of previous ROI work through Mr. Colclough.
	Capt Winthrop will examine additional Air Force Strategic documents to glean values.
	AFIT/ENS set up meeting with VA Division Chiefs to confirm values and definitions.
Done	Clarify reusability and recoverable definitions
Done	Change definitions and names for Detectability, countermeasures and vulnerability under survive under Power/Gain and Sustain

	Add Lethality under Power both Gain and Sustain and define measure
	Define Adversary when evaluation measures are being built
	Remove overlap in definitions or evaluation measures for Expand our Frontier (Potential for new warfighting capability) and Simplify Operations (enable)

VA-AFIT Value Hierarchy Meeting Highlights/19 Jan 99

AFRL/VA: Dick Colclough, Al Boudreau
AFIT/ENS: Capt Winthrop, Dr. Dick Deckro, LTC Jack Kloeber

Subject: Breakout Space and Air evaluation Measures Question
Comments: AFIT brought up concerns about differences in value for space and air evaluation measures. The question was whether weight reduction should be different for space programs and air programs since it is weighted differently for space vehicles then for air vehicles and is scored differently. That is, a savings for 200 pounds on a space vehicle can have much higher value than 200 pounds saved on an aircraft. This concept was rejected. Air Vehicles felt the value model should be equally applicable to both types of vehicles and no special weightings should be given due to the type of vehicle under consideration.

VA-AFIT Value Hierarchy Meeting Highlights/20 Jan 99

AFRL/VA: Dick Colclough, Dr. Moorhouse, Mike Ziegler, Brian Van Vliet
AFIT/ENS: Capt Winthrop, Dr. Dick Deckro, LTC Jack Kloeber

Subject: Lethality
Comments: Concepts of payload and energy generated made no sense here. These measures were replaced with effectiveness and quantity. Air Vehicles directly influences these measures.

Subject: Regeneration and Reusability
Comments: VA cannot distinguish between reliability and reusability. The two metrics should be combined under an availability measure. Availability should be placed under Reach, not power. Additionally, regeneration should be placed under reach. Availability can be defined from Air Force documentation. Regenerate should be redefined in terms without using "generate" in it.

Subject: Feasible
Comments: VA renamed number of technology challenges to technological challenge. This measure will be subjective (High, Medium, Low). There is no known way to improve this measurement. The concept of TRL was proposed as a possible measure. This measure is about maturity level and is covered by the concept of technological challenge.

Subject: Warfare advantage
Comments: VA cannot distinguish between different types of warfare and the advantage level (i.e. nuclear war, conventional war, irregular war, etc.). The technology they develop is not developed with these concepts in mind.

Subject: Cost to adversary
Comments: This cannot be estimated as a percent of GNP for another country. At best, this either is a subjective measure or can be measured in orders of magnitude. A project that costs more orders of magnitude than another for our closest technical adversary to overcome would be better for us then one that costs less.

Subject: "Closest Adversary"
Comments: Definition of our closest adversary makes no sense. This term was changed slightly to be our closest technical adversary. The term then makes sense to VA.

Subject: Open Action Items

	Capt Winthrop will examine additional Air Force Strategic documents to glean values.
Done	AFIT/ENS set up meeting with VA Division Chiefs to confirm values and definitions.
Done	Remove overlap in definitions or evaluation measures for Expand our Frontier (Potential for new warfighting capability) and Simplify Operations

	(enable)
	Prepare for 1 Feb meeting with Col Wood.
	Prepare for 29 Feb meeting on evaluation measures with Integrated Concept Leads and Strategic IPT leads.
Done	Set up a meeting(s) with VAS, VAA, and or VAC to develop some evaluation measures.

VAA: L/D Evaluation Measure/25 Jan 99

Anderson identifies L/D or lift-to-drag ratio as a measure of the aerodynamic efficiency of an airplane (Anderson, 1985: 256). For further information on lift and drag concepts, consult Anderson or any other standard aeronautical engineering text. The discussion below is a summary of an interview with Mr. Russ Osbourne of the Air Vehicles Directorate at AFRL held on 25 Jan 1999.

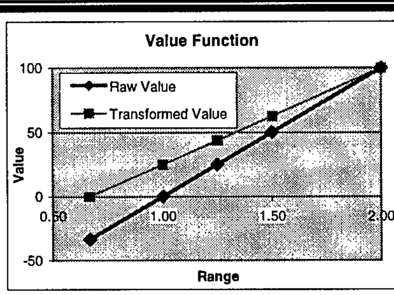
L/D depends on what air vehicle type is being discussed as shown in Table 20. Therefore, this quantity must be considered as the ratio: $(L/D)_N/(L/D)_0$. The difference $(L/D)_N-(L/D)_0$ was considered as the X-axis value, but it inaccurately describes reality. Specifically, a change in L/D from 2 to 4 is not the same as the change from 4 to 6. However, a change of L/D from 2 to 4 is the same as a change of 20 to 40 in terms of value to Air Vehicles.

L/D	Vehicle Type
0-6	Hypersonic Cruise Vehicles and some supersonic vehicles (F-15)
6-12	Transonic Fighters
9-11	Supersonic Transports
12-18	Bombers
15-28	Transports (C-5, C-141, etc.)
28-40	Sail Planes and Endurance Vehicles

Table 20: L/D categories for Aerospace Vehicles (Source: Personal Interview with Mr. Russ Osborne in Air Vehicles Directorate of AFRL)

The highest value for $(L/D)_N/(L/D)_0$ was set at 2 and the lowest value was set at 2/3. This considers conventional air vehicles and possible future developments in hypersonic vehicles. Doubling L/D is unlikely in most situations, although endurance vehicles and hypersonic vehicles might achieve this. The lower value of 2/3 was set with the idea that L/D might be traded off against other attributes resulting in a reduction of L/D for a system with corresponding increases in other attributes. There is little chance of $(L/D)_N/(L/D)_0$ being allowed to drop any less than 2/3 in a real situation. An example of this is when weapon pods or instrumentation pods are placed on fighters. These pods could increase the power or awareness of the weapon system but will decrease L/D.

The process defined in Chapter 2, **Error! Reference source not found.**, was implemented for a continuous evaluation measure. It was determined that value versus $(L/D)_N/(L/D)_0$ was a straight line. A drop in L/D from 1 to anything less than 1 should be penalized and follows the same straight line value function as increasing the L/D does. Hence, this function requires rescaling so the value will be positive. Figure 23 shows the both the transformed and original value functions developed.



Evaluation Measure: L/D

Range Units: Unitless

Definition: The ratio of the system L/D with the technology to the system L/D without the technology. L/D is the lift-to-drag ratio for a vehicle and measures the aerodynamic efficiency of the vehicle (Anderson, 1985: 256)

Comments: The X axis considers hypersonic vehicle improvements in technology, endurance vehicles and conventional aircraft improvements. The function accounts for drops in L/D allowing tradeoffs with other attributes. To do this, however, the function was transformed so the value would always be between 0 and 100.

	X	Y	Slope	Intercept
	2/3	-33 1/3		
	1.00	0	100	-100
	1.50	50	100	-100
	2.00	100	100	-100
Minimum	2/3	-33 1/3		
Maximum	2.00	100		

ReScale

Transform Range
-33 1/3
100

Copy Sheet

L/D Old - New	Value	Transformed	
0.67	-33.33	-2.8422E-14	
1.00	0.00	25	<<-- Do Nothing Alternative
1.25	25.00	43.75	
1.50	50.00	62.5	
2.00	100.00	100	

Figure 23: $(L/D)_N/(L/D)_0$ Value Function

VAC-AFIT Reach Measures/27 Jan 99

AFRL/VAC: Dennis Sedlock, Ralph Speelman, Bruce Clough, Roy Robertas,
AFIT/ENS: Capt Winthrop, Dr. Dick Deckro

Subject: Regeneration
Comment: Regeneration concept might be better if changed to turn-around-time or down time.

Subject: Availability
Comment: VAC has expertise on the reliability portion of this concept.

Subject: Evaluation Measure expertise
Comment: VAC believes they have expertise to help develop Availability, Missions Enabled, Regeneration and Safety Measures. Logistical expertise is required for some of these measures.

Subject: Open Action Items

Done	Capt Winthrop will examine additional Air Force Strategic documents to glean values.
Done	Verify no overlap in definitions or evaluation measures for Expand our Frontier (Potential for new warfighting capability) and Simplify Operations (enable).
Done	Prepare for 1 Feb meeting with Col Wood.
Done	Prepare for 29 Feb meeting on evaluation measures with Integrated Concept Leads and Strategic IPT leads.
Done	Prepare for 2 Feb meeting with VAC.
Done	Contact Bill Baron and Doug Dolvin of VAS for weight reduction measure.

VA-AFIT Reach, Power, Tech. Sup. Measures/29 Jan 99

AFRL/VA: Dick Colclough, Brian Van Vliet, Al Boudreau, Yvette Weber, Rikki Peters
AFIT/ENS: Capt Winthrop, Dr. Dick Deckro, LTC Jack Kloeber

Subject: Evaluation Measure Ranges
Comments: Ranges for most of the evaluation measures were developed. The information is documented in Appendix F: Air Vehicles' Evaluation Measures on page 199. Some important elicitation results are documented below.

Subject: Gain and Sustain under Power
Comments: VA cannot differentiate between gain and sustain issues under Power. Gain and sustain values were removed from the Power value. Lethality, afford and survival are the important values for power for Air Vehicles.

Subject: Gain and Sustain definitions
Comments: VA thinks of sustain as increasing the life of existing weapon systems while gain is development of new weapon systems. Gain and sustain definitions require some changes.

Subject: AF Savings Ratio Evaluation Measure
Comments: Space programs have the potential of savings of 100 for this measure. Air vehicles are not likely to gain more than 1.2 or 1.5 for the measure. The savings to the Air Force is calculated using recurring costs and nonrecurring costs. Savings are fairly easy to estimate. It will also include leveraging (cost savings multiplied by number of weapon systems). The Air Vehicles' investment cost is difficult to estimate.

Subject: L/D
Comments: The measure needs to be revisited. Space vehicles using hypersonic technology have the potential tripling L/D from existing systems (space shuttle).

Subject: Response Time
Comments: Goals are to be anywhere in the world within 3 hours. It assumes travel distance of 12,000 miles. Current time is 24 hours. This measure is for an individual weapon system.

Subject: Multiuse
Comments: Discussions on multiuse brought up the need to determine the rating level each MAJCOM places on an VA program. All VA customers are MAJCOMs, who must be satisfied. Multiuse at one time considered supporting both integrated concepts in VA and supporting outside users. The discussion defined outside users as USAF MAJCOMs and established the new measure.

Subject: Future Opportunities and New Warfighting Spectrum under Expand our Frontier

Comments: It is the experience of the group that human beings have nearly always underestimated the potential of technology. As such, both measures are binary. Further, Future Opportunities is the wrong concept and has been redefined as revolutionary. Revolutionary is defined as a scientific advance that could potentially change VA's entire paradigm and learning curve.

Subject: Feasible Value under Technological Superiority
Comments: The evaluation measure concepts of technology challenge and readiness time do not fit. Technology challenge is not the right concept. A better concept is technological risk. This will be defined in terms of the unknowns faced. The concept of readiness time will be removed from the value model and will be treated as a constraint. VA is generally given deadlines for maturing technology to a useable level. The current maturity level is measured by the VA technology readiness scale measurement.

VA Directorate-AFIT Meeting Highlights/1 Feb 99

AFRL/VA: Dr. Borger
AFIT/ENS: Capt Winthrop, Dr. Dick Deckro, LTC Jack Kloeber

Subject: Approval of Value Model
Comments: The value model takes into account Air Force Strategic values, which is critical. Dr. Borger recommends changing the problem statement slightly to say "be consistent with Air Force values" rather then "its values," which implies Air Vehicles values not Air Force values.

Dr. Borger explained how aeronautics is almost entering its 100th year (since 1903 with the Wright brothers) and is wondering if everything that can be done has been done in the field. The measures in the value hierarchy are traditional measures. He wonders what measures we should be using now? Examples of industries with lots of measures they are working with are the pharmaceutical industry and electronics industry. These industries invest 10%-15% of their profits in R&D. The oil industry invests 1% of their profits in R&D. Is aeronautics like the oil industry now or can it be like the pharmaceutical or electronics industries?

VAS-AFIT Weight Reduction Measure/2 Feb 99

AFRL/VA: VAS/William Baron, Douglas Dolvin (Had to leave early)
AFIT/ENS: Capt Winthrop

The X-axis for this evaluation measure was defined as the ratio:

$\left[\frac{\text{Airframe Weight}}{\text{Dry Vehicle Weight}}\right]_N \Big/ \left[\frac{\text{Airframe Weight}}{\text{Dry Vehicle Weight}}\right]_0$. In the ratio, "N" is stands for using the technology in a new system while "0" stands for the baseline system being compared with. A typical value for $\left[\frac{\text{Airframe Weight}}{\text{Dry Vehicle Weight}}\right]_0$ in current fighters is 0.35. The $\left[\frac{\text{Airframe Weight}}{\text{Dry Vehicle Weight}}\right]_N$ might ever become based on current understanding and pushing to the limits is 0.22. This ratio always assumes a particular mission has been selected, but by dividing the new system by the old system, the mission parameter is canceled out. The value function was determined to be a straight-line curve for this evaluation measure.

While selecting a mission sets the likely values for the ratio, selecting the mission can be difficult. For existing missions, it is clear existing weapon systems should be examined. It is important to pick the best known technology for the mission class for this evaluation measure to work. It might be possible to "game the system" by comparing new technology with something less than deployed state of the art. The effect would be to inflate this evaluation measure.

Another issue with the evaluation measure occurs when evaluating a technology for a mission that has never been performed. In this situation, the evaluators should identify a baseline system that enables the mission to be performed. Then, alternatives can be proposed that improve over the baseline system.

Weight reduction technologies will consists of likely consist of several technologies which together may reduce weight more than the sum of the individual technologies. That is, technology T1 by itself might reduce weight in a system by 1 % and technology T2 might reduce weight by 2 %. However, combining technologies T1 and T2 in the system might reduce the weight by 5 %. Hence, an alternative technology should include several technologies working together.

Considerable uncertainty may result in the measure of merit since it is uncertain how combing technologies will actually reduce weight. In the situation, the technological risk becomes very important since it will help establish the likelihood of achieving a particular desired result.

Additional information on $\left[\frac{\text{Airframe Weight}}{\text{Dry Vehicle Weight}}\right]_0$ is expected within the next day or two. This may change the X-axis scale, somewhat.

VAC-AFIT Reach Measures/2 Feb 99

AFRL/VAC: Maj Jeff Cole, Ralph Speelman, Bruce Clough, Mart Lentz
AFIT/ENS: Capt Winthrop, Dr. Dick Deckro

Subject: Awareness
Comments: VAC works on technologies that improve awareness. An example is health monitoring systems, which potentially could be used to reduce the time required to diagnose problems in aircraft. Another possible way of looking at this would be to identify the number of systems a health monitoring system can monitor. It is also possible that the health system could determine what actually caused combat damage and could use this information as a source of intelligence about an adversary.

Subject: L/D and Weight Reduction
Comments: These measures seem out of place in the hierarchy in comparison to the other measures in the same group. A possible fix is to move these two measures down a level in the hierarchy and place them under a higher tier value such as "Mission Effectiveness."

Subject: Loss of an Aircraft
Comments: The cost of the loss of an aircraft is probably not well accounted for in the model. Cost of an aircraft loss could be scored in the savings portion (lack of savings) to the Air Force.

Subject: Gain Availability
Comments: Availability needs to include "a single system which prevent the Aircraft from performing its mission" in the definition. Modern aircraft are typically available 80%-90% of the time. The measure is P_{AN}/P_{A0}, which can range from 0 to 1.5. This allows for an increase up to 100% in most situations and for decreasing availability in the case of a new weapon system performing a new mission. The measure assumes time between failure and time to repair is considered in determining the probability of availability. The shape of the value function is an s-curve which will require verification on the steepness. This attribute is mutually exclusive with Regeneration because it does not cover repair of battle damage or the time to replenish consumeables on the weapon system.

Subject: Sustain Availability
Comments: The same changes to definition and the assumptions mentioned in "Gain Availability" apply here. In Sustainment, there is no value for decreasing the availability and a program would not do this. The curve is the same as the Gain Availability curve when the measure is greater than 1.

Subject: Gain Missions Enabled and Sustain Missions Enabled
Comments: Adding missions to a weapon system takes place fairly often. In no situation will a mission be taken away from an aircraft and without adding a new mission, so the lowest this measure can be is 0. It is common to add a single mission to a weapon system

and possible though unusual to add 2 missions to an aircraft. Most of the value for the function in this measure is gained by adding a single new mission and adding two missions is "icing on the cake."

Subject: Regeneration
Comments: The evaluation measure should be redefined to encompass the turn around time on the ramp rather than defining it in terms of sorties. The operations should be "normal mission" operations, rather then "normal operations." Scoring this attribute requires consideration of combat damage and replenishment of consumables. Repair of combat damage includes assessment, design of repair, repair execution and accreditation. Replenishment of consumables includes rearming, refueling, and downloading mission specific information. The evaluation measure is mutually exclusive with Availability because it does not include reliability or the time to repair normal failures of equipment.

Subject: Safety
Comments: Safety is to be redefined as the change in the number of class A incidents that take place or ΔR_0. The number of incidents is typically measured per hour. A doubling in the number of safety incidents is bad and has the least value. Decreasing the number of incidents to 0 is the best case scenario.

VA-AFIT Reach, Power, Tech. Sup. Measures/4 Feb 99

AFRL/VA: Dick Colclough, Mike Ziegler, Brian Van Vliet, Al Boudreau, Yvette Weber
AFIT/ENS: Capt Winthrop, LTC Jack Kloeber

Subject: VAC Question – Lifecycle cost not calculated in all programs
Comments: The Strategic IPT and Integrated Concept Leaders recognize this issue. They believe it will be necessary to compute this quantity in the future. It is expected that calculation of AF Savings Ratio will be difficult for the engineers of VA. This quantity should be watched closely and if a better measure is found, it may be replaced.

Subject: VAC Question – Loss of aircraft due to attrition not explicitly calculated in model
Comments: Air Force regulations do not permit this quantity to be used.

Subject: The 6.1, 6.2, and 6.3 customer is not considered in the model
Comments: It is true these groups are customers. However, the ultimate customer is the warfighter. Another customer is the System Program Offices (SPO's). The evaluation measure called "User Rating" was modified to allow consideration of endorsements by SPO's.

Subject: Alternatives
Comments: Air Vehicles plans to provide 2 each of their red, green and blue programs for grading by the model. Further, they will provide names of contacts of who can score these programs. A red program is one on the critical path for their roadmap. A green program is an important program, but not critical. A blue program is a "nice to have" program and is the first to go in case of budget cuts.

Subject: Afford
Comments: AFIT realized a problem existed in dividing affordability between Reach and Power. How much money is Reach savings and how much is Power savings? VA agreed there was a problem and Afford was moved under Technological Superiority so all savings could be measured in one place.

Subject: Evaluation Measures
Comments: Nearly all evaluation measures were determined in the meeting. Quantity under Lethality was changed to Firepower. No definition for Firepower was available in the meeting. Both Firepower and Warfare Advantage measures were deferred to the Air Vehicles' Directorate level. The Ratio of People is believed to be difficult to measure for a technology. A technologist might have better luck with part counts. Program managers in VA may have better ideas for this quantity.

VA Directorate-AFIT Weight Elicitation Summary/4 Feb 99

AFRL/VA: Dr. Borger
AFIT/ENS: Capt Winthrop, Dr. Dick Deckro

Subject: Awareness
Comments: The decision-maker believes Air Vehicles will contribute to Awareness in the future in an integration role. He believes availability, missions enabled, and regeneration are the measures of the value. These measures are expected to be the same as the values under Reach/Gain and are expected to score the same as those under Reach/Gain. VA has no sustainment value in Awareness, but this may change in the future.

Subject: Rank Order of Reach Evaluation Measures
Comments: The decision-maker ranked ordered the evaluations measures as follows: 1) Availability, 2) Response Time, 3) Missions Enabled, 4) Regeneration and 5) Mission Effective for Gain under Reach. The decision-maker ranked ordered the evaluation measures as follows: 1) Achieve/Extend Life, 2) Missions Enabled, 3) Availability, 4) Regeneration, 5) Safety, 6) Weight Reduction for Sustain under Reach.

Subject: Power Evaluation Measures Ranking
Comments: During the elicitation, the decision-maker realized Standoff was important as a measure of power. The decision-maker ranked evaluation measures as follows: 1) Effectiveness, 2) Firepower, and 3) Survival. However, when asked to compare Effectiveness with Achieve/Extend Life, he realized Standoff was missing from Power. Adding Standoff changed the weighting he provided between Power and Reach. The new ranking was: 1) Standoff, 2) Effectiveness, 3) Firepower, and 4) Survival.

Subject: Technological Superiority measures Ranking
Comments: The decision-maker ranked Be Efficient Measures as follows: 1) User Rating, 2) Multiuse, 3) Uniqueness, 4) Dual Use, 5) Intermediate Projects. The decision-maker ranked Expand our Frontier measures as follows: 1) New Warfighting Spectrum, 2) Revolutionary. . The decision-maker ranked Simplify Operations measures as follows: 1) Enables, 2) Interoperability, 3) Ratio of People. The decision-maker ranked Win measures as follows: 1) Warfare Advantage, 2) Lead, 3) Cost to Adversary.

Subject: Reach/Gain versus Sustain
Comments: The decision-maker commented that sustainment in Air Vehicles will become less important and Gain more important around 2002.

Subject: Weights of Values
Comments: Summary of elicited weights follows. Note: The "-" is used interchangeably with "_".

Weight Variable	Definition
w_{Aware}	Awareness
$w_{A\text{-}Ga}$	Awareness/Gain

Weight Variable	Definition
$w_{AG\text{-}Av}$	Awareness/Gain/Availability
w_{Power}	Power
$w_{P\text{-}Le}$	Power/Lethality
$w_{PL\text{-}St}$	Power/Lethality/Standoff
w_{Reach}	Reach
$w_{R\text{-}Ga}$	Reach/Gain
$w_{RG\text{-}Av}$	Reach/Gain/Availability
$w_{R\text{-}Su}$	Reach/Sustain
$w_{RS\text{-}Ac}$	Reach/Sustain/Achieve/Extend Life
w_{TS}	Technological Superiority
$w_{T\text{-}AF}$	Technological Superiority/Afford
$w_{TA\text{-}AF}$	Technological Superiority/Afford/AF Savings Ratio
$w_{T\text{-}Be}$	Technological Superiority/Be Efficient
$w_{TB\text{-}Us}$	Technological Superiority/Be Efficient/User Rating
$w_{T\text{-}Ex}$	Technological Superiority/Expand our Frontier
$w_{TE\text{-}Ne}$	Technological Superiority/Expand our Frontier/New Warfighting Spectrum
$w_{T\text{-}PR}$	Technological Superiority/Programmatic Risk
$w_{T\text{-}SO}$	Technological Superiority/Simplify Operations
$w_{TSO\text{-}En}$	Technological Superiority/Simplify Operations/Enables
$w_{T\text{-}Wi}$	Technological Superiority/Win
$w_{TE\text{-}Wa}$	Technological Superiority/Win/Warfare Advantage

Elicited Weights from Air Vehicles' Head Office.

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1. Purpose: Relate Reach to Awareness
Reach/Sustain/Achieve/Extend Life is three times as important as Awareness/Gain/Availability.

$$w_{RS\_Ac} \cdot w_{R\_Su} \cdot w_{Reach} = 3 \cdot \left(w_{AG\_Av} \cdot w_{A\_Ga} \cdot w_{Aware}\right)$$

$$w_{A\_Ga} = 1$$

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2. Purpose: Relate Reach to Power
Achieve/Extend Life is as important as standoff

$$w_{RS\_Ac} \cdot w_{R\_Su} \cdot w_{Reach} = w_{PL\_St} \cdot w_{P\_Le} \cdot w_{Power}$$

$$w_{P\_Le} = 1$$

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3. Purpose: Relate Tech. Sup. to Reach
New Warfighting Spectrum is twice as important as Sustain/Extend Life.

$$2 \cdot \left(w_{RS\_Ac} \cdot w_{R\_Su} \cdot w_{Reach}\right) = w_{TS} \cdot w_{T\_Wi} \cdot w_{TE\_Wa}$$

---

4. Purpose: Relate Reach/Gain to Reach/Sustain

Reach/Sustain/Achieve/Extend Life is twice as important as Reach/Gain/Availability. Sustainment will be most important until 2002 when gain will increase in importance.

$${}^{w}RS\_Ac \cdot {}^{w}R\_Su \cdot {}^{w}Reach = 2 \cdot \left({}^{w}RG\_Av \cdot {}^{w}R\_Ga \cdot {}^{w}Reach\right)$$

Reduces to:

$${}^{w}RS\_Ac \cdot {}^{w}R\_Su = 2 \cdot \left({}^{w}RG\_Av \cdot {}^{w}R\_Ga\right)$$

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5. Purpose: Relate Tech. Sup./Be Eff. to Tech. Sup./Exp. our Fron.
User Rating is as important as New Warfighting Spectrum

$${}^{w}TS \cdot {}^{w}T\_Be \cdot {}^{w}TB\_Us = {}^{w}TS \cdot {}^{w}T\_Ex \cdot {}^{w}TE\_Ne$$

Reduces to:

$${}^{w}T\_Be \cdot {}^{w}TB\_Us = {}^{w}T\_Ex \cdot {}^{w}TE\_Ne$$

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6. Purpose: Relate Tech. Sup./Be Eff. to Tech. Sup./Simplify Operations
User Rating is twice as important as Enables

$${}^{w}T\_Be \cdot {}^{w}TB\_Us = 2 \cdot \left({}^{w}T\_SO \cdot {}^{w}TSO\_En\right)$$

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7. Purpose: Relate Tech. Sup./Exp. our Fron. to Tech. Sup./Win
Warfare Advantage is as important as New Warfighting Spectrum.

$${}^{w}T\_Ex \cdot {}^{w}TE\_Ne = {}^{w}T\_Wi \cdot {}^{w}TE\_Wa$$

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8. Purpose: Relate Tech. Sup./Exp. our Fron. to Tech. Sup./Win
Warfare Advantage is three times more important then AF savings Ratio.

$${}^{w}T\_Wi \cdot {}^{w}TE\_Wa = 3 \cdot \left({}^{w}T\_AF \cdot {}^{w}TA\_AF\right)$$

$${}^{w}TA\_AF = 1$$

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9. Purpose: Relate AF Savings Ratio to Programmatic Risk
AF Savings Ratio is 5 times as important as Programmatic Risk

$${}^{w}T\_AF \cdot {}^{w}TA\_AF = 5 \cdot {}^{w}T\_PR$$

VA-AFIT Measures, Preferential Independence, Weights/10 Feb 99

AFRL/VA: Dick Colclough, Mike Ziegler, Brian Van Vliet, Al Boudreau, Yvette Weber
AFIT/ENS: Capt Winthrop

Subject: Warfare Advantage
Comments: The group did not feel they had the expertise to accurately estimate the value increment changes for each level in the measure. This evaluation measure has equal value interval levels. Any technology that can be linked to a system that achieves a certain level in this measure will have the same level. An example is an improved landing gear. By itself, the landing gear has no value to the warfighter. On the right vehicle, it contributes to the vehicles' ability to neutralize, deter, overwhelm, etc. an adversary.

Subject: Mutual Preferential Independence
Comments: A matrix for pairwise comparing each evaluation measure against all of the others was developed to establish mutual preferential independence was developed. Each row compared one evaluation measure with all other evaluation measures in the value model. The evaluation measure was set to a particular level. The other measures being compared with were set to an arbitrary low level and an arbitrary high level. The group was asked if they would still prefer the high level to the low level given the other evaluation measure is fixed at a particular level. They were asked if there preferences for the levels of any evaluation measure would change given one evaluation measure is set to a various fixed values. The group responded they would not change their preferences. This test validates that the mutual preferential independence assumption holds for the value model.

Subject: Weights
Comments: Below the weight elicitation process is summarized. Those weights that are struck out are because an evaluation measure was eliminated from the value model. L/D and Weight Reduction along with the Mission Effective value were removed because these items are design parameters. They are design parameters while the other parameters look at changes in operational capabilities. Standoff was eliminated because it is covered by survival. Standoff was originally used to establish the relationship between values by the VA head office. It is assumed Survival can replace Standoff using the same relationship originally stated for Standoff. The Firepower evaluation measure is believed to be a part of Effectiveness. Mr. Jim Grove (x5-3538) plans to provide additional information that may change the definition of Effectiveness slightly to cover the concept Firepower would have covered.

	Reach/Gain		
1	Regeneration	=	Missions Enabled
2	Regeneration	=	Response Time
3	Regeneration	=	Availability
4	~~L/D or Weight Reduction~~	~~=~~	~~Availability~~
	Reach/Gain		

~~5~~	~~Mission Effective L/D (Cruise)~~	~~=~~	~~Mission Effective Weight Reduction~~
	Reach/Sustain		
6	1.5 * Missions Enabled	=	Achieve/Extend Life
7	1.2 * Missions Enabled	=	Missions Enabled
8	1.5 * Missions Enabled	=	Availability
9	1.5 * Missions Enabled	=	Regeneration
10	1.7 * Missions Enabled	=	Safety
	Awareness/Gain		
11	Regeneration	=	Availability
12	Regeneration	=	Missions Enabled
	Power/Lethality		
~~13~~	~~Survival~~	~~=~~	~~Firepower~~
14	1.3 * Survival	=	Effectiveness
~~15~~	~~Survival~~	~~=~~	~~Standoff~~
	Tech. Sup./Be Efficient		
16	1.4 * Dual Use	=	Intermediate Products
17	1.8 * Dual Use	=	Uniqueness
18	1.5 * Dual Use	=	Multiuse
19	2 * Dual Use	=	User Rating
	Tech. Sup./Expand Our Frontier		
20	Revolutionary	=	New Warfighting Spectrum
	Tech. Sup./Simplify Ops.		
21	Ratio of People	=	Interoperability
22	Ratio of People	=	Enables
	Tech. Sup./Win		
23	1.2 * Cost to Adversary	=	Lead
24	1.5 * Cost to Adversary	=	Warfare Advantage

Subject: Weights for Reach/Gain, Awareness/Gain, and Tech. Superiority/Simplify Operations
Comments: The Integrated Concept Leaders found themselves splitting up on which evaluation measures were more important. Under Reach/Gain, the Space ICL thought the evaluation measures ranked by importance was: 1) Missions Enabled, 2) Regeneration, 3) Response Time, and 4) Availability. The UAV ICL felt the order was: 1) Availability, 2) Response Time, 3) Missions Enabled, and 4) Regeneration (which agrees with the Air Vehicles head office, incidentally).

Subject: L/D and Weight Reduction under Reach
Comments: Removed from model because it did not "fit" with the other measurements.

VA-AFIT Concerns over some Measures and Weights/19 Feb 99

AFRL/VA: Dick Colclough, Mike Ziegler, Al Boudreau
AFIT/ENS: Capt Winthrop, LTC Kloeber, Dr. Deckro

Subject: L/D and Weight Reduction
Comments: L/D and Weight Reduction do not fit in the model, but something is missing if it is removed. The group agreed to add a combined measure called "Payload-Range" which would measure the effects of both. This can be done because payload and range directly trade off with each other. For more details on this, see Appendix E: Value Hierarchies and Means Networks.

Subject: Remove Weight Reduction from Sustain?
Comments: The group decided to leave this evaluation measure in the hierarchy. Sustainment actions can result in changes in weight for existing vehicles, but rarely is it enough to significantly impact the payload or range of the vehicle.

Subject: Survival
Comments: The question of whether or not a separate value for human survival and weapon system survival was brought up. A person flying an Air Vehicle is at far less risk than a person in a manned aircraft during combat. Air Vehicles felt survival should encompass both the human element and the weapon system element. Hence, this measure was not changed.

Subject: Weights for evaluation measures under Reach under Gain
Comments: The weights for all of the measures under were determined to be equally weighted.

VA-AFIT Scoring/22 Feb 99, 24 Feb 99 – 25 Feb 99.

AFRL/VA: Doug Dolvin, Jim McDowell, Forrest Sandow
AFIT/ENS: Capt Winthrop, LTC Kloeber

Comments: The 22 Feb 99 meeting established the scoring team that would use the Air Vehicles' model for the first time on real programs.

Subject: Scoring Results and Notes
Begin with measures under sustain
Forrest Sandow - Doug Dolvin

Weapons Bay Door Noise Suppression - Alternative A

Composite Repair of Aircraft Structures - Alternative B

ITAC - Alternative C

Number of Missions enabled (sustain under reach)

A	B	C	D	E	F
2	0			0	

Comments: A- Active suppression allows larger Mach number, which enables a lot more missions
B: Just fixing structures so no new missions

Other comments: Maybe new missions shouldn't be included in sustain column.

Achieve Extend Life (sustain under reach)
Years until the system must be replaced

A	B	C	D	E	F
T0=Tn	1.5			2	

Comments: A-no change in design but possibly slight increase in life due to current out-of-range use
B- Mainly large transport A/C, future in fighters
E- Doubling useable life by monitoring condition. No routine maintenance.

Availability (sustain under reach)

A	B	C	D	E	F
1	42 vs 3 over			No Change	

	life			from Gain	

Comments: A-just about a push - more electronics - less mechanical systems - assume stay within boundaries of speed

B- bonded repairs are more permanent so time to repair is longer short term

fatigue cracks, corrosion, different aircraft, different systems-large transport

with → 3 days and good for life of aircraft
without → 1 day and good for 5 years then 6 weeks for part replacement
Looks like 42 days without and 3 days with.
E- No change because it is an add on technology, same effect either way.

Regeneration Time (sustain under reach)

A	B	C	D	E	F
1	1			50% decrease	

Comments: A-No effect
B-No effect, especially with combat damage- long term fatigue
E-See Gain

Decrease in # of class A incidents per flight hour(sustain under reach)

A	B	C	D	E	F
No effect	No effect			No Change	

Comments: A-
B-

Comments other: Decrease in probability of occurrence -10-7 to 10-7

Weight Reduction (sustain under reach)

A	B	C	D	E	F
No effect	No effect			Negligible	

Comments: A-too little to count
B-too little to count

Comments other:

Only A-Weapons Bay, C-ITAC ,D-SITE-M,E-HMS ,F-SB System, G-MTV

Availability (gain under reach)

A	B	C	D	E	F	G
		No effect	20% decrease	10% increase	7 times??	15%
					Pn=80%	

Comments: A-no effect in domain
C- system compared - 6→ F-16D same aircraft being used
D- system compared - UCAV Lethal C
E-system compared - F-15E/F-16 - assume 65% now- 71.5% with tech
F- system compared - Space shuttle - 2/13 -Harry Karosopoulos - 8 hours flight/per week
G-system compared - F-18EF/F-22- old is 65% without hydraulic systems

Comments other: P stands for percent ready.

Missions enabled(gain under reach)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
		2	2	0	2	0

Comments: A-no effect in domain - high speed missions not currently available
C- system compared - 6→ F-16D same aircraft being used
D- system compared - UCAV Lethal C - covert strike - main benefit
E-system compared - F-15E/F-16 - long endurance - Chernobyl - SEAD
F- system compared - Space shuttle -
G-system compared - F-18EF/F-22-

Comments other - more than two new missions for both high scorers.

Only A,C,D,E,F,G
Regeneration(gain under reach)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB SystemSMV,G-MTV

A	B	C	D	E	F	G
no effect		no effect	no effect	50% decrease	50% decrease	25% decrease
					Tn=18 Hours	

Comments: A-no effect in domain
C- system compared - 6→ F-16D same aircraft being used
D- system compared - F117A- extra 20 minutes but concurrent

E-system compared - F-16 - central hydraulic system decrease regeneration time due to damage assessment. Eliminates Flight Control System can not duplicates.

F- system compared - Space shuttle - 2 days for new vs 30 days- Harry Karosopoulos-2nd floor middle aisle-243

G-system compared - F-18EF/F-22- combat repair time is much better - lost hydraulic system and modular LRUs-2 level maintenance scheme

Comments otherOnly A,C,D,E,F,G

Response Time (gain under reach)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
No effect		no increase	20% less time	No improvement	No Improvement	20% less time
					t_n = 90 Minutes	

Comments: A-no effect in domain

C- system compared - 6→ F-16D same aircraft being used→48 hours to 48 hours (800 mile range) assume no refueling available for ITAC prepositioned people and prepositioned fueling

D- system compared - F117A - in theater logistics setup - otherwise no effect.

E-system compared - F-15E/F-16 -

F- system compared - Space shuttle - Precision covert strike but weapons delivery only

G-system compared - F-18EF/F-22-- in theater logistics setup - otherwise no effect

Comments other: This is speed based only-assuming CONUS base. Assuming no logistics tail.

Payload-Range (gain under reach)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System, G-MTV

A	B	C	D	E	F	G
No effect		20%	no improvement	No improvement	10%	10% increase

Comments: A-no effect in domain

C- system compared - 6→ F-16D same aircraft being used→trajectory optimization ITAC(geese flying)

D- system compared - F117A - in theater logistics setup - otherwise no effect.

E-system compared - F-15E/F-16 -

F- system compared - Space Operating vehicle (replace all other measures) - 10%. 6000 lbs to LEO, 1000 lbs to Polar orbit, 25,000 lbs "popup" to LEO

G-system compared - F-18EF/F-22-- F22- 10%-;weight reduction

Comments other: This is speed based only-assuming CONUS base. Assuming no logistics tail.

Availability (Awareness/Gain)
Only A-Weapons Bay, C-ITAC ,D-SITE-M,E-HMS ,F-SB System, G-MTV

A	B	C	D	E	F	G
No Change	No Change		No Change	No Change	No Change	No Change

Comments:

Comments other:

Missions Enabled(Awareness/Gain)
Only A-Weapons Bay, C-ITAC ,D-SITE-M,E-HMS ,F-SB System, G-MTV

A	B	C	D	E	F	G
No Change	No Change		No Change	No Change	No Change	No Change

Comments:

Comments other:

Regeneration (Awareness/Gain)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
No Change	No Change		No Change	Yes	No Change	No Change

Comments:

Comments other:

Effectiveness (Power/Lethality)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
No Change	No Change	20% Improvement	0			

Comments:

A -
C - This value is a guess. Can send in 4 UAV's and they can get closer for better accuracy with less risk to a person.
D - No Change

Comments other:

Survival (Power/Lethality)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
10% Improvement	No Change	20% Improvement	50% Improvement	N o	N o	%15 decrease

Comments:

A - Uncertain of actual effect.
C - This value is a guess.
D - Low Observable compared to F-117 due to better technology.
G – Based on analysis of aircraft returning with combat damage, identification of where damage was not taken estimates the vulnerable areas of the aircraft (i.e. those aircraft did not return). Elimination of hydraulics eliminates a single point vulnerability that brings down aircraft.

Comments other:

AF Savings Ratio (Tech. Superiority)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
4/1	3/1	10/1	0	$35M/20 Years	$25B/20 Years	$10B/20 Years
$7M	$6M	$11M	$2M	$4M	$25 M	$25 M

Comments:
A- Design of spoilers is challenging. Initial design is cheaper. This number is a best case for Gain. Retrofitting is a lot harder.
C-$11M from French and $11M from Air Vehicles. Slightly less than $10M ($9.8M) from Air Vehicles. Requires an ATD before this can actually be used. Replacing a squadron of F-16's with unmanned F-16's
D - Savings for this is negative. 12% more than a baseline system.

Comments other:

Dual Use (Tech. Superiority/Be Efficient)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
NO	Yes	Yes	No	Yes	No	Yes

Comments:
B - Airlines interested along with FAA.
C - Border Patrol people interested in the program.

Comments other:

Intermediate Products (Tech. Superiority/Be Efficient)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
No	Yes	Yes	No	Yes	No	Yes

Comments:

C - Questionable about 12 months. Might be 24 months.

Comments other:

Multiuse (Tech. Superiority/Be Efficient)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
2 IC	1 IC	2 IC	1IC	3IC	1IC	2IC

Comments:
A - UAV,Sustainment
C - UAV, Space

Comments other:

Uniqueness (Tech. Superiority/Be Efficient)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
Partner (Austrailia)	Partner (Cost Share w/ FAA)	Partner	Partner	Part ner	Part ner	Partn er

Comments:

Comments other:

User Rating (Tech. Superiority/Be Efficient)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
No Rating	Endorsed	No Rating	No Rating	JSF Endorsed	ATD	NASA endorsed

Comments:
B - Not top 10 ATD

Comments other:

Revolutionary (Tech. Superiority/Expand our Frontier)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
No	No	No	No	Yes	Yes	Yes

Comments:
C - Yes to warfighter.

Comments other: Should be redefined to be technology that changes the Warfighter's operation.

New Warfighting Spectrum (Tech. Superiority/Expand our Frontier)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
No	No	Yes	Yes	No	No	No

Comments:
C- Cooperative Ops. Flexibility is greater. Training of pesonell is less. Allows quick changes in posture.
D- Covert ingress allows surpise.

Comments other:

Programmatic Risk(Tech. Superiority)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
Low (90-10)	Low (80-20)	Low (80-20)	Low (75-25)	Low	High	Med

Comments: If the money is available, there should be no problem. Risk is whether or not the money will be available.

A, B Tech. Risk Low.

C - 20% chance of not completing all of the goals. Medium Tech. Risk.
D - 25% chance of not completing all of the goals. Medium Tech. Risk.

Comments other: Tech. risks should be a separate factor.

Enables (Tech. Superiority/Simplify Operations)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
Yes	No	Yes	Yes	Yes	Yes	Yes

Comments:
Assume operations does not include Maintenance.
B - Change to Yes if Maintenance is included.
C- Co-operative effort, collision avoidance.
D - Covert Ingress is enabled.
Comments other:

Interoperability (Tech. Superiority/Simplify Operations)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
Coalition	All Services	Coalition	All Services	Coal	USAF	Coal

Comments:
A- Australian Connection
C - French Connection
D - USAF, Navy, JTCG

Comments other:

Ratio of People(Tech. Superiority/Simplify Operations)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
No Change	No Change	1/3	No Change	1	1/3	2/3

Comments:

B- Difficult to ratio people reduction. Does not include changes in Depot Maintenance.
C-Losing 4 pilots. Can be better with larger numbers of unmanned vehicles.

D-Adds people. Look at Maintenance crew for 117 versus Maintenance crew +2

Comments other:

Cost to Adversary (Tech. Superiority/Win)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
Medium	Low	Low	High	Low	High	Med

Comments:

C- Developing for UCAV would be very expensive.
Comments other:

Lead (Tech. Superiority/Win)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
5-10 Years	< 1 Year	1-5 Years	5-10 Years	1-5 Years	5- 10 Years	1-5 Years

Comments:

A - Counteracting is not known.
B - Tech. being Given Away
C -
D -

Comments other: Intervals may be too large (1-2 years)

Warfare Advantage (Tech. Superiority/Win)
Only A-Weapons Bay,C-ITAC ,D-SITE-M,E-HMS ,F-SB System,G-MTV

A	B	C	D	E	F	G
Degrade	No Effect	Degrade	Neutralize	Keep Pace	Neutralize	Degrade

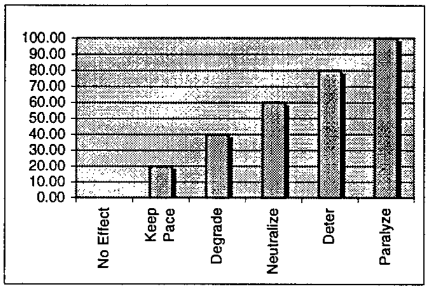
Comments:

Comments other:

Appendix C: Evaluation Measure Templates and Macros

Evaluation Measure Types

A set of Excel templates and macros were developed to simplify the development of the evaluation measures. Evaluation measures types implemented were the discrete measure, exponential measure, piecewise fit, and S-curve. Each type is discussed, in turn.



ReScale

Copy Sheet

Scale
Maximum 100.00

Comments:

	Evaluation Measure		Uniqueness
Number	Category	Value	Category Definition
0	No Effect	0.00	Technology that is ineffective against an adversary.
1	Keep Pace	20.00	Technology that is needed to stay at the same level as an adversary.
2	Degrade	40.00	Technology that results in a tactical advantage for our forces.
3	Neutralize	60.00	Technology advances that render some or all of an adversaries military capability ineffective and cannot be countered at the completion of the advance
4	Deter	80.00	Technology that discourages an adversary from acting because of doubt, fear or cost.
5	Paralyze	100	Technology that makes it impossible for an adversary to act.

Figure 24: Sample Discrete Evaluation Measure Calculation Sheet

Figure 24 shows a sample discrete measure. The discrete measure is used when several categories exist that describe the attribute. The calculation sheet has the ability to graphically display each category and its value. Each category has a name defined below the graphical display, has a value associated with it, and a has a detailed definition associated with the name. The "comments" block can be used to record information from the expert providing the information.

The Excel sheet has the capability of automatically rescaling the value axis or y-axis to the value scale selected by the user. This is accomplished using an Excel macro, which is activated by the "ReScale" button. Rescaling the X-axis is accomplished by adding or subtracting evaluation measure categories and then changing the data series references of the graph. The "copy sheet" button for all evaluation measures will be discussed later.

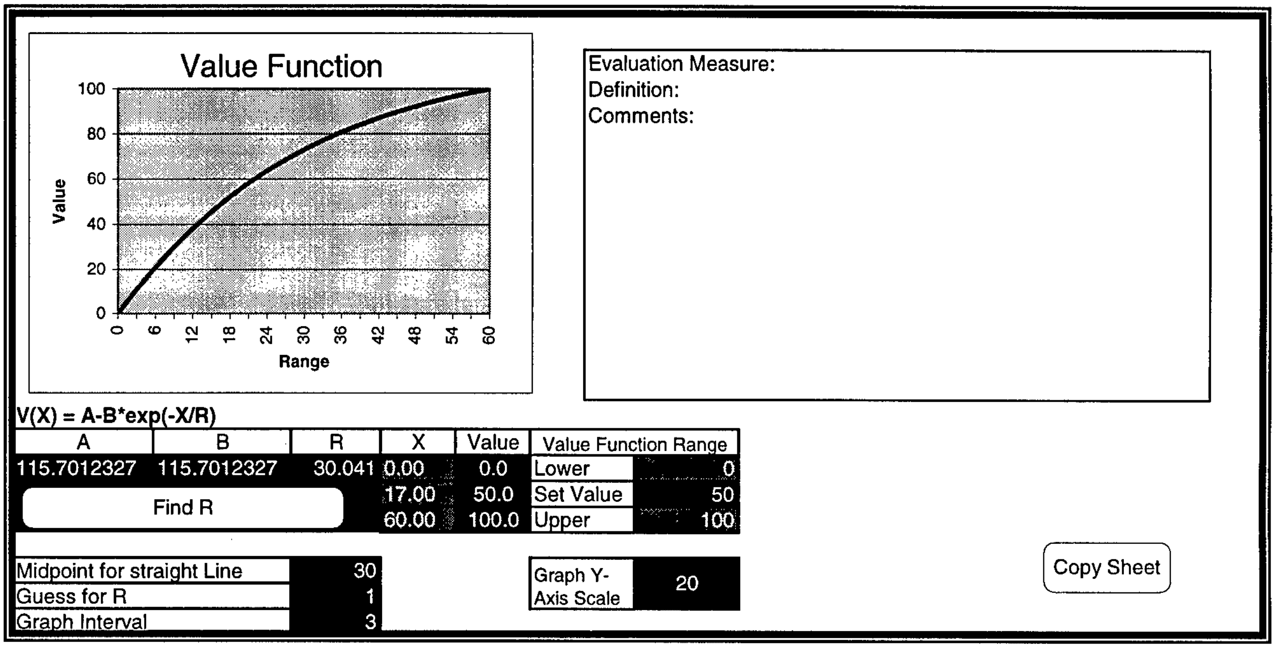


Figure 25: Sample Exponential Evaluation Measure Calculation Sheet

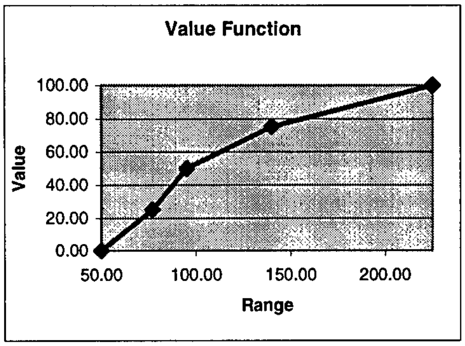
Figure 25 shows the Excel sheet to use for exponential functions. The values under the X column and the values under "Value Function Range" for "Lower" and "Upper" can be changed by the user. Setting values in the X column are used to determine the lower, upper and midvalue area where the change in value from the lower to the midvalue point is the same change in value as from the midvalue point to the upper value level. Pressing the "Find R" macro button automatically calculates the values for A, B and R using numerical methods supported by Excel. The "Lower" and "Upper" values under "Value Function Range" can be changed to any range. This allows rescaling of the value axis or y-axis, which takes place automatically when "Find R" is pressed. Additionally, it allows the development of curves over smaller ranges. This capability allows the analyst to fit several exponential curves together to develop a "piecewise exponential" curve.

The equations used in deriving value for the exponential function were:

$$v(x) = A - B * \exp(-x_M / R)$$
$$A = L + B * \exp(-x_L / R) \qquad \textbf{Equation 10}$$
$$B = \frac{H - L}{\exp(-x_L / R) - \exp(-x_H / R)}$$

where L is the lowest value to be considered for the function and H is the highest value being considered for the function. The variable x is a possible level in the measure where x_L is the lowest level of the measure possible, x_H is the highest level of the measure, and x_M is the value where the decision maker equally prefers a change in value from the increment x_L to x_M as the increment from x_M to x_H. The value R is calculated using Excel's "Goal Seek" command. The variable v(x) is set to the value being searched for by the numerical method.

Figure 26 shows a sample Excel sheet for calculating piecewise linear functions. The Excel graph automatically displays each function. The analyst simply inputs values in the X and Y column and the slope and intercepts are automatically calculated. The analyst can input scale values for "Minimum" and "Maximum" in the X and Y column. By hitting the "ReScale" button in the sheet, a macro is invoked which automatically rescales the graph based on the scaling values that were entered into the Excel sheet. A section is provided in the Excel sheet to identify the evaluation measure, define it, and provide comments during the elicitation process.



Evaluation Measure:
Definition:
Comments:

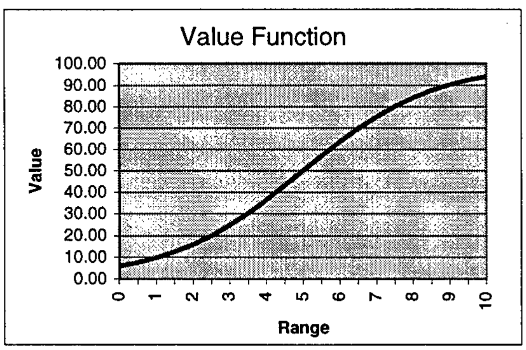
X	Y	Slope	Intercept
50.00	0.00		
77.00	25.00	0.925926	-46.2963
95.00	50.00	1.388889	-81.94444
140.00	75.00	0.56	-2.78
225.00	100.00	0.29	33.82

Minimum	50.00	0.00
Maximum	225.00	100.00

ReScale

Copy Sheet

Figure 26: Sample Piecewise Linear Calculation Sheet



Evaluation Measure:
Definition:
Comments:

V(X) = A/(A+exp[(-X -B)/T])*Scale

A	B	T	X	Utility
1	-5	1.8	0.00	5.85
			2.50	19.96
Bias			5.00	50.00
			7.50	80.04
Steepness			10.00	94.15

Value	Elicited Point	Calculate T
25	3	1.820478
75	7	1.820478

Rescale

Graph Y-Axis Scale Constant	100.0	Graph Y-Axis Scale Increment	10.0

Copy Sheet

Figure 27: Sample S-Curve Calculation Sheet

Figure 27 shows a sample sheet for calculating an S-curve evaluation measure.

The S-curve allows the analyst to enter the lowest value and highest value for the curve under the “X” column. Slider bars allow the analyst to change the bias and the steepness of the curve. Changing the “Graph Y-Axis Scale Constant” can rescale the graph value and hitting the “Rescale” button, automatically. Additionally, it is possible to calculate “T” from elicited points with a decision-maker. All the analyst does is to type in the elicited points in the elicited point column and the value of T is automatically calculated.

The “Copy Sheet” button copies the current sheet to a new Excel Workbook called “VA Value Model.xls.” The Excel sheets shown above were developed an placed in an Excel workbook called “Measure Calc.xls.” The “Copy Sheet” button allows the analyst to develop an evaluation measure in the “Measure Calc.xls” workbook and then copy the evaluation measure over to the “VA Value Model.xls” workbook, once it is completed. This allows repeated use of the “Measure Calc.xls” tools and quick saving of the results in the new workbook.

Excel Button Macros

Several Excel macros, connected to buttons in Excel sheets, were developed to simplify evaluation measure development. What these macros do was discussed in the last section. These macros were developed using the “Record Macro” option in Excel. They were modified slightly, in some cases. Actual macrocode written in visual basic and a short explanation of their function is shown below:

```
Sub Find_R()
'
' Find_R Macro
' Macro recorded 11/4/98 by Michael Winthrop
' Implemented by the "Find R" button in the Exponential Excel Sheet

'
    Range("C23").Select
    Selection.Copy
    Range("C18").Select
```

```
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
    Application.CutCopyMode = False
    Range("E19").GoalSeek Goal:=Range("G19"), ChangingCell:=Range("C18")

    ActiveSheet.ChartObjects("Chart 2").Activate
    ActiveChart.Axes(xlValue).Select
    With ActiveChart.Axes(xlValue)
        .MinimumScale = Range("G18")
        .MaximumScale = Range("G20")
        .MinorUnitIsAuto = True
        .MajorUnit = Range("G22")
        .Crosses = xlAutomatic
        .ReversePlotOrder = False
        .ScaleType = xlLinear
    End With
    Range("C18").Select
End Sub

Sub S_Curve_Rescale()
'
'ReScales the Y axis in the S-Curve Excel Sheet, only.
'The Rescale button implements this macro.

    ActiveSheet.ChartObjects("Chart 12").Activate
    ActiveChart.Axes(xlValue).Select
    With ActiveChart.Axes(xlValue)
        .MinimumScale = 0
        .MaximumScale = Range("D23")
        .MinorUnitIsAuto = True
        .MajorUnit = Range("G23")
        .Crosses = xlAutomatic
        .ReversePlotOrder = False
        .ScaleType = xlLinear
    End With
    Range("C18").Select
End Sub

Sub PL_Rescale()
'
'This Macro rescales the piecewise linear Excel Graph and is implemented using
'the rescale button on that sheet.

    ActiveSheet.ChartObjects("Chart 1").Activate
    ActiveChart.Axes(xlValue).Select
    With ActiveChart.Axes(xlValue)
```

```
        .MinimumScale = Range("D24")
        .MaximumScale = Range("D25")
        .MinorUnitIsAuto = True
        .MajorUnitIsAuto = True
        .Crosses = xlAutomatic
        .ReversePlotOrder = False
        .ScaleType = xlLinear
    End With
    ActiveChart.Axes(xlCategory).Select
    With ActiveChart.Axes(xlCategory)
        .MinimumScale = Range("C24")
        .MaximumScale = Range("C25")
        .MinorUnitIsAuto = True
        .MajorUnitIsAuto = True
        .Crosses = xlAutomatic
        .ReversePlotOrder = False
        .ScaleType = xlLinear
    End With
    Range("C18").Select
End Sub

Sub D_Rescale()
'
'This macro rescales the discrete excel sheet automatically.  It is activated
'by hitting the rescale button on the sheet.

    ActiveSheet.ChartObjects("Chart 1").Activate
    ActiveChart.Axes(xlValue).Select
    With ActiveChart.Axes(xlValue)
        .MinimumScale = 0
        .MaximumScale = Range("G3")
        .MinorUnitIsAuto = True
        .MajorUnitIsAuto = True
        .Crosses = xlAutomatic
        .ReversePlotOrder = False
        .ScaleType = xlLinear
    End With
End Sub
Sub Copy_Sheet()
'
'This macro copies the current sheet to an new workbook called "VA Value Model.xls"
'By changing the file in the quotes, other files can be copied to.
    ActiveSheet.Copy After:=Workbooks("VA Value Model.xls").Sheets( _
        1)
 End Sub
```

Excel Value Function Implementations

Several macros were developed based on Kirkwood's implementation of value functions (Kirkwood, 1997: 80-81). Kirkwoods "ValuePL" function was used as provided in his book. It is recopied and shown below for reference. Functions were developed to calculate an exponential curve, an S-Curve, and a discrete function. Additionally, functions were developed to help in sensitivity analysis, allow combining of two functions, and to perform interval scale transformations. The discrete function curve is a modified version of Kirkwood's ValuePL function. The exponential function and the S-Curve function are simple implementation of the equations for this type of function. The functions in visual basic code are shown below:

```
Function Con_Ratio(weight_change, weight_constant_ratio, w_others)
' This function is used to calculate a constant weight ratio in sensitivity
' analysis.

 Con_Ratio = (1 - weight_change) * (weight_constant_ratio / w_others)
End Function


Function ValuePL(X, Xi, Vi)
' This function takes piecewise curves and interploates between the points
' This function comes from Kirkwood
 i = 2
 Do While X > Xi(i)
  i = i + 1
 Loop
 Z = Vi(i - 1) _
    + (Vi(i) - Vi(i - 1)) * (X - Xi(i - 1)) / (Xi(i) - Xi(i - 1))
 If (Z < 0) Then
  Z = 0
 End If
 If (Z > 100) Then
   Z = 100
 End If
 ValuePL = Z
End Function

Function ValueE2(X, a, B, Rho)
'Custom function for calculating the value of an exponential function
  Z = a - B * Exp(-X / Rho)
  If Z < 0 Then
    Z = 0
  End If
```

```
  If Z > 100 Then
    Z = 100
  End If
  ValueE2 = Z
End Function

Function SCurve(X, Value_Scale, a, B, T)
'Function calculates value from an S-curve
 Z = (a / (a + Exp((-X - B) / T))) * Value_Scale
 If (Z < 0) Then
   Z = 0
 End If
 If (Z > 100) Then
   Z = 100
 End If
 SCurve = Z
End Function

Function ValueDis(X, Xi, Vi)
'Function calculates the value from a discrete function
 i = 1
 Result = "Mispelled"   ' Default Output of function if no match is made
 For Each Z In Xi
  If X = Z Then
    Result = Vi(i)    ' A match was made - determine value
    Exit For
  Else
    i = i + 1         ' No match was made, - Check the next one
  End If
 Next
 ValueDis = Result
End Function

Function Tran(X, Lower_Range, Upper_Range, Vu)
'Function transforms value over a range to be between 0 and an upper value, Vu.
'
  a = Vu / (Upper_Range - Lower_Range)
  B = -(Lower_Range * Vu) / (Upper_Range - Lower_Range)
  Tran = a * X + B

End Function

Function Two_F(Score, X1, X2, X3, Function_1, Function_2)
'Function allows use of two functions in two different ranges
'
  If Score >= X1 And Score < X2 Then
    Two_F = Function_1
  Else
    Two_F = Function_2
  End If

End Function
```

Macros for Integer and Linear Programs in Excel

Macros were developed to automatically run Solver and record the results. For more understanding of how to drive Solver using Excel Macros, or how to implement math programs with solver, see:

Help for Microsoft Excel Solver Users. Frontline Systems, Inc. On Line. Available at http://www.frontsys.com/xlhelp.htm.

The project required some automation, since it was desired to optimize a portfolio of programs for a large number of budgets. The macros are "hardwired" to run with "Portfolio.xls." It requires the decision variables (a total of seven) be located at cell locations "C16-C22" on the excel sheet. It requires the objective function to maximize change in warfighter support due to technology to be located at cell "C15" and requires the constraint "Investment Cost" be located at cell "C14." The "Available Budget" is located at "C13." The formula in "C13" was set to "D13-1." This formula propagates itself as a side benefit of the way the macro runs. The farthest right budget cell is the highest possible budget that will be allocated.

The macro runs by running solver using the variables defined. Solver provides an answer by changing the decision variables in "C16-C22." The macro then inserts part of a column, which shifts cells "C13-C22" right one column, but does not shift any other part of the column. The macro next copies "D13-D22" into the new cells "C13-C22." The macro is then complete. By restarting the macro, the user can calculate the policy for the new conditions. The macro for solving an integer program is shown below:

```
Sub Run_Integer()
'
' Run_Solver Macro
' Macro recorded 3/7/99 by Michael Winthrop
' The macro has been modified from what was recorded by removing redundant lines.

' The following resets the solver, adds constraints, sets the objective function and runs solver.
```

```
    SolverReset
    SolverOk SetCell:="$C$15", MaxMinVal:=1, ValueOf:="0", ByChange:="$C$16:$C$22"
    SolverAdd CellRef:="$C$16:$C$22", Relation:=5, FormulaText:="binary"
    SolverAdd CellRef:="$C$14", Relation:=1, FormulaText:="$C$13"
    SolverSolve (True)

' The following moves the calculated column of results over by one and prepares
' the new column for the next calculation
    Range("C13:C22").Select
    Selection.Insert Shift:=xlToRight
    Range("D13:D22").Select
    Selection.Copy
    Range("C13").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
    Range("C13").Select
End Sub
```

The macro for solving a Linear Program is shown below:

```
Sub Run_LP()
'
' Run_Solver Macro
' Macro recorded 3/7/99 by Michael Winthrop
'
' The macro has been modified from what was recorded by removing redundant lines.

' The following resets the solver, adds constraints, sets the objective function and runs solver.
    SolverReset
    SolverOk SetCell:="$C$15", MaxMinVal:=1, ValueOf:="0", ByChange:="$C$16:$C$22"
    SolverAdd CellRef:="$C$16:$C$22", Relation:=1, FormulaText:="=1"
    SolverAdd CellRef:="$C$16:$C$22", Relation:=3, FormulaText:="$E$2:$E$9"
    SolverAdd CellRef:="$C$14", Relation:=1, FormulaText:="$C$13"
    SolverAdd CellRef:="$C$16:$C$22", Relation:=3, FormulaText:="Fund_Program?"
    SolverSolve (True)

' The following moves the calculated column of results over by one and prepares
' the new column for the next calculation
    Range("C13:C22").Select
    Selection.Insert Shift:=xlToRight
    Range("D13:D22").Select
    Selection.Copy
    Range("C13").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
    Range("C13").Select
End Sub
```

It is possible to add constraints to these macros or change the constraints by changing or adding lines that say "SolverAdd." The "SolverOK" command sets locations for the objective function information. Use of the "Record Macro" feature of Excel (the ways these macros were originally developed) can have problems. A problem was not all of the constraints were added into solver using the macro, but it worked fine when added manually. The problem was solved when it was realized the "Record Macro" routine of Excel had made a syntax error. The "FormulaText:=" keyword was recorded in some constraints was recorded as:

FormulaText:="1"

instead of:

FormulaText:="=1"

This problem had to be fixed, manually for the macro to work.

Appendix D: S-Curves as a Value Measure

The S-curve method of identifying a value function uses the following equation:

Equation 11

$$V(X) = \frac{1}{1 + \exp\left(\frac{-X - B}{T}\right)}$$

where B is the bias of the curve and T is the steepness of the curve. At the middle value point of 0.5 (assume value ranges from 0 to 1), the value of $B = -X_M$ where X_M is an arbitrary measure level for the quantity under consideration. Figure 28 shows the effects of changing the bias for a sample S-curve and simple algebra proves the result:

$$0.5 = \frac{1}{1 + \exp\left(\frac{-X_M - B}{T}\right)}$$

$$0.5\left(1 + \exp\left(\frac{-X_M - B}{T}\right)\right) = 1$$

$$\exp\left(\frac{-X_M - B}{T}\right) = 1$$ and by taking the natural log of both sides and simplifying

$$B = -X_M$$

This property is interesting because it allows determination of the mid-value from a decision-maker in the same manner as elicitation for the midvalue of the exponential function. A second point could be elicited between the midvalue and either the highest or lowest value in the function using the same process. Since B is known, it would be a simple matter to solve for T. If it could be determined from the decision-maker that there was a place in a measure where value increased dramatically and further changes resulted in little improvement in value, Equation 11 would be a useful one. Figure 29 shows the effects of changing the steepness for the S-curve for a generic evaluation measure.

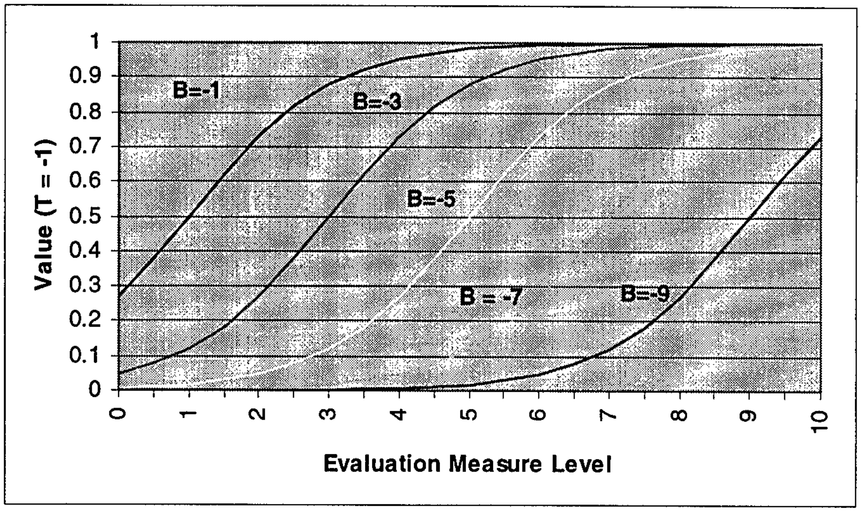


Figure 28: Examples of S-Curve Single Dimension Value Functions (Changes in Bias)

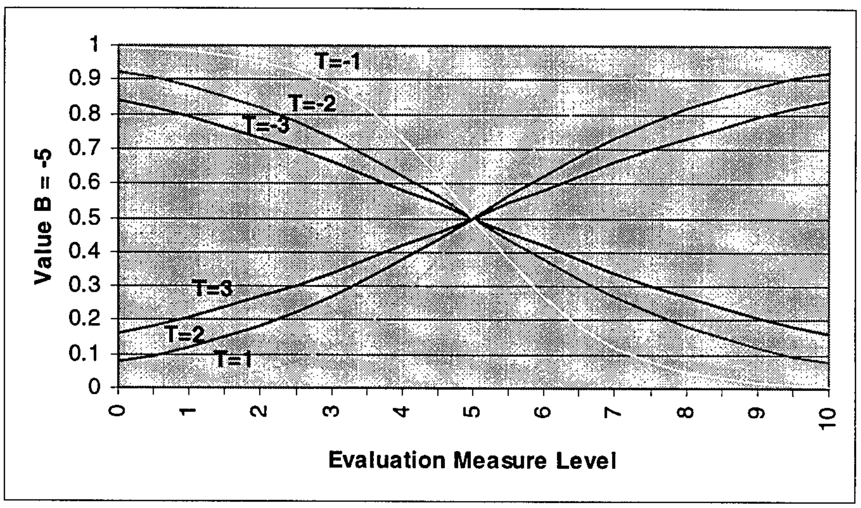


Figure 29: Examples of S-Curve Single Dimension Value Functions (Changes in Steepness)

Appendix E: Value Hierarchies and Means Networks

An essential issue in developing a value model is to separate values from the means to accomplish the value. "A means objective is of interest in the decision context because of its implications for the degree to which another (more fundamental) objective can be achieved. Simply stated, the means objectives are important because they are means to the achievement of the fundamental objectives" (Keeney, 1992: 34).

The relationship among adjacent objectives in a means objective network is causal. The lower-tier objective is a means to the higher-tier objective. The means objectives do not need to be collectively exhaustive or mutually exclusive. It is possible to have one lower-tier objective below a higher tier objective. Additionally, means objectives can have complex interrelationships (Keeney, 1992: 78).

Factual knowledge is used to construct means to achieve higher tier objectives. Value judgements are used to construct fundamental objective hierarchies (Keeney, 1992: 81). When disagreements occur, "it is easier to determine whether they are based on different facts, different judgements about facts, different values, different expressions of value judgements, or a combination of these." Separating facts and values makes it possible to bring those in who are knowledgeable about facts and those knowledgeable about values separately. Hence, experts in facts are not required to make value judgements and experts in values are not required to make fact judgements (Keeney, 1992: 93-94).

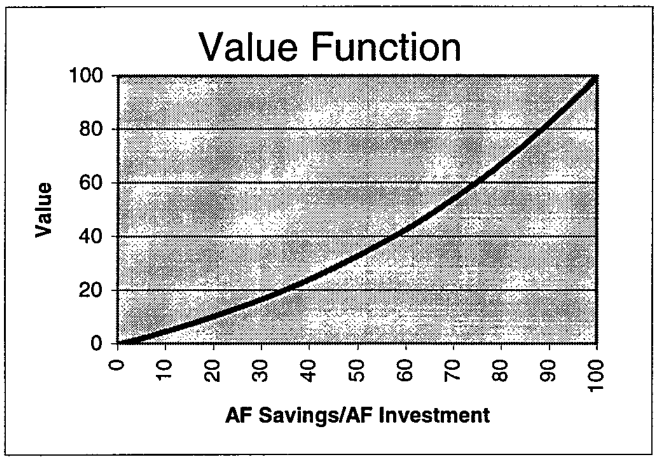
The fundamental objectives and the means objectives combined allow a decision-maker to find the best decisions. According to Clemen, the means networks can be used in three ways. First, it assures the decision-maker that fundamental objectives are in the decision model, not means objectives. Second, an easily measured means objective can sometimes be substituted for a fundamental objective that is more difficult to measure. Finally, a means-objective network can be used to generate creative new alternatives (Clemen, 1996, 45).

In the thesis, a means network was not specifically developed. Keeney and Clemen both document the need to separate values and means, which was considered during development of the Air Vehicles' value model. For example, during meetings with Air Vehicles, a few of the evaluation measures identified were "not at the same level" as the others. Evaluation measures originally being considered under "Reach" under "Gain" were "Availability," "Missions Enabled," "Regeneration," "Response Time," "Lift to Drag Ratio," and "Weight Reduction." Air Vehicles did not believe "Lift to Drag Ratio and "Weight Reduction" should be in the hierarchy, but something that measured changes in payload and range, but did not trade off, was needed.

The reason "Lift to Drag Ratio" and "Weight Reduction" did not fit under Reach was that the parameters are technical measurements, while all of the other parameters in the hierarchy are performance measurements. Further, if the "Why is this important" question is asked about the parameters, the answer is "because they are the means to improving payload and range of an air vehicle." While Clemen states a means objectives can be used as a proxy measure for a value, Alexander and Mitchel state these measures are extremely poor for measuring performance. Based on the resistance from Air Vehicles in using this measure combined with the evidence of the literature, the measures were redefined into a single "Payload/Range" constructed measure.

Appendix F: Air Vehicles' Evaluation Measures

Discussions of how the evaluation measures were determined are summarized in Appendix B: Documentation of Meetings with VA. Discussion summaries of evaluation measures under Reach can be found on pages 158, 159, 162, 164, 170, and 172. Discussion summaries of evaluation measures under Awareness, Power and Technological Superiority begin on pages 159 and 166.



Evaluation Measure: AF Savings Ratio

Range Units: Ratio of expected savings to investment cost

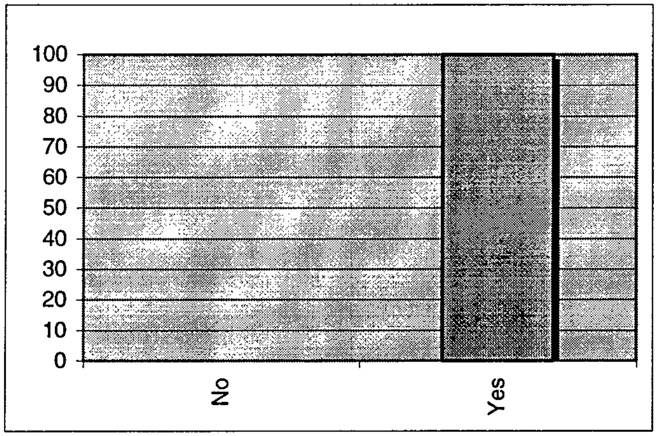
Definition:VA's "Savings Multiple for Cost" measure in widespread use. Defined as the ratio of cost savings potential to the U.S. Air Force to Air Vehicles' investment cost.

Comments: The purpose of Air Vehicles' investment cost is to normalize the savings for the Air Force. For values less than 1, this measure has 0 value.

V(X) = A-B*exp(-X/R)

A	B	R	X	Value	Value Function Range	
-32.31365601	-31.8567943	-70.228	1.00	0.0	Lower	0
Find R			66.67	50.0	Set Value	50
			100.00	100.0	Upper	100

Figure 30: Technological Superiority/Air Force Savings Ratio

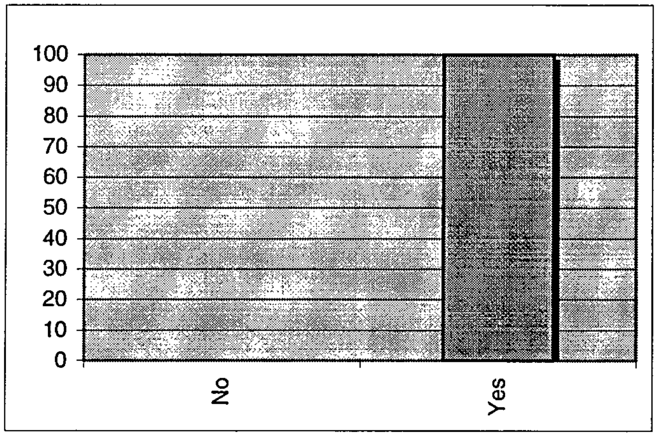


ReScale

Range Units: Categories as defined
Definition:An alternative with identified military and commercial application.
Comments:

Evaluation Measure:			Be Efficient: Dual Use
Abreviation	Category	Value	Category Definition
X1	No	0	Not Dual Use.
X2	Yes	100	Dual Use Program.

Figure 31: Technological Superiority/Be Efficient/Dual Use

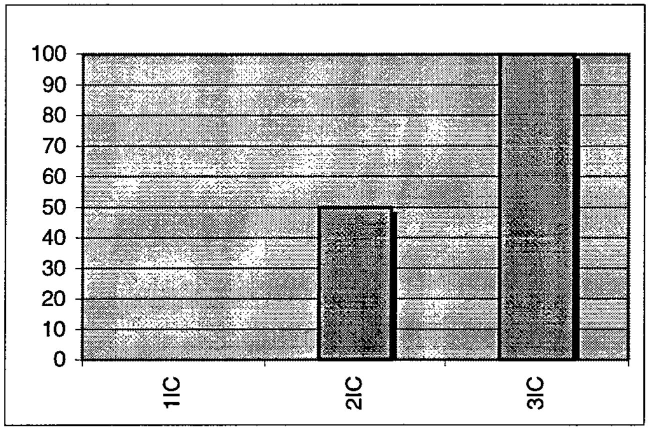


ReScale

Range Units: Categories as defined
Definition:Whether or not there are intermediate product(s) at 12 month intervals.
Comments:

Evaluation Measure:			Be Efficient: Intermediate Projects
Abreviation	Category	Value	Category Definition
X1	No	0	No Intermediate Projects at 12 month intervals.
X2	Yes	100	Intermediate Projects at 12 month intervals.

Figure 32: Technological Superiority/Be Efficient/Intermediate Projects

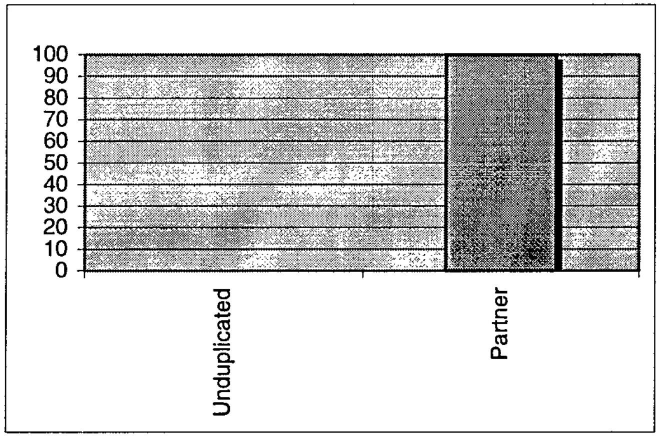


ReScale

Range Units: Categories as defined
Definition: Number of integrated concepts supported by the proposed program.
Comments:

Evaluation Measure:			Be Efficient: Multiuse
Abreviation	Category	Value	Category Definition
X1	1IC	0	Supports one of Air Vehicle's Integrated Concepts.
X2	2IC	50	Supports two of Air Vehicle's Integrated Concept.
X3	3IC	100	Supports three Air Vehicle's Integrated Concepts.

Figure 33: Technological Superiority/Be efficient/Multiuse

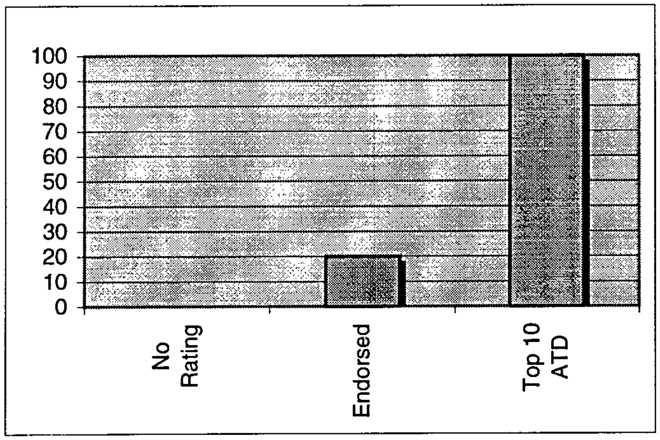


ReScale

Range Units: Categories as defined
Definition: Levels documenting who else is working to develop the technology.
Comments:

Evaluation Measure:			Be Efficient: Uniqueness
Abreviation	Category	Value	Category Definition
X1	Unduplicated	0	Military technology being developed at AFRL only.
X2	Partner	100	Military technology being developed in concert with other Government agencies or with Industry. The other agency must be funding some portion of the program to qualify for this level.

Figure 34: Technological Superiority/Be Efficient/Uniqueness

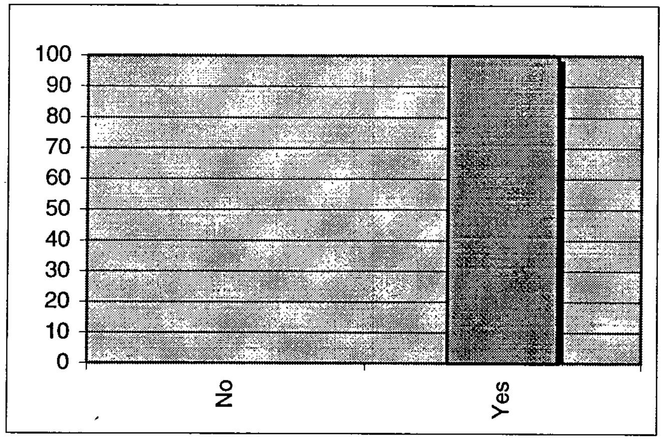


ReScale

Range Units: Categories as defined
Definition: The rating of the program given by the appropriate agency.
Comments: A program in the Top 10 ATD's has tremendous importance. Endorsement by a SPO or MAJCOM is good, but far less useful.

Evaluation Measure:			Be Efficient: User Rating
Abreviation	Category	Value	Category Definition
X1	No Rating	0	Not rated.
X2	Endorsed	20	Written endorsement by MAJCOM or SPO.
X3	Top 10 ATD	100	In the MAJCOM's top 10 Advanced Technology Development List

Figure 35: Technological Superiority/Be Efficient/User Rating

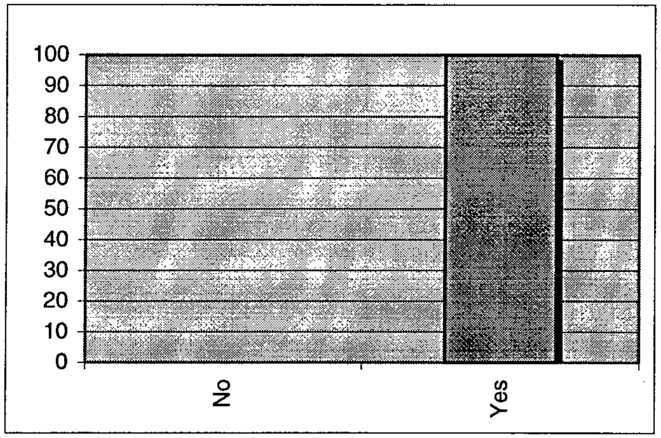


ReScale

Range Units: Categories as defined
Definition: A scientific advance that could potentially change VA's entire paradigm and learning curve.
Comments:

Evaluation Measure:			Expand our Frontier: Revolutionary
Abreviation	Category	Value	Category Definition
X1	No	0	No potential for revolutionary change.
X2	Yes	100	Potential for revolutionary change.

Figure 36: Technological Superiority/Expand Our Frontier/Revolutionary

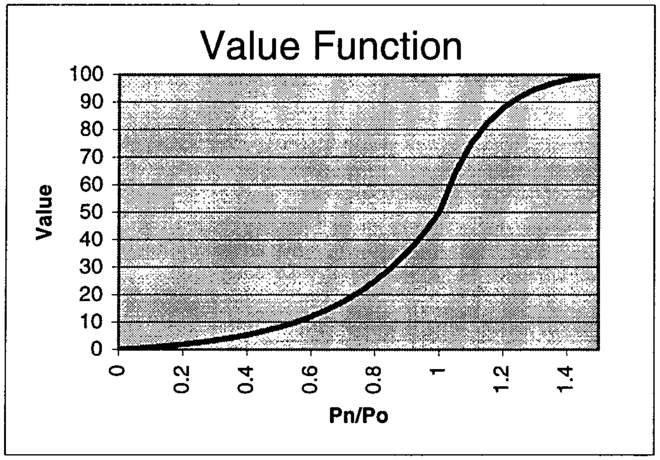


ReScale

Range Units: Categories as defined
Definition: Possiblity the technology will result in a new warfighting spectrum for further development. Past Examples: Electronic Warfare, Information Operations, All Weather Technology
Comments:

Evaluation Measure:			Expand our Frontier: New Warfighting Spectrum
Abreviation	Category	Value	Category Definition
X1	No	0	No possiblity of new warfighting spectrum.
X2	Yes	100	Possiblity of new warfighting spectrum.

Figure 37: Technological Superiority/Expand our Frontier/New Warfighting Spectrum



Evaluation Measure: Gain Availability

Range Units: Unitless

Definition: Pn/Po where:

Pn is the probability the weapon system is availabile with the proposed new technology

Po is the probability the weapon system is available without the proposed technology.

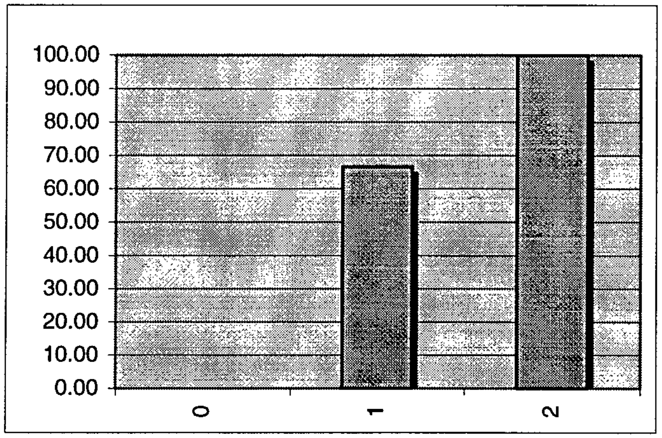
Availability is the probability the weapon system can complete its normal combat mission on demand. A weapon system is not available when mission critical equipment fails.

Comments: This measure combines both the time between failures or the reliability of the system with the time to repair the system.

V(X) = A-B*exp(-X/R)

A	B	R	X	Value	Value Function Range	
-1.952378196	-1.9523782	-0.3048	0.00	0.0	Lower	0
Find R			0.80	25.0	Set Value	25
			1.00	50.0	Upper	50

Figure 38: Reach/Gain/Availability



ReScale

Evaluation Measure: Gain Missions Enabled

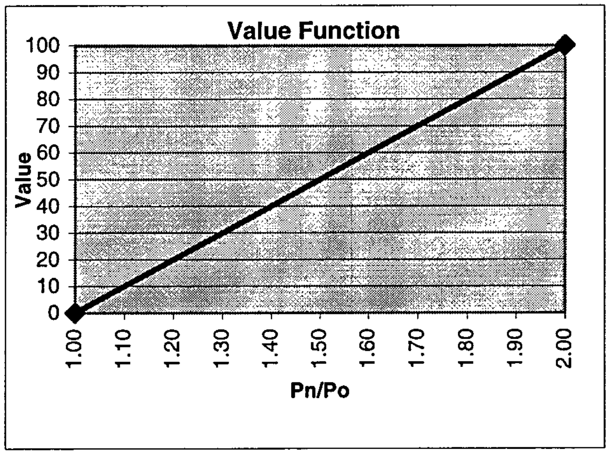
Range Units: Missions Enabled

Definition:Defined as the number of new or additional missions enabled by the technology for the system.

Comments:

Evaluation Measure:			Cost to Adversary
Abreviation	Category	Value	Category Definition
X1	0	0.00	Change in the number of missions.
X2	1	66.67	Change in the number of missions.
X3	2	100.00	Change in the number of missions.

Figure 39: Reach/Gain/Missions Enabled



Evaluation Measure: Gain Payload-Range

Range Units: Unitless

Definition: The maximum of either the weight of mission equipment and/or people the platform can carry or the distance a platform can travel without refueling.

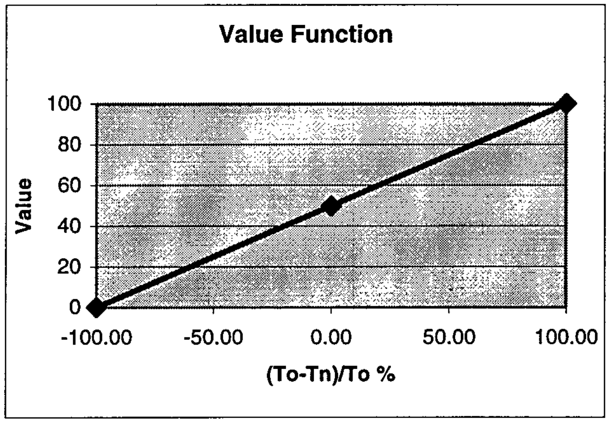
Po is the payload/range of the system without the technology.

Pn is the payload/range of the system with the technology

Comments:

X	Y	Slope	Intercept
1.00	0		
2.00	100	100.00	-100.00

Figure 40: Reach/Gain/Payload-Range



X	Y	Slope	Intercept
-100	0		
0	50	1	50
100	100	1	50

Evaluation Measure: Gain Regeneration

Range Units: Percent change in time

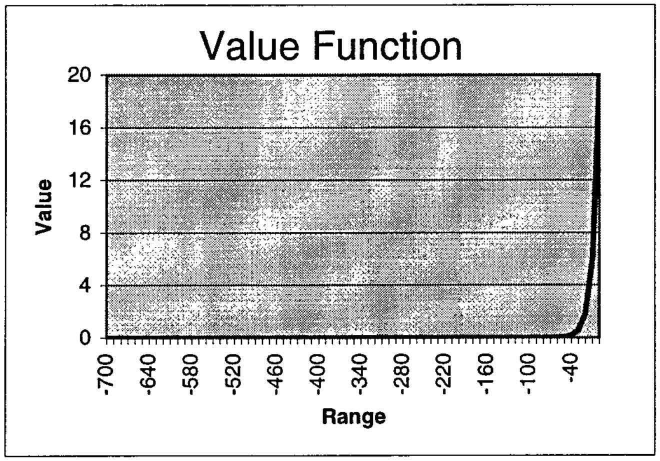
Definition: (To-Tn)/To where:

Tn is the turn around time for the system in normal combat operations with the technology.

To is the turn around time for the system in normal combat operations with out the technology.

Comments: Scoring this attribute requires consideration of combat damage and replenishment of consumables. Repair of combat damage includes assessment, design of repair, repair execution and accreditation. Replenishment of consumables includes rearming, refueling, and downloading mission specific information. The evaluation measure is mutually exclusive with Availability because it does not include reliability or the time to repair normal failures of equipment.

Figure 41: Reach/Gain/Regeneration



Evaluation Measure:

Range Units:

Definition: See Gain Response Time. This is one portion of the curve.

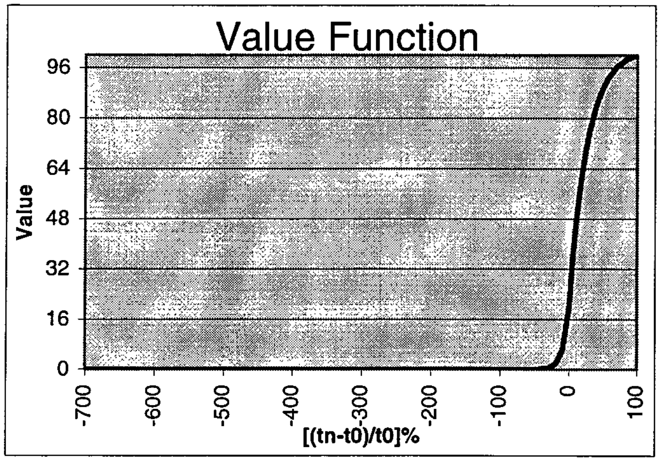
Comments:

V(X) = A-B*exp(-X/R)

A	B	R	X	Value	Value Function Range	
-7.45058E-36	-20	-8.3452	-700.00	0.0	Lower	0
Find R			-50.00	0.1	Set Value	0.05
			0.00	20.0	Upper	20

Measure Roster

Figure 42: Reach/Gain/Response Time (Portion of Function in Figure 43)



V(X) = A-B*exp(-X/R)

A	B	R	X	Value	Value Function Range	
101.7160053	81.71600528	25.8849	0.00	20	Lower	20
Find R			80.00	98	Set Value	98
			100.00	100	Upper	100

Evaluation Measure: Gain Response Time

Range Units: Percent Decrease [(tn-t0)/t0]%

Definition: Response time is the average number of hours required to arrive at any location world wide from call up.

tn is the response time for the system with the new technology

t0 is the response time for the system without the technology

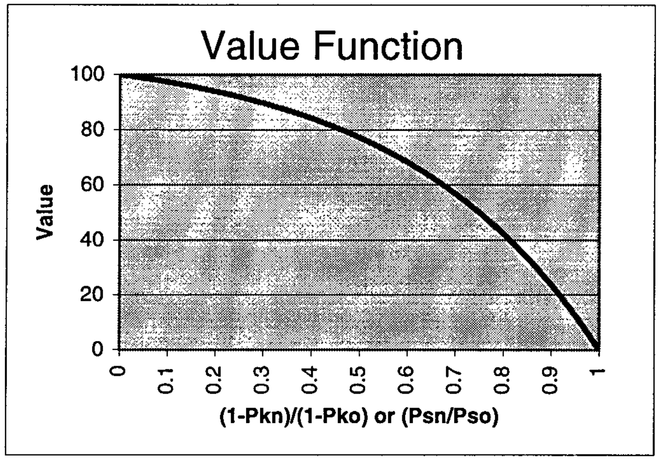
Comments: Response time is expected to range from 3-24 hours.

Assumptions:

- Weapon system is sitting on alert.
- Travel distance of 12,000 miles.
- Measure is for an individual weapon system.

Measure Roster

Figure 43: Reach/Gain/Response Time (Combined Function with Figure 42)



Evaluation Measure: Lethality Effectiveness

Range Units:

Definition: The probability of not rendering a target ineffective or the probability the target survives.

(1-Pkn)/(1-Pko)

Pko is the probability before use of the tech.

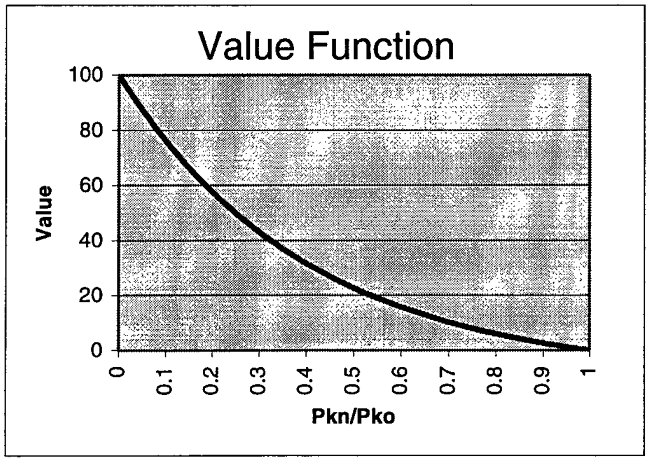
Pkn is the probability after use of the tech.

Comments: Examples of ways VA can affect effectiveness is agility, high angle of attack, maneuverability, and pointing accuracy. Assumes that "bullet" has left the platform.

$V(X) = A-B*\exp(-X/R)$

A	B	R	X	Value	Value Function Range	
109.5743942	9.574394183	-0.4103	1.00	0	Lower	0
Find R			0.75	50	Set Value	50
			0.00	100	Upper	100

Figure 44: Power/Lethality/Gain/Effectiveness



Evaluation Measure: Lethality Survival

Range Units: Unitless

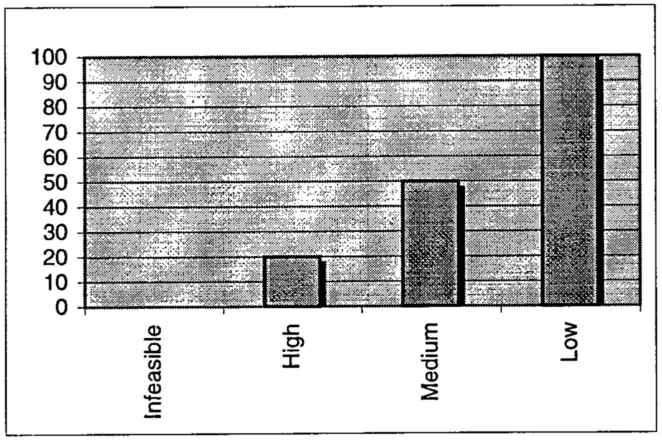
Definition: Technology that provides the "capability of an aircraft to avoid and/or withstand a man-made hostile environment" (Ball, 1985: 1). Survivability is made up of susceptibility (PH) and vulnerability (PKIH). The probability of survival is defined as : PS = 1 - PK = 1 - PHPKIH (Ball, 1985: 2) PS0 is the probability before using the technology. PSN is the probability after using the technology. Metric is Pkn/Pko. This metric measures the reverse by measuring the change in the probability of dying.

Comments: Does not include the survivability of a bullet.

V(X) = A-B*exp(-X/R)

A	B	R	X	Value	Value Function Range	
-9.574394183	-109.574394	0.41025	1.00	0	Lower	0
Find R			0.25	50	Set Value	50
			0.00	100	Upper	100

Figure 45: Power/Lethality/Gain/Survival

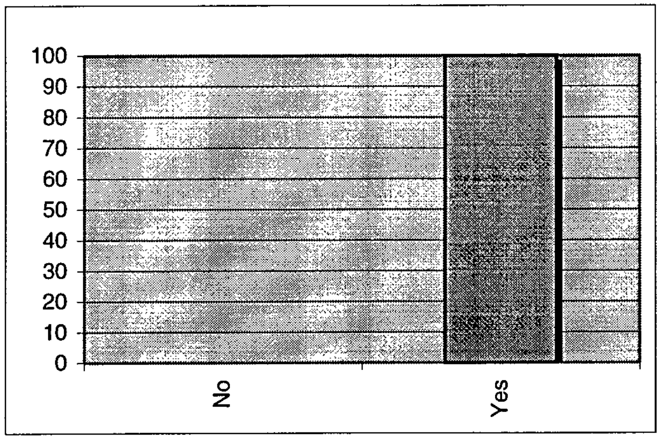


ReScale

Range Units: Categories as defined
Definition: The likelihood of not completing the proposed program within the proposed time for the proposed cost.
Comments: Technological risk is quantified in the 6.1, 6.2 and 6.3 breakdown assigned to a program.

Evaluation Measure:			Programatic Risk
Abreviation	Category	Value	Category Definition
X1	Infeasible	0	The program cannot be completed in the proposed time and cost.
X2	High	20	There is little confidece of completing the proposed program in the proposed time and cost.
X3	Medium	50	There is equally likely to complete or fail to complete the proposed program in the proposed time and cost.
X4	Low	100	There is high confidence of completing the proposed program in the proposed time and cost.

Figure 46: Technological Superiority/Programmatic Risk

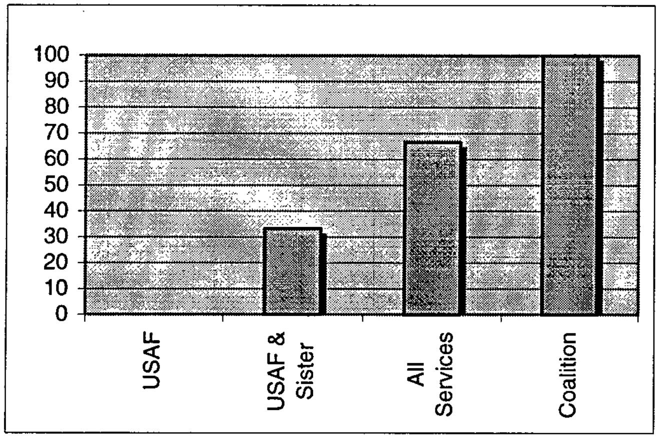


ReScale

Range Units: Categories as defined
Definition: A technology that allows a desired operation formerly too difficult to perform.
Comments:

Evaluation Measure:			Simplify Operations: Enables
Abreviation	Category	Value	Category Definition
X1	No	0	Does not Simplify Operations.
X2	Yes	100	Simplifies Operations.

Figure 47: Technological Superiority/Simplify Operations/Enables

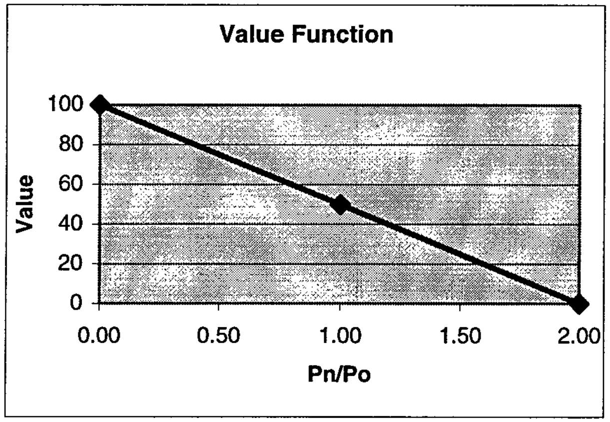


ReScale

Range Units: Categories as defined
Definition: A technology that develops interfaces between one or more systems making cooperative actions easier.
Comments:

Evaluation Measure:			Simplify Operaitons: Interoperability
Abreviation	Category	Value	Category Definition
X1	USAF	0	Interoperability between U.S. Air Force Systems with this technology.
X2	USAF & Sister	33	Interoperability between U.S. Air Force Systems, a sister U.S. armed service with this technology.
X3	All Services	67	Interoperability between all U.S. armed Services with this technology.
X4	Coalition	100	Interoperability between all U.S. armed Services and potential coalition forces with this technology.

Figure 48: Technological Superiority/Simplify Operations/Interoperability



X	Y	Slope	Intercept
0.00	100		
1.00	50	-50	100
2.00	0	-50	100

Evaluation Measure: Ratio of People

Range Units: Unitless

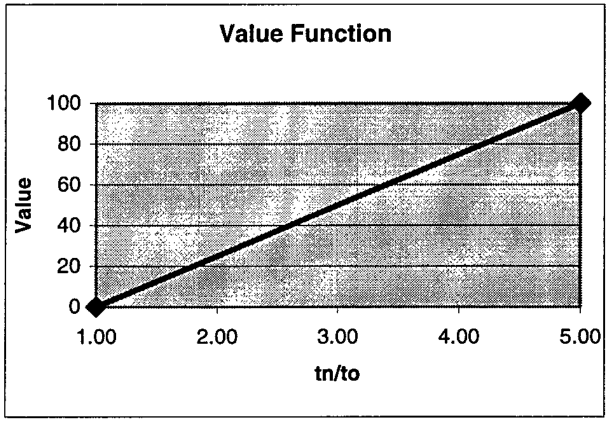
Definition: Pn/Po: A technology that automates an operation and decreases the number of people needed to perform the same operation.

Po is the total number of people for the old system

Pn is the total number of people for the new system.

Comments:

Figure 49: Technological Superiority/Simplify Operations/Ratio of People



X	Y	Slope	Intercept
1	0		
5	100	25	-25

Evaluation Measure: Achieve/Extend Life

Range Units: Unitless

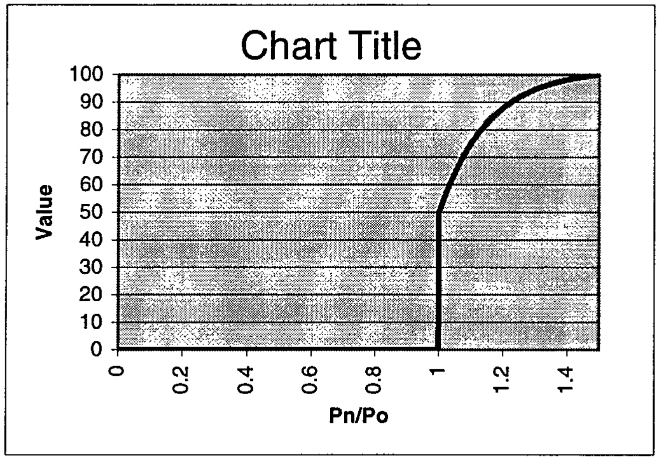
Definition: tn/to where:

tN is the expected failure time for the system with the technology.

t0 is the expected failure time for the system without the technology.

Comments:

Figure 50: Reach/Sustain/Achieve/Extend Life



Evaluation Measure: Sustain Availability

Range Units: Unitless

Definition: Pn/Po where:

Pn is the probability the weapon system is availabile with the proposed new technology

Po is the probability the weapon system is available without the proposed technology.

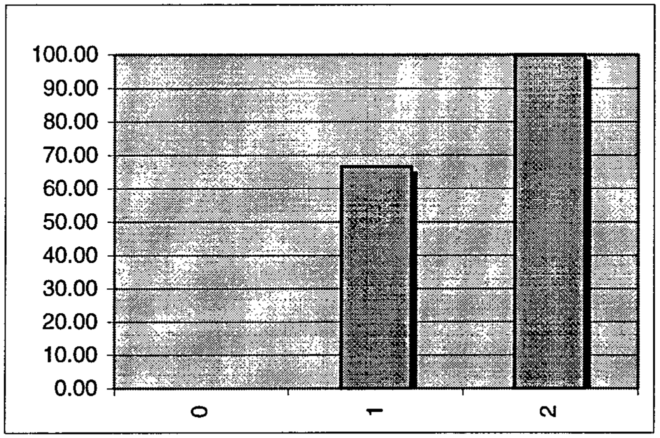
Availability is the probability the weapon system can complete its normal combat mission on demand. A weapon system is not available when mission critical equipment fails.

Comments: This measure combines both the time between failures or the reliability of the system with the time to repair the system. The availability of a weapon system will never be intentionally decreased.

V(X) = A-B*exp(-X/R)

A	B	R	X	Value	Value Function Range	
101.9524131	36785.25421	0.15238	1.00	50.0	Lower	50
Find R			1.10	75.0	Set Value	75
			1.50	100.0	Upper	100

Figure 51: Reach/Sustain/Availability



ReScale

Evaluation Measure: Sustain Missions Enabled

Range Units: Missions Enabled

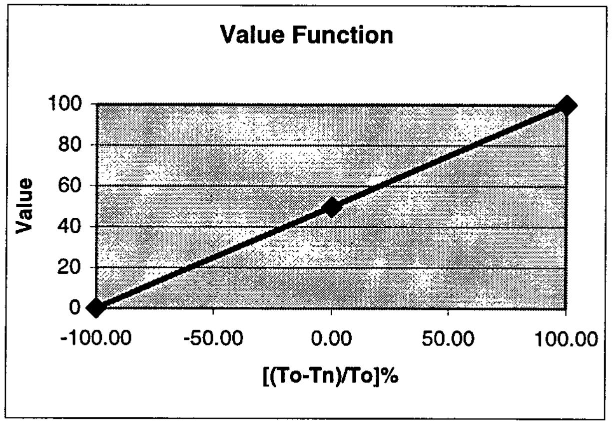
Definition:Defined as the number of new or additional missions enabled by the technology for the system.

Comments:

Evaluation Measure: Cost to Adversary

Abreviation	Category	Value	Category Definition
X1	0	0.00	Change in the number of missions.
X2	1	66.67	Change in the number of missions.
X3	2	100.00	Change in the number of missions.

Figure 52: Reach/Sustain/Missions Enabled



X	Y	Slope	Intercept
-100	0		
0	50	1	50
100	100	1	50

Evaluation Measure: Sustain Regeneration

Range Units: Percent change in time

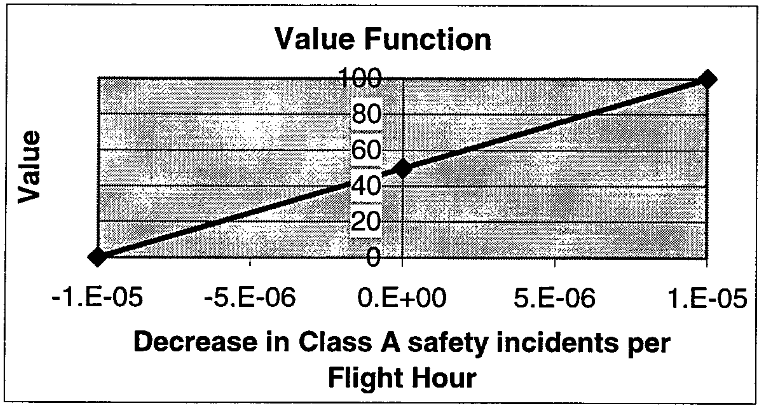
Definition: (To-Tn)/To where:

Tn is the turn around time for the weapon system in normal combat operations using the technology.

To is the turn around time for the weapon system in normal combat operations with out the technology.

Comments: Scoring this attribute requires consideration of combat damage and replenishment of consumables. Repair of combat damage includes assessment, design of repair, repair execution and accreditation. Replenishment of consumables includes rearming, refueling, and downloading mission specific information. The evaluation measure is mutually exclusive with Availability because it does not include reliability or the time to repair normal failures of equipment.

Figure 53: Reach/Sustain/Regeneration



X	Y	Slope	Intercept
-1.00E-05	0		
0.00E+00	50	5000000	50
1.00E-05	100	5000000	50

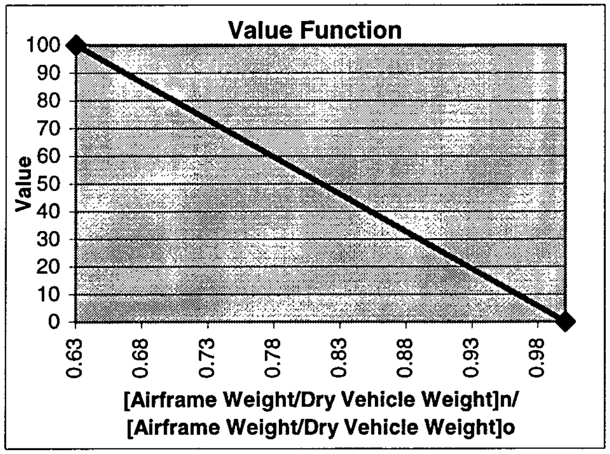
Evaluation Measure: Sustain Safety

Range Units: The decrease in the number of Class A safety incidents.

Definition: Safety is to be defined as the change in the number of class A incidents that take place or delta Ro. The number of incidents is typically measured per flight hour.

Comments: A decrease in Class A incidents less than 0 increases the number of incidents and is a "do nothing" alternative, everything else being equal. The evaluation measure is esentially transformed to prevent increases in safety incidents from scoring negative value. The Ro of 1E-05 used here is a rough order of magnitude number based on the F-16.

Figure 54: Reach/Sustain/Safety



Evaluation Measure: Sustain Weight Reduction

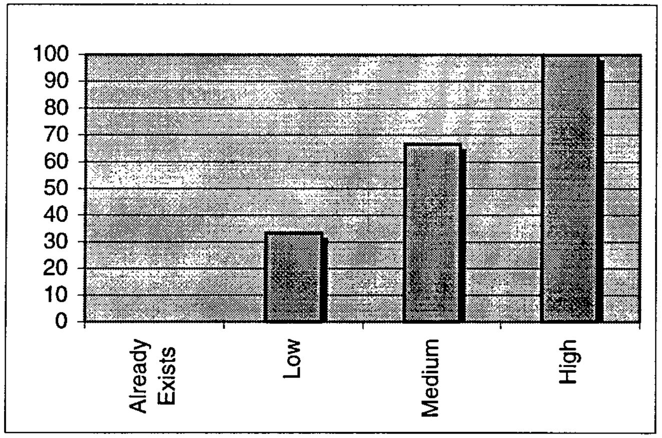
Range Units: Unitless

Definition: [Airframe Weight/Dry Vehicle Weight]n/ [Airframe Weight/Dry Vehicle Weight]o

Comments: The mission must be defined to establish the baseline.

X	Y	Slope	Intercept
0.63	100		
1.00	0	-269.23	269.23

Figure 55: Reach/Sustain/Weight Reduction



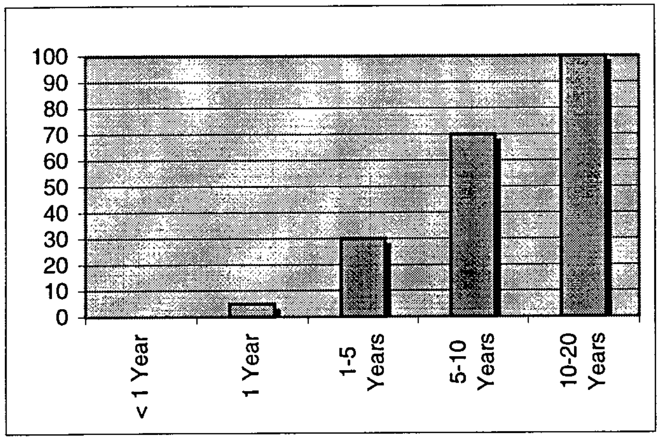
ReScale

Range Units: Categories as defined
Definition: Cost for our closest technical adversary to counter or duplicate the technology.
Comments:

Evaluation Measure: Win: Cost to Adversary

Abreviation	Category	Value	Category Definition
X1	Already Exists	0	The technology already exists.
X2	Low	33	Minimal or no investment cost for our closest adversary to counter.
X3	Medium	67	Significant cost but feasible for our adversary to overcome.
X4	High	100	Countering the technology cost our adversary too much and requires desperate measures to overcome.

Figure 56: Technological Superiority/Win/Cost to Adversary



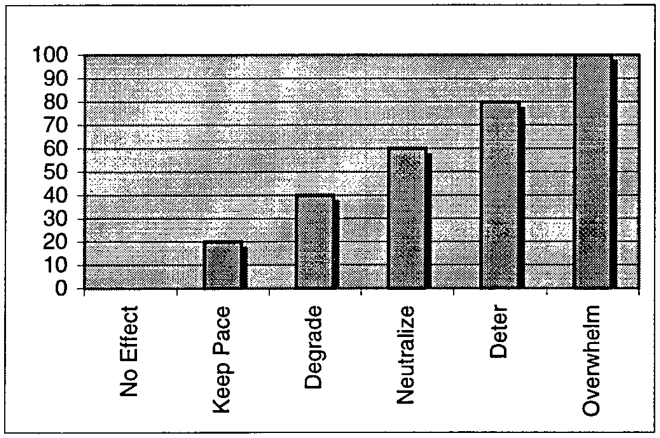
ReScale

Range Units: Categories as defined
Definition:The amount of time our closest adversary needs to duplicate or counteract the technology.
Comments:

Evaluation Measure: Win Lead

Abreviation	Category	Value	Category Definition
X1	< 1 Year	0	Technology that would requires our adversary to spend the indicated time to counter or duplicate.
X2	1 Year	5	Technology that would requires our adversary to spend the indicated time to counter or duplicate.
X3	1-5 Years	30	Technology that would requires our adversary to spend the indicated time to counter or duplicate.
X4	5-10 Years	70	Technology that would requires our adversary to spend the indicated time to counter or duplicate.
X5	10-20 Years	100	Technology that would requires our adversary to spend the indicated time to counter or duplicate.

Figure 57: Technological Superiority/Win/Lead



ReScale

Range Units: Categories as defined
Definition: Capability level generated by the technology's potential effect on our closest adversary in conventional warfare.
Comments: Category is defined based on the system the technology will be used in.

Evaluation Measure:			Win Warfare Advantage
Abreviation	Category	Value	Category Definition
X1	No Effect	0	Technology that is ineffective against an adversary.
X2	Keep Pace	20	Technology that is needed to stay at the same level as an adversary.
X3	Degrade	40	Technology that results in a tactical advantage for our forces against an adversary.
X4	Neutralize	60	Technology that renders some or all of an adversaries military capability ineffective in battle.
X5	Deter	80	Technology that discourages an adversary from acting because of doubt, fear or cost.
X6	Overwhelm	100	Technology that eliminates armed conflict as an option for our closest adversary.

Figure 58: Technological Superiority/Win/Warfare Advantage

Appendix G: Air Vehicles' Weight Calculations

Weights for Reach/Gain evaluation measures.

Space ranks Reach/Gain in the following order: 1) Missions Enabled, 2) Regeneration, 3) Response Time, 4) Availability. UAV ranks Reach/Gain in following order: 1) Availability, 2) Response Time, 3) Missions Enabled, 4) Regeneration. Sustainment ranks same as UAV except switches Regeneration with Missions Enabled. Payload-Range was added later and was not ranked.

$$\begin{bmatrix} w_{RG\_Avail} \\ w_{RG\_Resp\_Time} \\ w_{RG\_mis\_enabled} \\ w_{RG\_Regen} \\ w_{RG\_Pay\_Rng} \end{bmatrix} := \begin{bmatrix} .2 \\ .2 \\ .2 \\ .2 \\ .2 \end{bmatrix}$$

Weights for Reach/Sustainment evaluation measures.

$$\begin{bmatrix} w_{RS\_Safety} \\ w_{RS\_Ach\_Ext} \\ w_{RS\_Avail} \\ w_{RS\_Regen} \\ w_{RS\_wt\_red} \\ w_{RS\_mis\_enabled} \end{bmatrix} := \begin{bmatrix} .1 \\ .1 \\ .1 \\ .1 \\ .1 \\ .1 \end{bmatrix}$$

Given

$$w_{RS\_Safety} = 1.7 \cdot w_{RS\_mis\_enabled}$$

$$w_{RS\_Regen} = 1.5 \cdot w_{RS\_mis\_enabled}$$

$$w_{RS\_Avail} = 1.5 \cdot w_{RS\_mis\_enabled}$$

$$w_{RS\_Ach\_Ext} = 1.5 \cdot w_{RS\_mis\_enabled}$$

$$w_{RS\_wt\_red} = 1.2 \cdot w_{RS\_mis\_enabled}$$

$w_{RS\_Safety} + w_{RS\_Regen} + w_{RS\_Avail} + w_{RS\_Ach\_Ext} + w_{RS\_wt\_red} + w_{RS\_mis\_enabled} = 1$

$$\begin{bmatrix} w_{RS\_Safety} \\ w_{RS\_Ach\_Ext} \\ w_{RS\_Avail} \\ w_{RS\_Regen} \\ w_{RS\_wt\_red} \\ w_{RS\_mis\_enabled} \end{bmatrix} := \mathrm{Find}\left(w_{RS\_Safety}, w_{RS\_Ach\_Ext}, w_{RS\_Avail}, w_{RS\_Regen}, w_{RS\_wt\_red}, w_{RS\_mis\_enabled}\right)$$

$w_{RS\_Safety} = 0.202380952380952$

$w_{RS\_wt\_red} = 0.142857142857143$

$w_{RS\_Ach\_Ext} = 0.178571428571429$

$w_{RS\_mis\_enabled} = 0.119047619047619$

$w_{RS\_Regen} = 0.178571428571429$

$w_{RS\_Avail} = 0.178571428571429$

Weights for Awareness/Gain evaluation measures.

$$\begin{bmatrix} w_{RG\_Avail} \\ w_{RG\_mis\_enabled} \\ w_{RG\_Regen} \end{bmatrix} := \begin{bmatrix} \frac{1}{3} \\ \frac{1}{3} \\ \frac{1}{3} \end{bmatrix}$$

See Reach/Gain for information.

Weights for Power/Lethality

$w_{PL\_eff} := .5$

$w_{PL\_survival} := .5$

Given

$w_{PL\_eff} = 1.3 \cdot w_{PL\_survival}$

$w_{PL\_eff} + w_{PL\_survival} = 1$

$$\begin{bmatrix} w_{PL\_eff} \\ w_{PL\_survival} \end{bmatrix} := \text{Find}\left(w_{PL\_eff}, w_{PL\_survival}\right)$$

$w_{PL\_eff} = 0.565217391304348$

$w_{PL\_survival} = 0.434782608695652$

Weights for Tech. Sup. Be Efficient

$$\begin{bmatrix} w_{TBE\_User} \\ w_{TBE\_Multi} \\ w_{TBE\_Uniq} \\ w_{TBE\_Int\_Prod} \\ w_{TBE\_Dual\_Use} \end{bmatrix} := \begin{bmatrix} .1 \\ .1 \\ .1 \\ .1 \\ .1 \end{bmatrix}$$

Given

$w_{TBE\_Int\_Prod} = 1.4 \cdot w_{TBE\_Dual\_Use}$

$w_{TBE\_Uniq} = 1.8 \cdot w_{TBE\_Dual\_Use}$

$w_{TBE\_Multi} = 1.5 \cdot w_{TBE\_Dual\_Use}$

$w_{TBE\_User} = 2 \cdot w_{TBE\_Dual\_Use}$

$w_{TBE\_User} + w_{TBE\_Multi} + w_{TBE\_Uniq} + w_{TBE\_Int\_Prod} + w_{TBE\_Dual\_Use} = 1$

$$\begin{bmatrix} w_{TBE\_User} \\ w_{TBE\_Multi} \\ w_{TBE\_Uniq} \\ w_{TBE\_Int\_Prod} \\ w_{TBE\_Dual\_Use} \end{bmatrix} := \text{Find}\left(w_{TBE\_User}, w_{TBE\_Multi}, w_{TBE\_Uniq}, w_{TBE\_Int\_Prod}, w_{TBE\_Dual\_Use}\right)$$

$w_{TBE\_User} = 0.25974025974026$

$w_{TBE\_Int\_Prod} = 0.181818181818182$

$w_{TBE\_Multi} = 0.194805194805195$

$w_{TBE\_Dual\_Use} = 0.12987012987013$

$w_{TBE\_Uniq} = 0.233766233766234$

Tech. Superiority Expand our Frontier Weights

$$\begin{bmatrix} w_{TEF\_Rev} \\ w_{TEF\_NWS} \end{bmatrix} := \begin{bmatrix} .5 \\ .5 \end{bmatrix}$$

Tech. Superiority/Simplify Operations

$$\begin{bmatrix} w_{TSO\_Enables} \\ w_{TSO\_ROP} \\ w_{TSO\_Int} \end{bmatrix} := \begin{bmatrix} \frac{1}{3} \\ \frac{1}{3} \\ \frac{1}{3} \end{bmatrix}$$

Tech. Superiority/Win

$w_{TSW\_War} := .1$

$w_{TSW\_Lead} := .1$

$w_{TSW\_CA} := .1$

Given

$w_{TSW\_Lead} = 1.2 \cdot w_{TSW\_CA}$

$w_{TSW\_War} = 1.5 \cdot w_{TSW\_CA}$

$w_{TSW\_Lead} + w_{TSW\_CA} + w_{TSW\_War} = 1$

$$\begin{bmatrix} w_{TSW\_War} \\ w_{TSW\_Lead} \\ w_{TSW\_CA} \end{bmatrix} := \mathrm{Find}\left(w_{TSW\_War}, w_{TSW\_Lead}, w_{TSW\_CA}\right)$$

$w_{TSW\_War} = 0.405405405405405$

$w_{TSW\_Lead} = 0.324324324324324$

$w_{TSW\_CA} = 0.27027027027027$

Reach/Sustain/Achieve/Extend Life is twice as important as Reach/Gain/Availability.

Sustainment will be most important until 2002 when gain will increase in importance.

Purpose: Relate Reach/Gain to Reach/Sustain

$w_{RS\_Ach\_Ext} \cdot w_{R\_Su} \cdot w_{Reach} = 2 \cdot \left(w_{RG\_Avail} \cdot w_{R\_Ga} \cdot w_{Reach}\right)$

Reduces to:

$w_{RS\_Ach\_Ext} \cdot w_{R\_Su} = 2 \cdot \left(w_{RG\_Avail} \cdot w_{R\_Ga}\right)$

$w_{R\_Su} := .5$

$w_{R\_Ga} := .5$

Given

$w_{RS\_Ach\_Ext} \cdot w_{R\_Su} = 2 \cdot \left(w_{RG\_Avail} \cdot w_{R\_Ga}\right)$

$w_{R\_Su} + w_{R\_Ga} = 1$

$$\begin{bmatrix} w_{R\_Su} \\ w_{R\_Ga} \end{bmatrix} := \text{Find}\left(w_{R\_Su}, w_{R\_Ga}\right)$$

$w_{R\_Su} = 0.788732394366197$

$w_{R\_Ga} = 0.211267605633803$

Purpose: Relate Tech. Sup./Be Eff. to Tech. Sup./Exp. our Fron.

User Rating is as important as New Warfighting Spectrum

$w_{TS} \cdot w_{T\_Be} \cdot w_{TBE\_User} = w_{TS} \cdot w_{T\_Ex} \cdot w_{TEF\_NWS}$

Reduces to:

$w_{T\_Be} \cdot w_{TBE\_User} = w_{T\_Ex} \cdot w_{TEF\_NWS}$

Purpose: Relate Tech. Sup./Be Eff. to Tech. Sup./Simplify Operations

User Rating is twice as important as Enables

$$w_{T\_Be} \cdot w_{TBE\_User} = 2 \cdot \left(w_{T\_SO} \cdot w_{TSO\_Enables} \right)$$

Purpose: Relate Tech. Sup./Exp. our Fron. to Tech. Sup./Win

Warfare Advantage is as important as New Warfighting Spectrum.

$$w_{T\_Ex} \cdot w_{TEF\_NWS} = w_{T\_Wi} \cdot w_{TSW\_War}$$

Purpose: Relate Tech. Sup./Exp. our Fron. to Tech. Sup./Win

Warfare Advantage is three times more important then AF savings Ratio.

$$w_{T\_Wi} \cdot w_{TSW\_War} = 3 \cdot \left(w_{T\_AF} \cdot w_{TA\_AF} \right)$$

$$w_{TA\_AF} = 1$$

Purpose: Relate AF Savings Ratio to Programatic Risk

AF Savings Ratio is 5 times as important as Programatic Risk

$$w_{T\_AF} \cdot w_{TA\_AF} = 5 \cdot w_{T\_PR}$$

$$w_{TA\_AF} = 1$$

$$w_{T\_AF} := .1$$

$$w_{T\_Ex} := .1$$

$$w_{T\_SO} := .1$$

$$w_{T\_Be} := .1$$

$^{w}T\_PR := .1$

$^{w}T\_Wi := .1$

Given

$^{w}T\_Be \cdot {}^{w}TBE\_User = 2 \cdot \left({}^{w}T\_SO \cdot {}^{w}TSO\_Enables\right)$

$^{w}T\_Ex \cdot {}^{w}TEF\_NWS = {}^{w}T\_Wi \cdot {}^{w}TSW\_War$

$^{w}T\_Ex \cdot {}^{w}TEF\_NWS = {}^{w}T\_Wi \cdot {}^{w}TSW\_War$

$^{w}T\_Wi \cdot {}^{w}TSW\_War = 3 \cdot \left({}^{w}T\_AF\right)$

$^{w}T\_AF = 5 \cdot {}^{w}T\_PR$

$^{w}T\_AF + {}^{w}T\_Be + {}^{w}T\_Ex + {}^{w}T\_PR + {}^{w}T\_SO + {}^{w}T\_Wi = 1$

$$\begin{bmatrix} {}^{w}T\_AF \\ {}^{w}T\_Be \\ {}^{w}T\_Ex \\ {}^{w}T\_PR \\ {}^{w}T\_SO \\ {}^{w}T\_Wi \end{bmatrix} := \mathrm{Find}\left({}^{w}T\_AF, {}^{w}T\_Be, {}^{w}T\_Ex, {}^{w}T\_PR, {}^{w}T\_SO, {}^{w}T\_Wi\right)$$

$$\begin{bmatrix} {}^{w}T\_AF \\ {}^{w}T\_Be \\ {}^{w}T\_Ex \\ {}^{w}T\_PR \\ {}^{w}T\_SO \\ {}^{w}T\_Wi \end{bmatrix} = \begin{bmatrix} 0.045681078340059 \\ 0.239675997477624 \\ 0.274086470040354 \\ 0.009136215668012 \\ 0.093380258757516 \\ 0.338039979716436 \end{bmatrix}$$

Purpose: Relate Reach to Awareness

Reach/Sustain/Achieve/Extend Life is three times as important as

Awareness/Gain/Availability.

$w_{RS\_Ach\_Ext} \cdot w_{R\_Su} \cdot w_{Reach} = 3 \cdot (w_{RG\_Avail} \cdot w_{A\_Ga} \cdot w_{Aware})$

$w_{A\_Ga} = 1$

Purpose: Relate Reach to Power

Achieve/Extend Life is as important as standoff

$w_{RS\_Ac} \cdot w_{R\_Su} \cdot w_{Reach} = w_{PL\_St} \cdot w_{P\_Le} \cdot w_{Power}$

$w_{P\_Le} = 1$

Purpose: Relate Tech. Sup. to Reach

New Warfighting Spectrum is twice as important as Sustain/Extend Life.

$2 \cdot (w_{RS\_Ac} \cdot w_{R\_Su} \cdot w_{Reach}) = w_{TS} \cdot w_{T\_Wi} \cdot w_{TE\_Wa}$

$w_{Reach} := .25$

$w_{Aware} := .25$

$w_{Power} := .25$

$w_{TS} := .25$

Given

$w_{RS\_Ach\_Ext} \cdot w_{R\_Su} \cdot w_{Reach} = 3 \cdot (w_{RG\_Avail} \cdot w_{Aware})$

$w_{RS\_Ach\_Ext} \cdot w_{R\_Su} \cdot w_{Reach} = w_{PL\_survival} \cdot w_{Power}$

$2 \cdot (w_{RS\_Ach\_Ext} \cdot w_{R\_Su} \cdot w_{Reach}) = w_{TS} \cdot w_{T\_Wi} \cdot w_{TSW\_War}$

$w_{Reach} + w_{Aware} + w_{Power} + w_{TS} = 1$

$$\mathrm{Find}\left(w_{Reach}, w_{Aware}, w_{Power}, w_{TS}\right) = \begin{bmatrix} 0.284068920432722 \\ 0.0400097071032 \\ 0.092022326337361 \\ 0.583899046126716 \end{bmatrix}$$

Appendix H: Air Vehicles' Programs and Scoring

Description of Air Vehicles Programs Scored

The following information was provided my Mr. Dave Perez of Air Vehicles. This information is comes from program charts, internal program summary sheets, and the *FY98 Air Vehicles Technology Area Plan.* The letters by each program represent an arbitrary coding system for the programs to make references to them simpler.

A. Weapons Bay Noise Suppression – The objective of this effort is to develop analysis methods for the prediction of flow-induced acoustic levels in weapon bays and unsteady aerodynamic loads impinging on structures. Suppression techniques will also be developed for both weapons bay acoustics and unsteady aerodynamic loads. Current passive suppression systems for weapons bays are only effective for single point designs. The active/adaptive system will provide acoustic suppression for all bay configurations and flight conditions resulting in significant cost savings by eliminating the required redesign of passive systems.

B. Composite Repair of Aircraft Structures – Objectives: Develop and demonstrate advanced composite repair technology for components of aging aircraft. Restore structural integrity, extended operational life, [and] reduce operating costs of aging aircraft.

C. UCAV-ITAC – The program is developing the flight control and flight management algorithms for cooperative semi-autonomous unmanned combat air vehicles with manned aircraft in a composite tactical strike package. Mission performance improvements resulting from cooperative flight operations of a multi-ship strike package will be evaluated and demonstrated. The adaptability and experience of the pilot(s) are integrated with automated decision aiding processes, advanced multi-ship flight path control, and cooperative planning technologies to accomplish the control tasks of multi-ship flight management. Air-to-Surface missions are being addressed. Management and supervision of the unmanned vehicles will be provided by a pilot in another aircraft of the strike formation or an operator aboard an AWACS/JSTARS aircraft.

D. Structurally Integrated Thermal Energy Management (SITE-M) – The objective of this program is to develop low observable compatible supportable advanced structural concepts for thermal energy management (structurally integrated nozzles).

E. Actuation Health-Monitoring Systems – This program will develop an intelligent monitoring system capable of diagnosing failures in actuation systems on air vehicles. This information will result in faster repair cycles since what is wrong will be quickly determined.

F. Space-Based System-of-Systems Advanced Development Demo & Validation Program – This program is still being defined. It will develop advanced technologies that enable an unmanned reusable space launch vehicle.

The program was difficult to score under "Reach" because it appeared there was nothing to compare the program to. This program is extremely new, but is supposed to be part of an effort that will develop a completely reusable two-stage launch vehicle. The only known reusable launch vehicle is the Space Shuttle, which is not completely reusable. The Space Shuttle is capable of placing 55,000 pounds into low Earth orbit (NASA, 1988), while Air Vehicles' proposed system will be capable of placing 6000 pounds into low Earth orbit. This large mismatch in scale makes the Shuttle a poor comparison.

A better comparison is the Delta II 7320 (McDonnell Douglas Corporation, 1996). The Delta II 7320 vehicle is capable of placing 6030 pounds into low earth orbit. The proposed system will also be capable of placing 6000 pounds into low earth orbit (McDonnell Douglas Corporation, 1996: "Table 2-3. Mission Capabilities," page 2-6). The Delta II takes 3 months to launch and is available only once during that time. Hence, availability is 1/60, assuming 20 working days in a month. It takes 3 months to erect, prepare and fuel the Delta II. (McDonnell Douglas Corporation, 1996: "Typical Mission Plan" schedule, page 6-29).

G. More Electric Aircraft Technology Validation (MTV) – In a joint Air Force/NASA effort, the More Electric Aircraft technology Validation (MTV) flight validation program will demonstrate that electric actuation is a mature technology for high horsepower flight-critical control applications. An electrohydrostatic actuator (EHA) will be developed and flown on a NASA F/A-18 aircraft. AFRL's Propulsion and Power Directorate will provide a secondary power generation and distribution system for the F/A-18. NASA will provide the flight test aircraft and support. Successful completion of this program will put power-by-wire actuation "on the shelf" for military and commercial applications. Electric actuation is desirable because of better reliability, easier maintainability, and potential weight savings.

Tabulated Raw Scores

Measure Roster	Reach											Awareness			Power	
	Gain					Sustain						Gain			Lethality	
Alternative/Evaluation Measure	Availability	Missions Enabled	Regeneration	Response Time	Payload-Range	Achieve/Extend Life	Availability	Missions Enabled	Regeneration	Safety	Weight Reduction	Availability	Missions Enabled	Regeneration	Effectiveness	Survival
Hypothetical Worst Case	0	0	-100	-700	1	1	0	0	-100	-1.00E-05	1.00	0	0	-100	1	1
Hypothetical Best Case	1.5	2	100	100	2	5	1.5	2	100	1.00E-05	0.63	1.5	2	100	0	0
Weapons Bay Noise Suppression	1	2	0	0	1	1	1	2	0	0.00E+00	1.00	1	0	0	1	0.9
Composite Repair of Aircraft Structures	1	0	0	0	1	1.5	1	0	0	0.00E+00	1.00	1	0	0	1	1
ITAC	1	2	0	0	1.2	1	1	0	0	0.00E+00	1.00	1	0	0	0.8	0.8
SITE-M	0.8	2	0	20	1	1	1	0	0	0.00E+00	1.00	1	0	0	1	0.5
Actuation Health-Monitoring Systems (HMS)	1.1	0	50	0	1	2	1.1	0	50	0.00E+00	1.00	1	1	50	1	1
Space-Based System-of-systems Advanced Dv Demo & Validation	48	2	98.8	97.9	1	1	1	0	0	0.00E+00	1.00	1	0	0	1	1
MTV	1.15	0	25	20	1.1	1	1	0	0	0.00E+00	1.00	1	0	0	1	0.85
No Change	1	0	0	0	1	1	1	0	0	0.00E+00	1.00	1	0	0	1	1

		Be Efficient					Expand our Frontier		
Alternative/Evaluation Measure	AF Savings Ratio	Dual Use	Intermediate products	Multuse	Uniqueness	User Rating	Revolutionary	New Warfighting Spectrum	Programmatic Risk
Hypothetical Worst Case	0.02	No	No	1IC	Unduplicated	No Rating	No	No	Infeasible
Hypothetical Best Case	100	Yes	Yes	3IC	Partner	Top 10 ATD	Yes	Yes	Low
Weapons Bay Noise Suppression	4	No	No	2IC	Partner	No Rating	No	No	Low
Composite Repair of Aircraft Structures	3	Yes	Yes	1IC	Partner	Endorsed	No	No	Low
ITAC	10	Yes	Yes	2IC	Partner	No Rating	No	Yes	Low
SITE-M	0	No	No	1IC	Partner	No Rating	No	Yes	Low
Actuation Health-Monitoring Systems (HMS)	175	Yes	Yes	3IC	Partner	Endorsed	Yes	No	Low
Space-Based System-of-systems Advanced Dv Demo & Validation	1000	No	No	1IC	Partner	Top 10 ATD	Yes	No	High
MTV	400	Yes	Yes	2IC	Partner	Endorsed	Yes	No	Medium
No Change	1	No	No	1IC	Unduplicated	No Rating	No	No	Infeasible

	Simplify Operations			Win		
Alternative/Evaluation Measure	Enables	Interoperability	Ratio of people	Cost to Adversary	Lead	Warfare Advantage
Hypothetical Worst Case	No	USAF	2	Already Exists	< 1 Year	No Effect
Hypothetical Best Case	Yes	Coalition	0	High	10-20 Years	Overwhelm
Weapons Bay Noise Suppression	Yes	Coalition	1	Medium	5-10 Years	Degrade
Composite Repair of Aircraft Structures	No	All Services	1	Low	< 1 Year	No Effect
ITAC	Yes	Coalition	0.333	Low	1-5 Years	Degrade
SITE-M	Yes	All Services	1.02	High	5-10 Years	Neutralize
Actuation Health-Monitoring Systems (HMS)	Yes	Coalition	1	Low	1-5 Years	Keep Pace
Space-Based System-of-systems Advanced Dv Demo & Validation	Yes	USAF	0.333	High	5-10 Years	Neutralize
MTV	Yes	Coalition	0.667	Medium	1-5 Years	Degrade
No Change	No	USAF	1	Already Exists	< 1 Year	No Effect

Appendix I: Graphical Sub-value Contribution to each Value

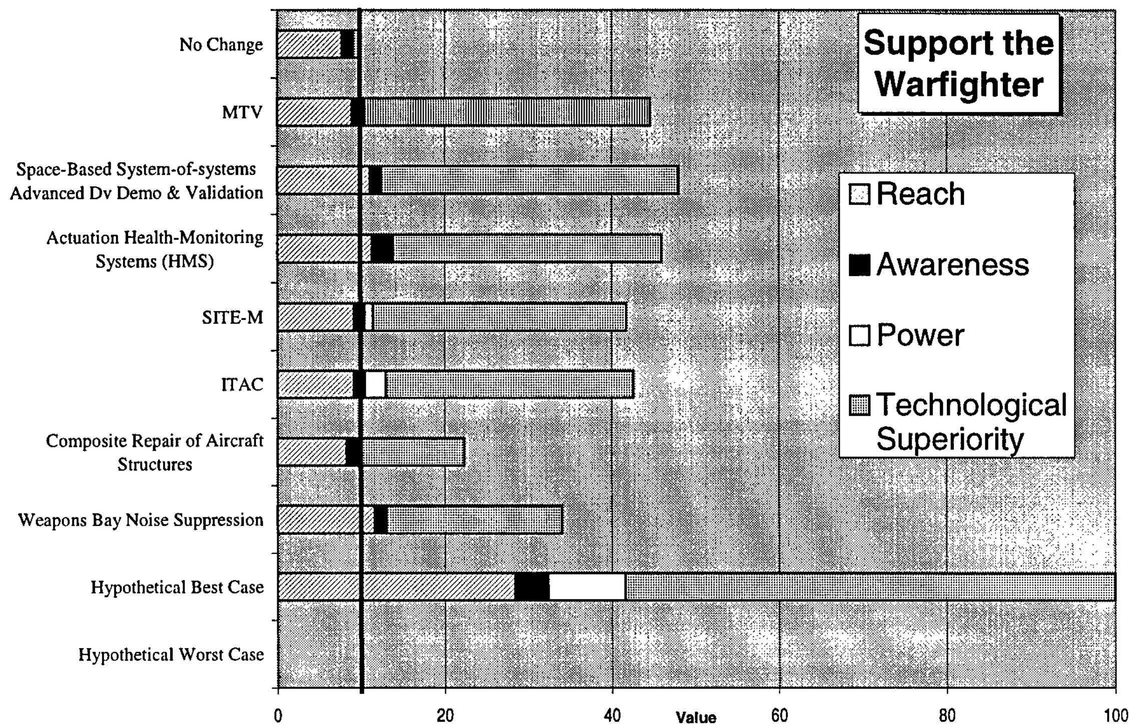


Figure 59: Value Contributions for "Support the Warfighter"

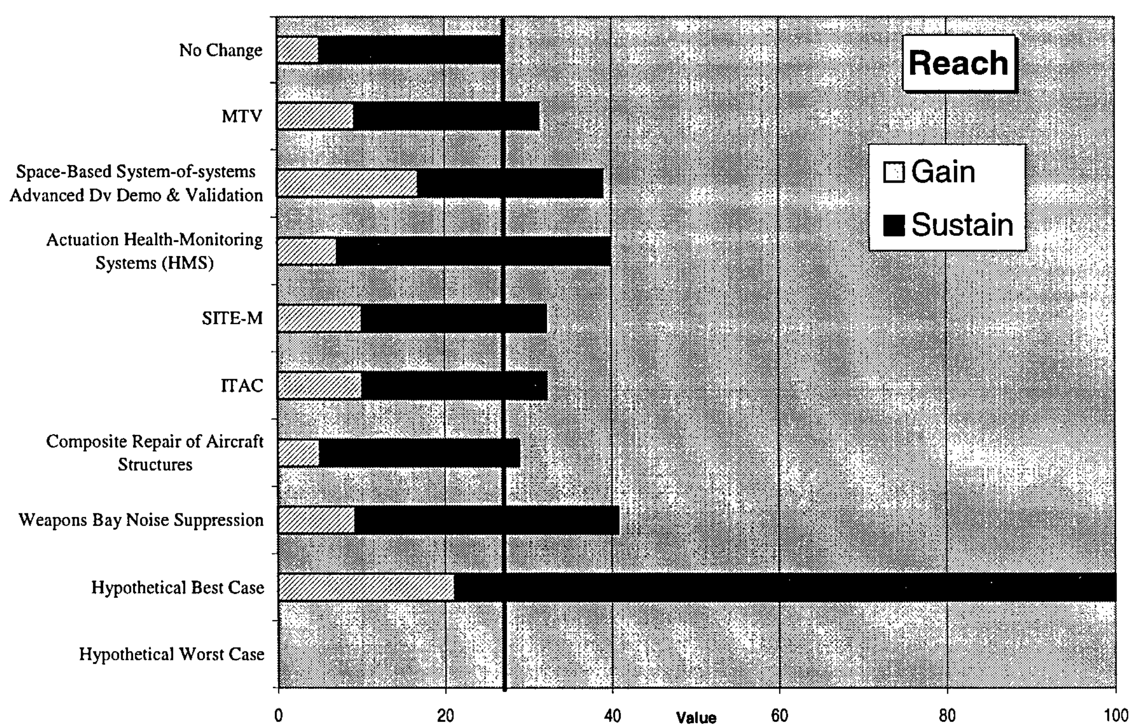


Figure 60: Value Contributions to "Reach"

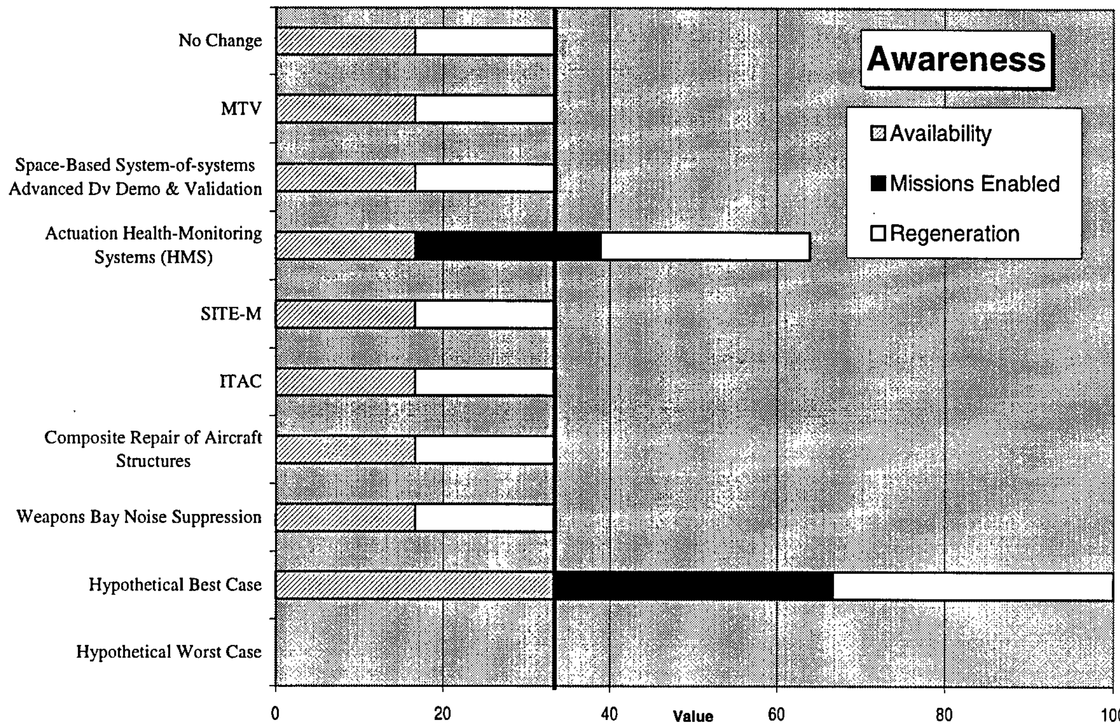


Figure 61: Value Contributions to "Awareness"

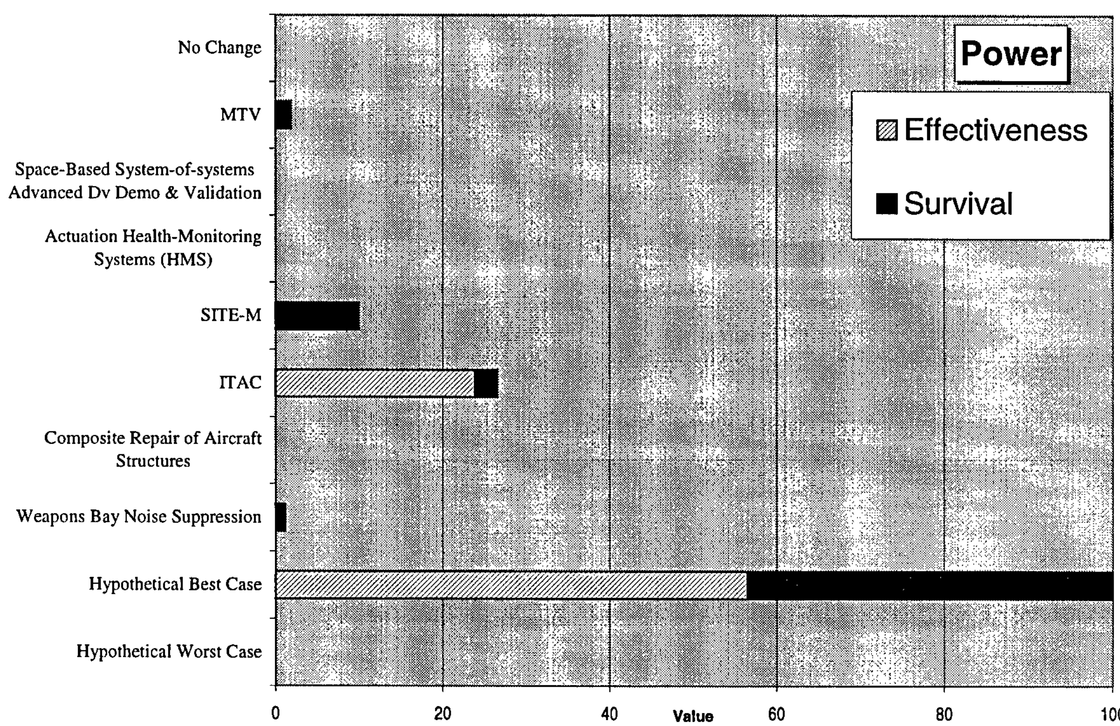


Figure 62: Value Contributions to Power

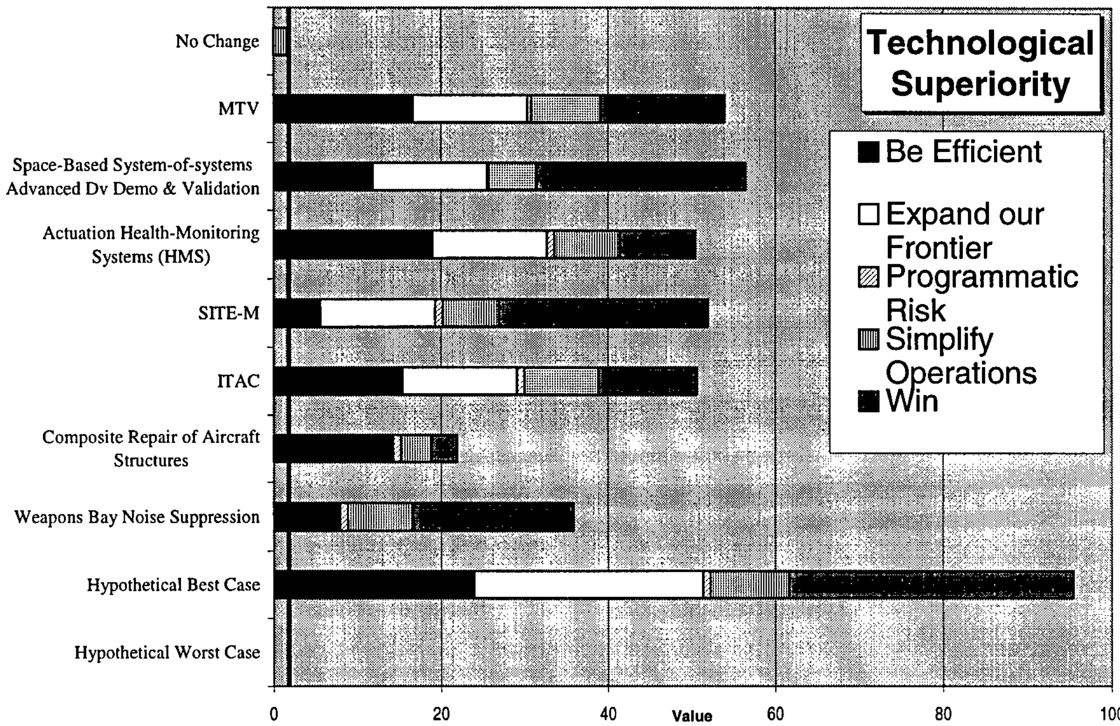


Figure 63: Value Contributions to Technological Superiority

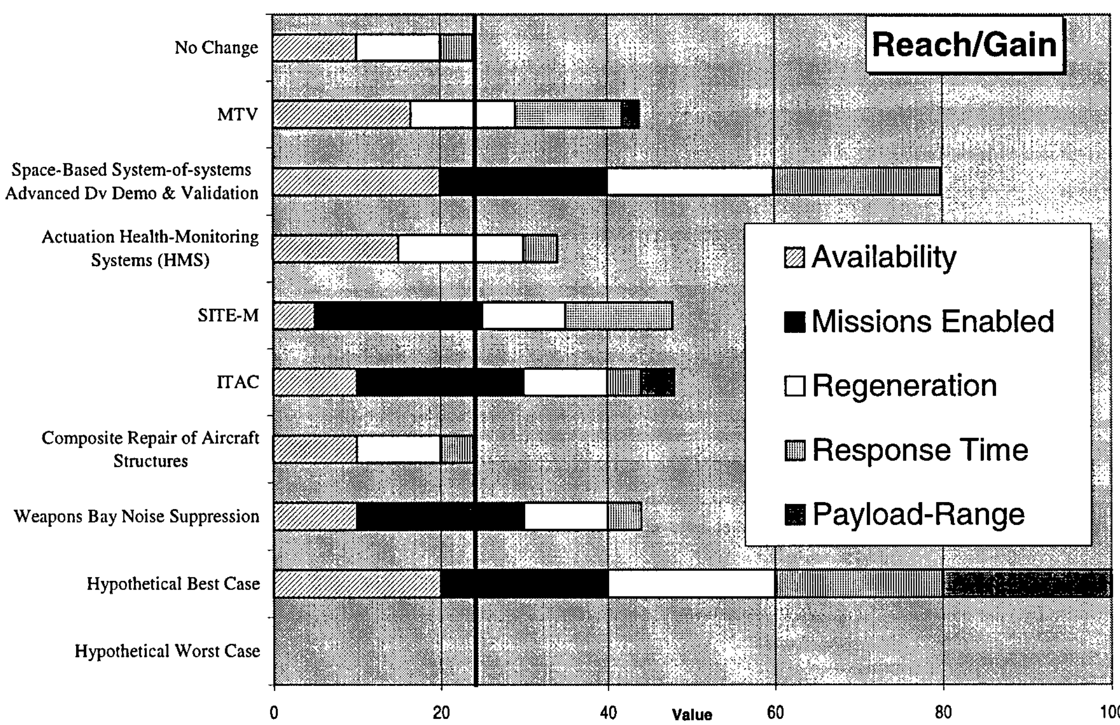


Figure 64: Value Contributions to "Reach/Gain"

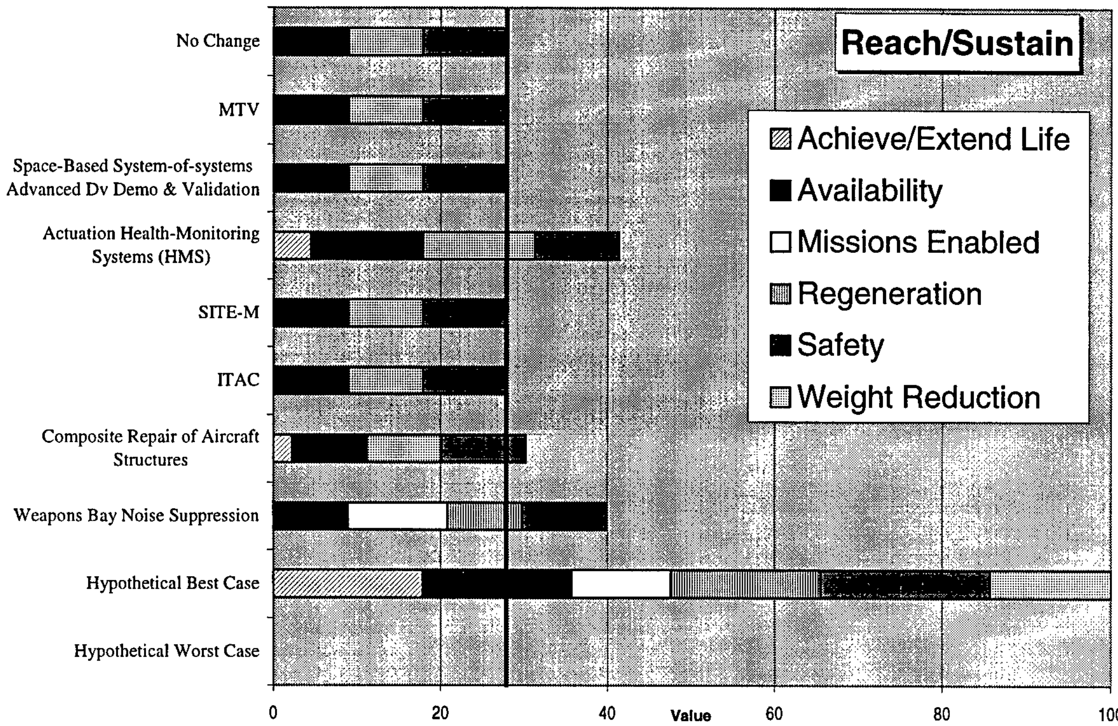


Figure 65: Value Contributions to "Reach/Sustain"

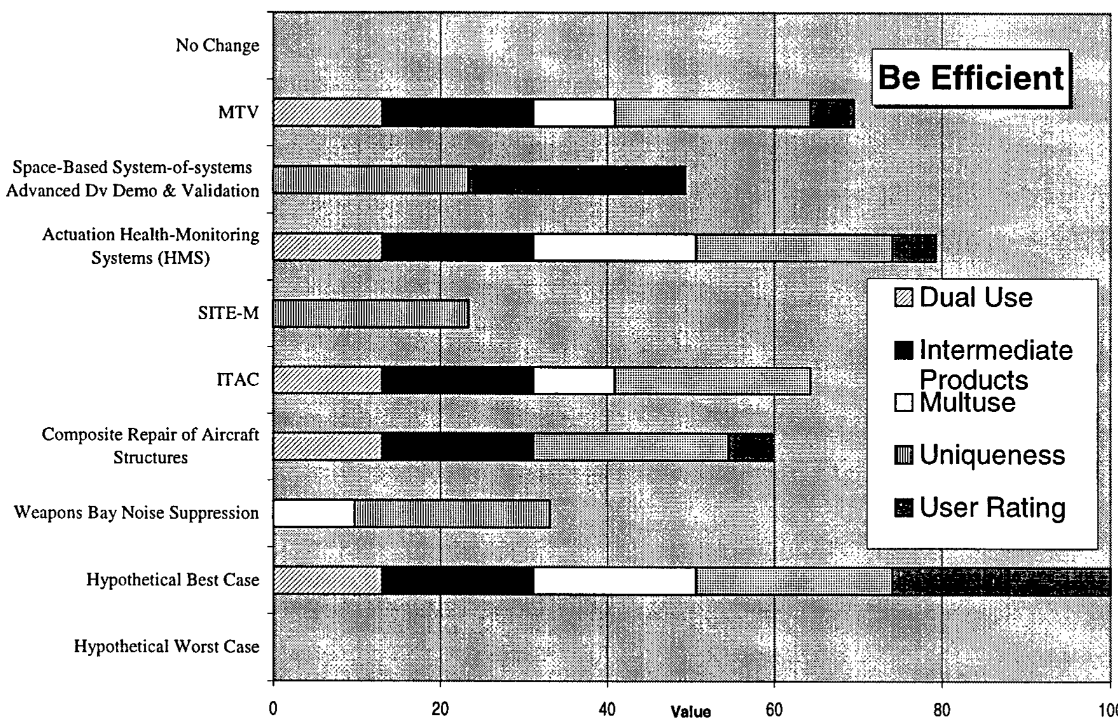


Figure 66: Value Contributions of "Be Efficient" under Technological Superiority

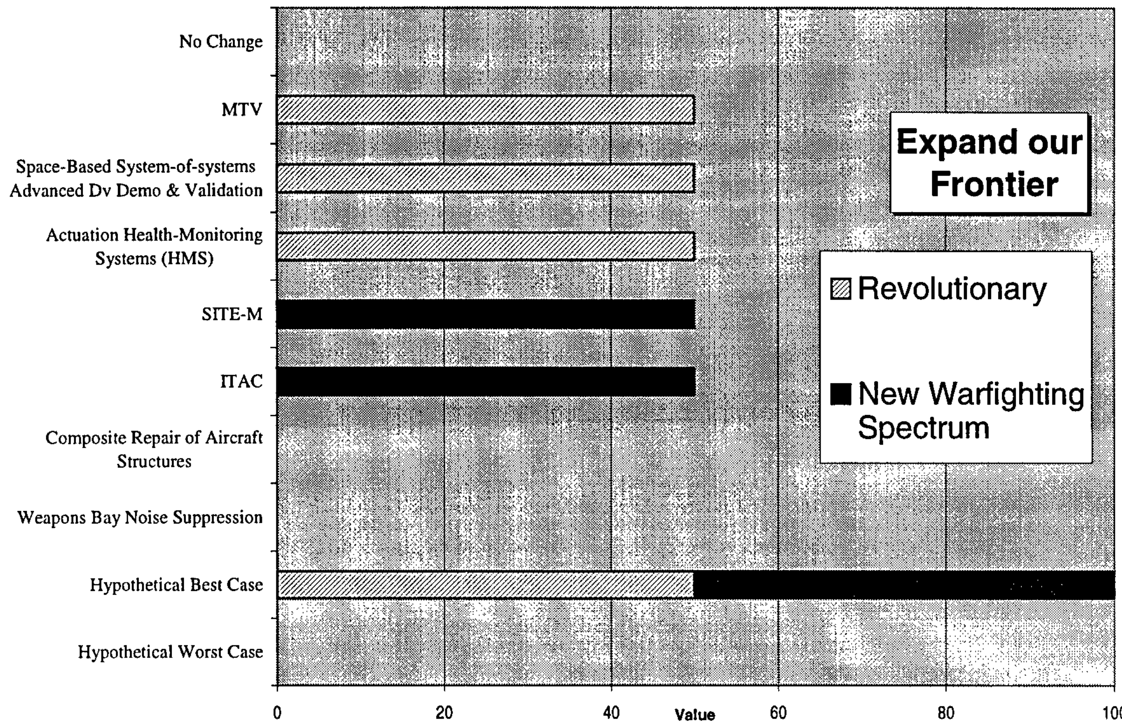


Figure 67: Value Contributions of "Expand our Frontier" under Technological Superiority

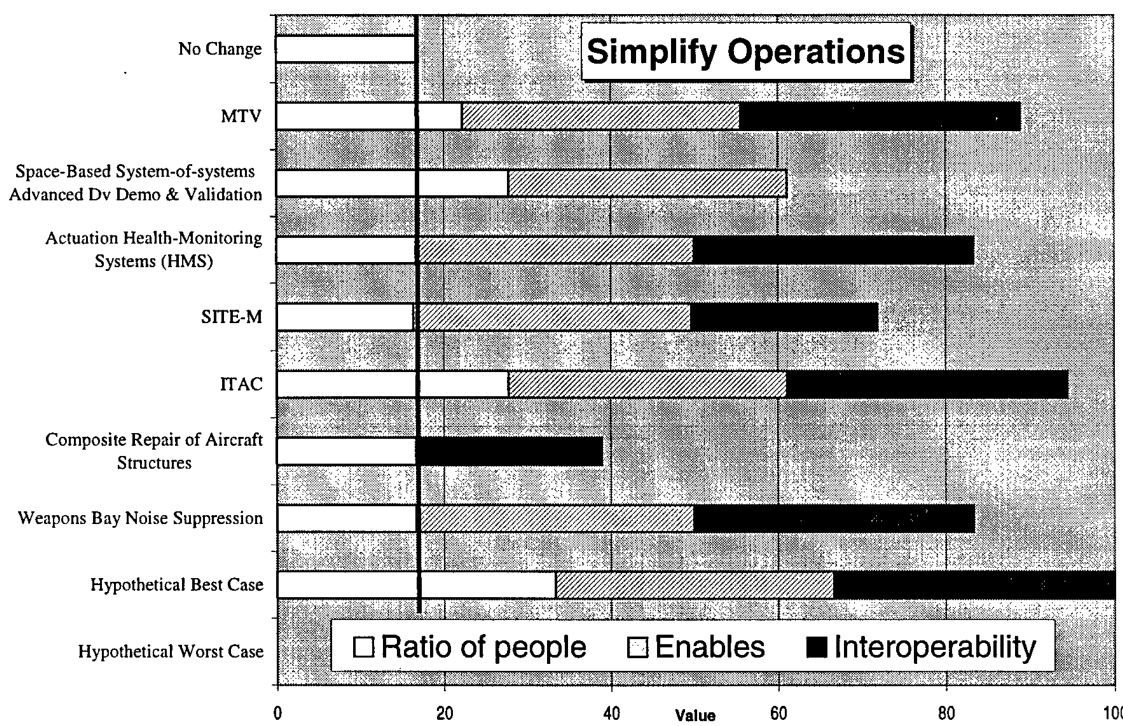


Figure 68: Value Contributions of "Simplify Operations" Under Technological Superiority

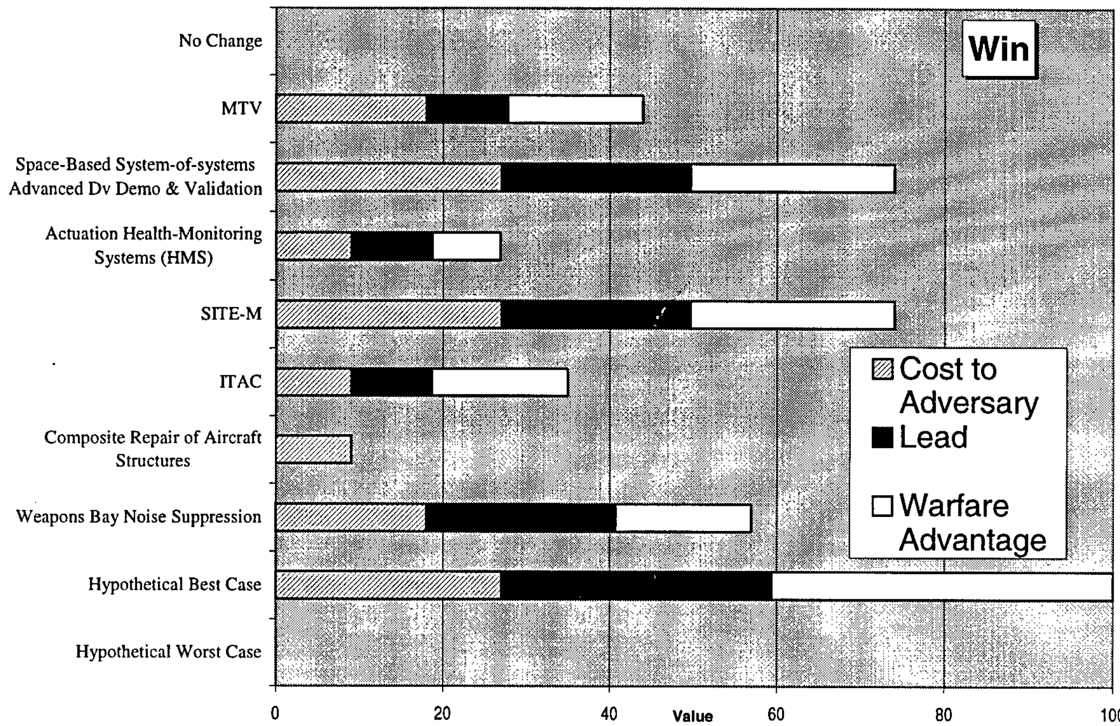


Figure 69: Value Contributions of "Win" Under Technological Superiority

Appendix J: Sensitivity Analysis of all Values and Evaluation Measures

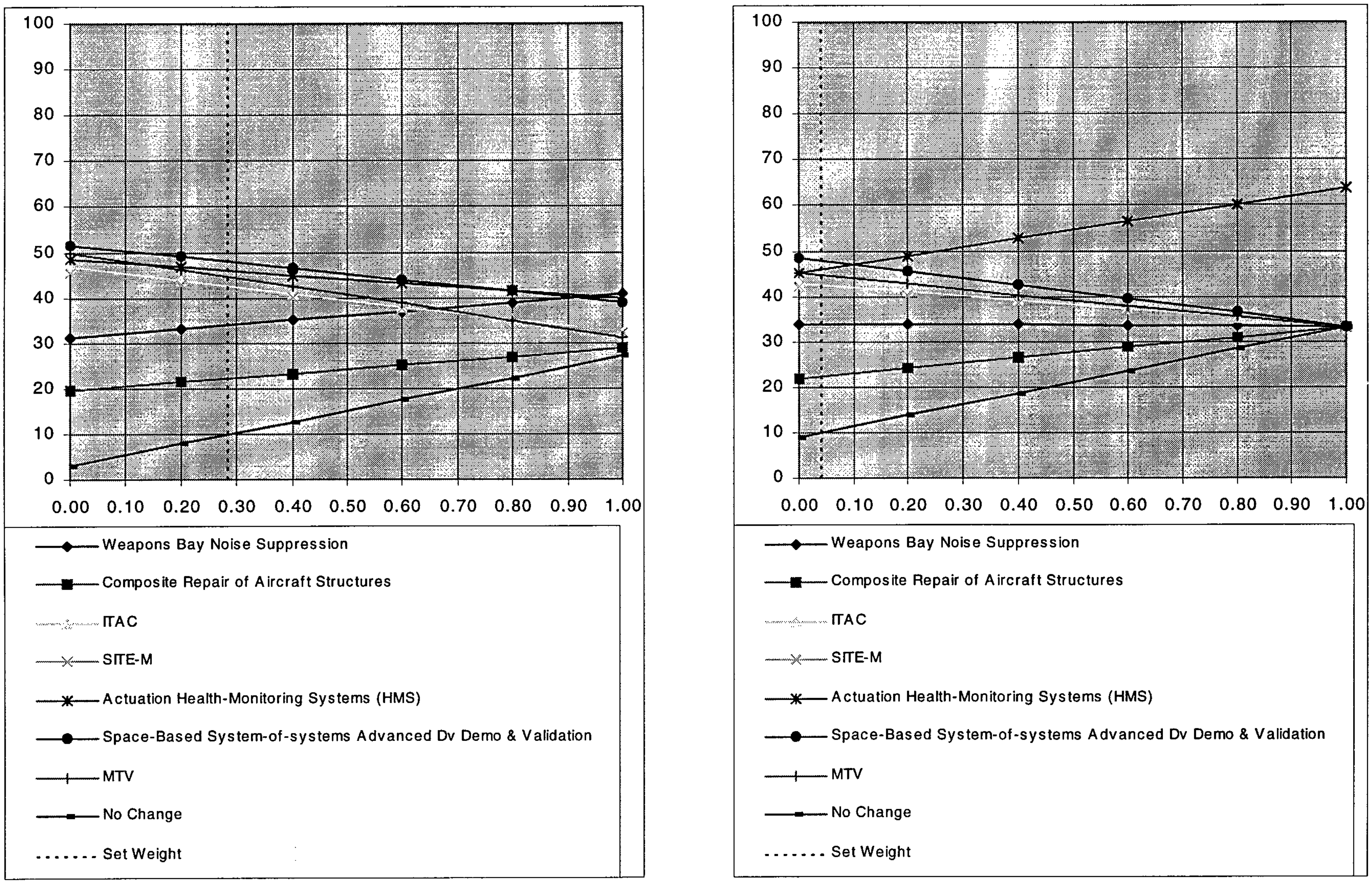
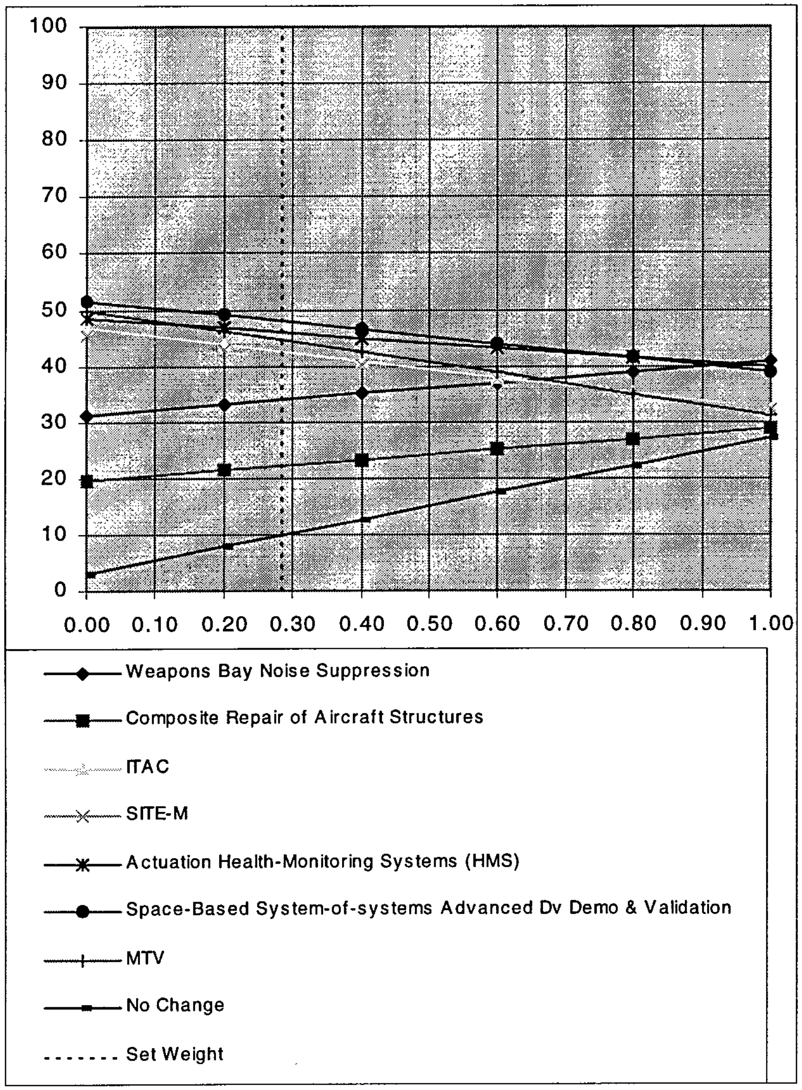


Figure 70: Sensitivity of Reach (Left) and Awareness (Right)



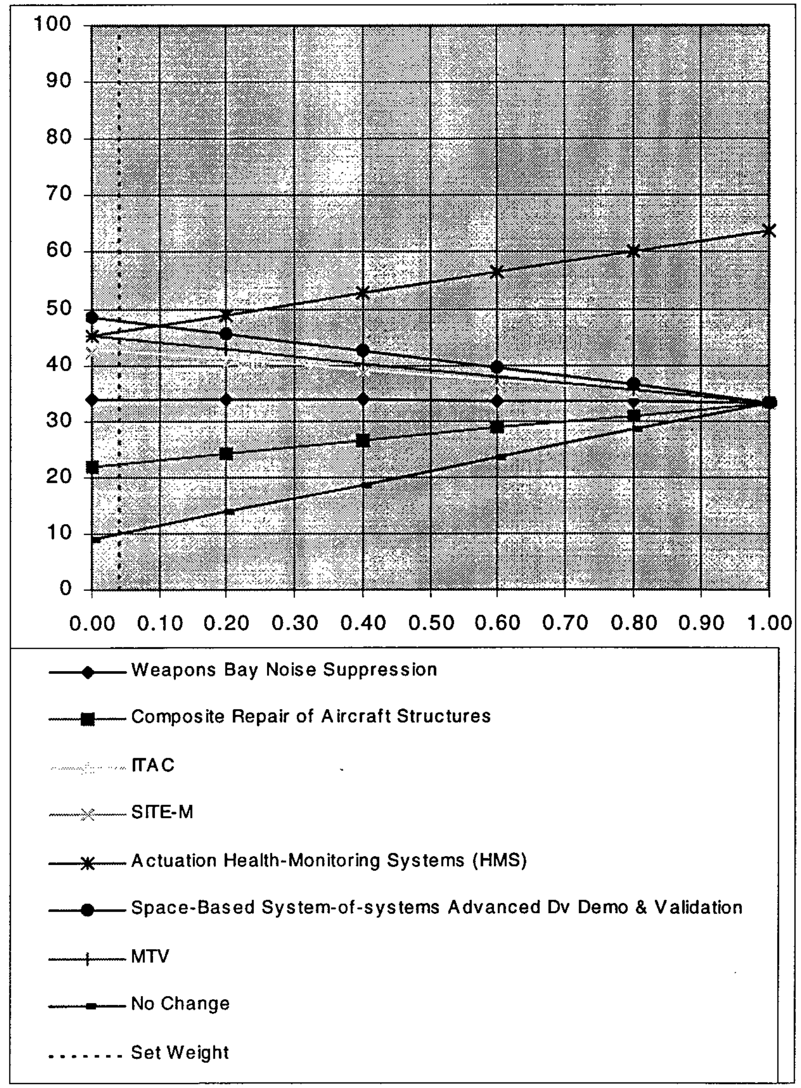
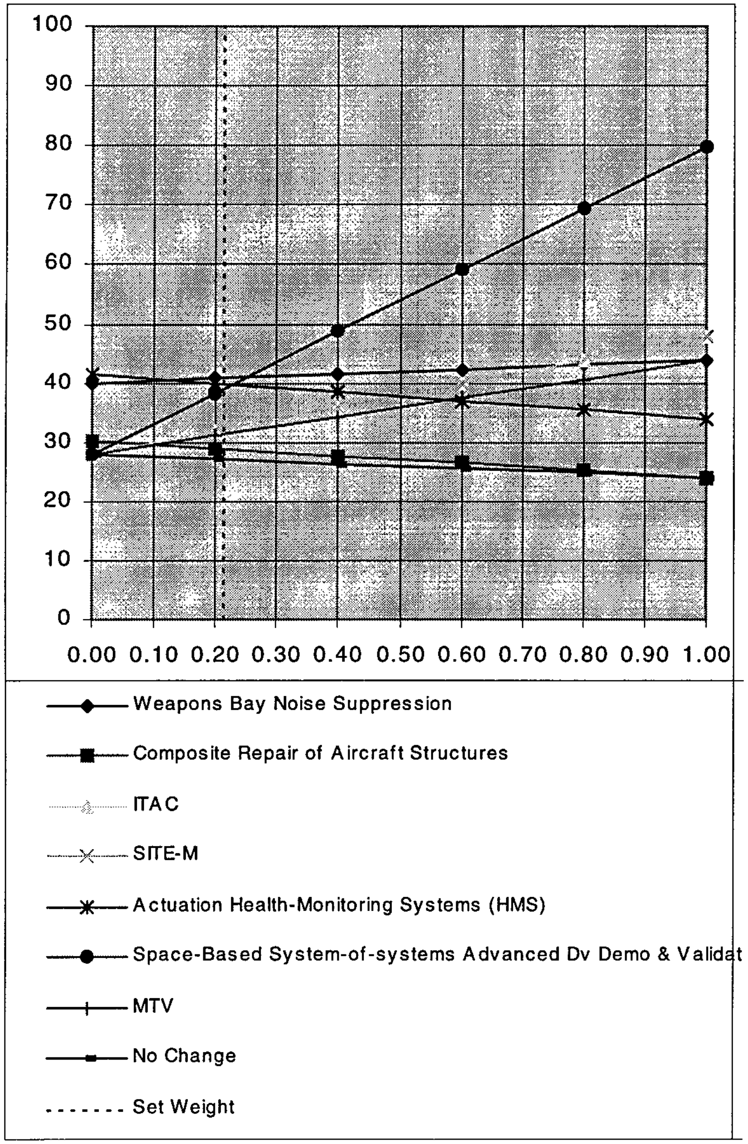


Figure 71: Sensitivity of Power (Left) and Technological Superiority (Right)



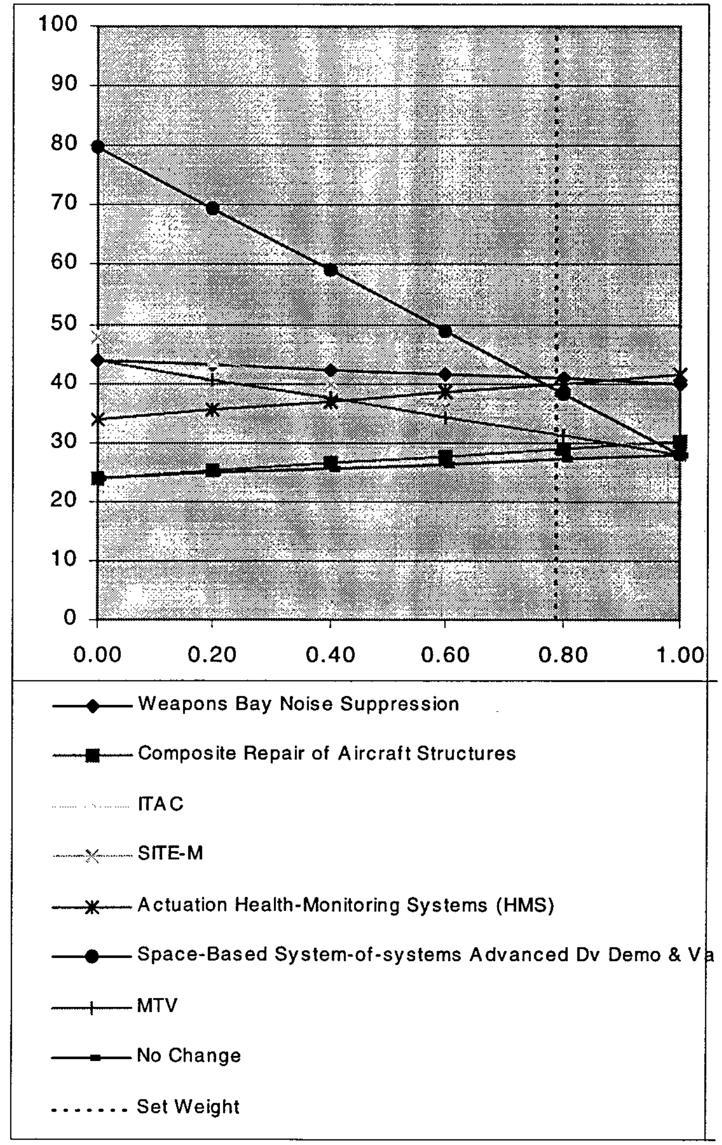


Figure 72: Sensitivity of Reach Gain (Left) and Reach Sustain (Right)

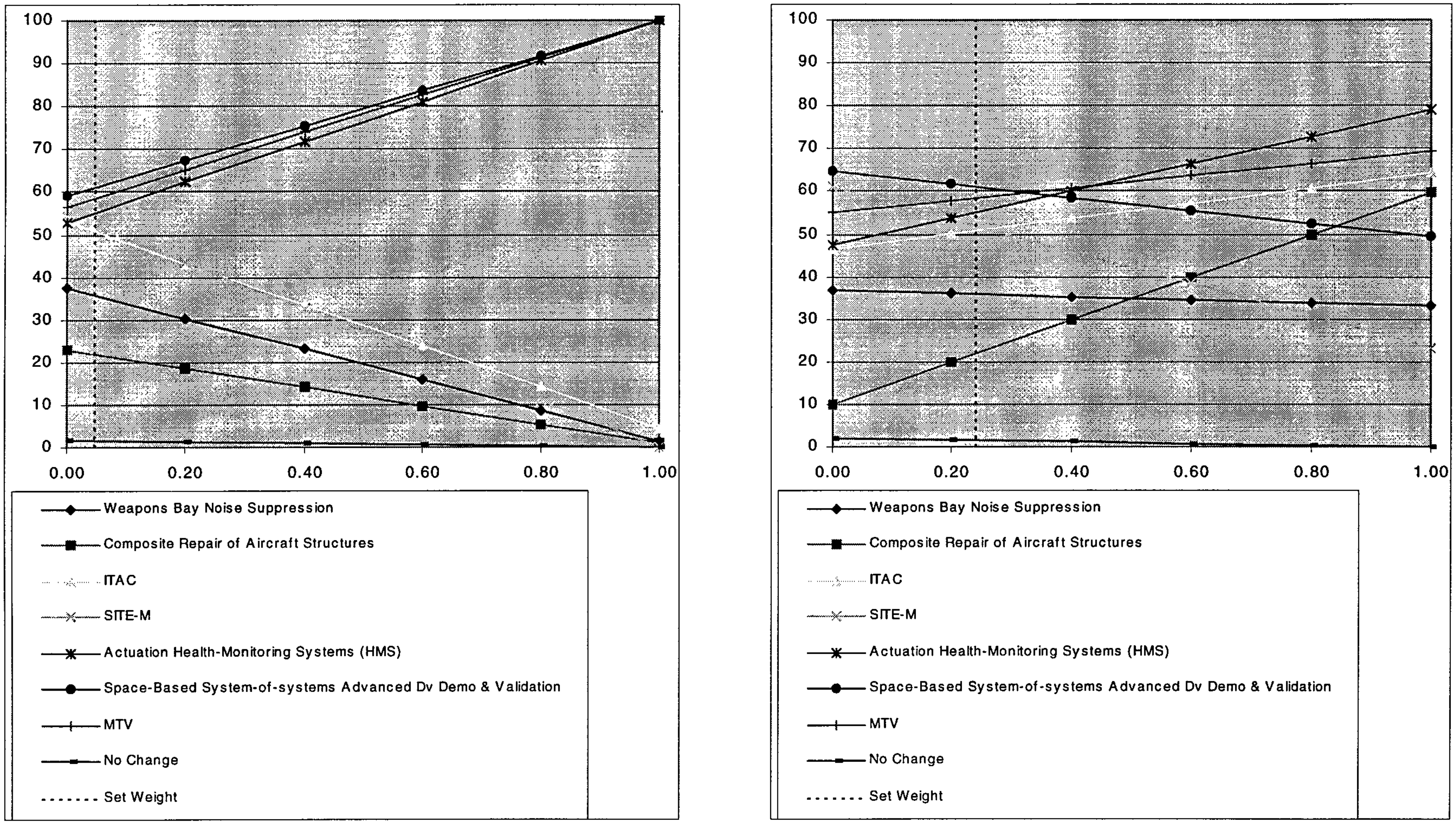


Figure 73: Sensitivity of Afford (Left) and Be Efficient (Right) under Technological Superiority

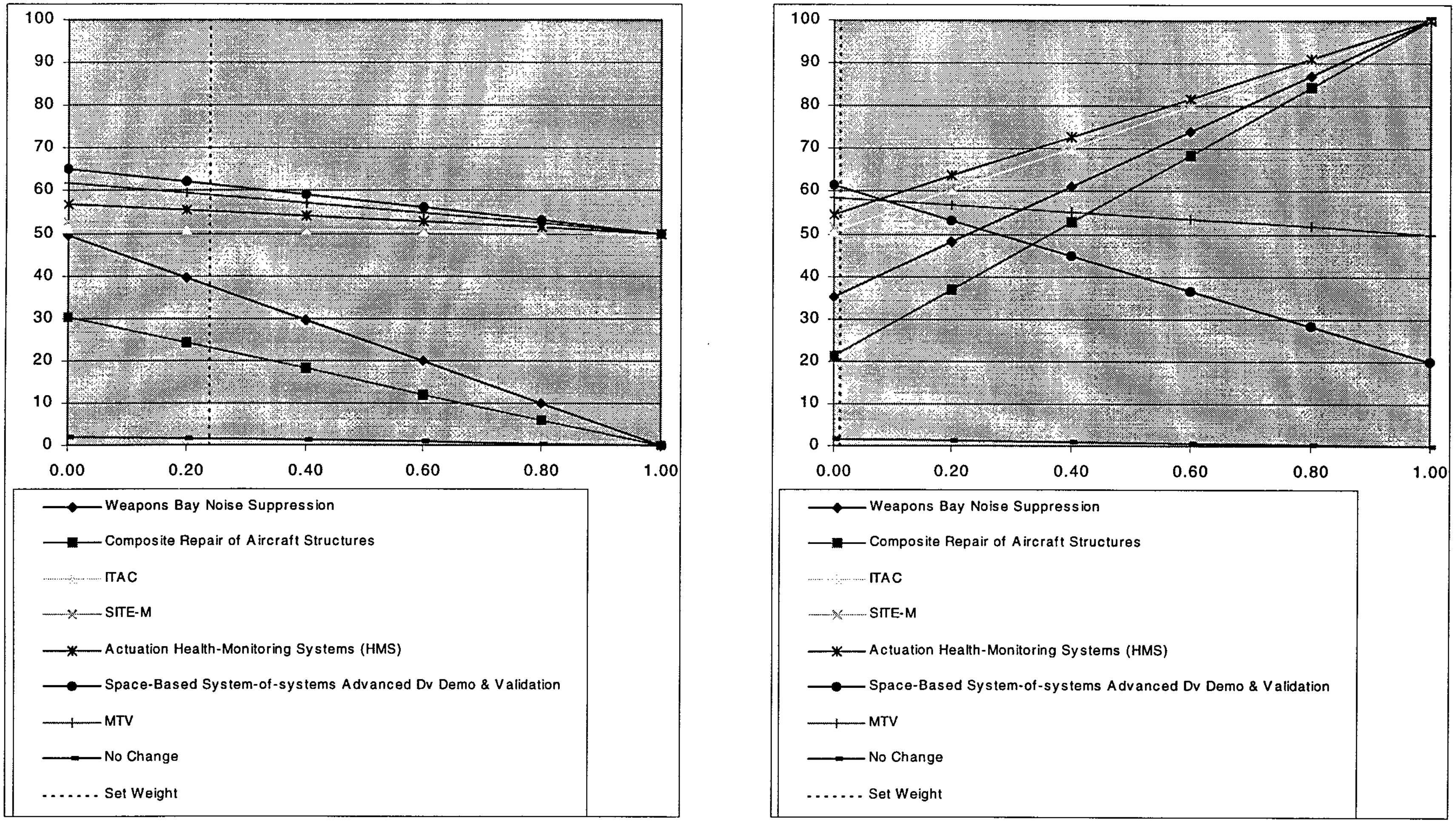


Figure 74: Sensitivity of Expand our Frontier (Left) and Programmatic Risk (Right) under Technological Superiority

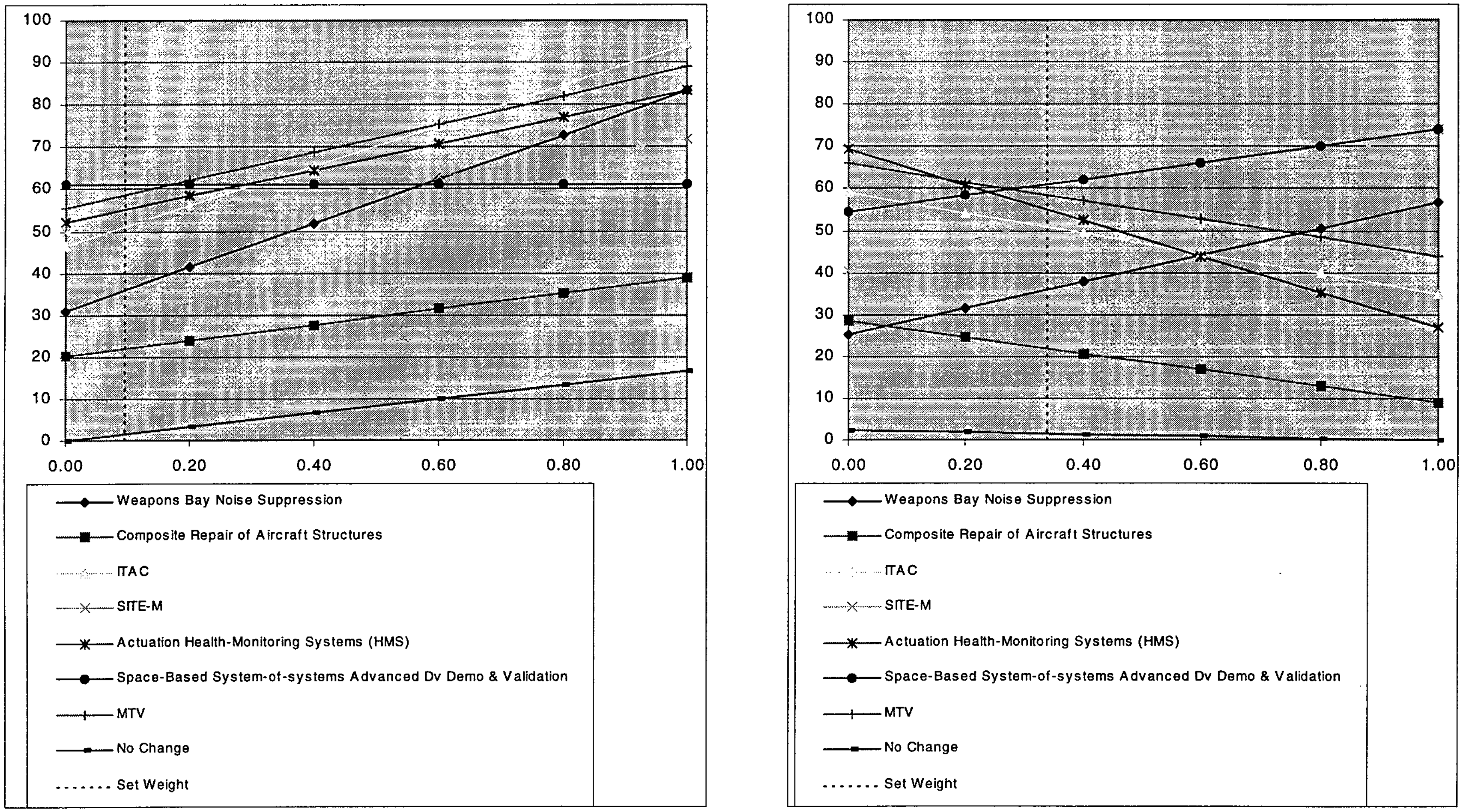
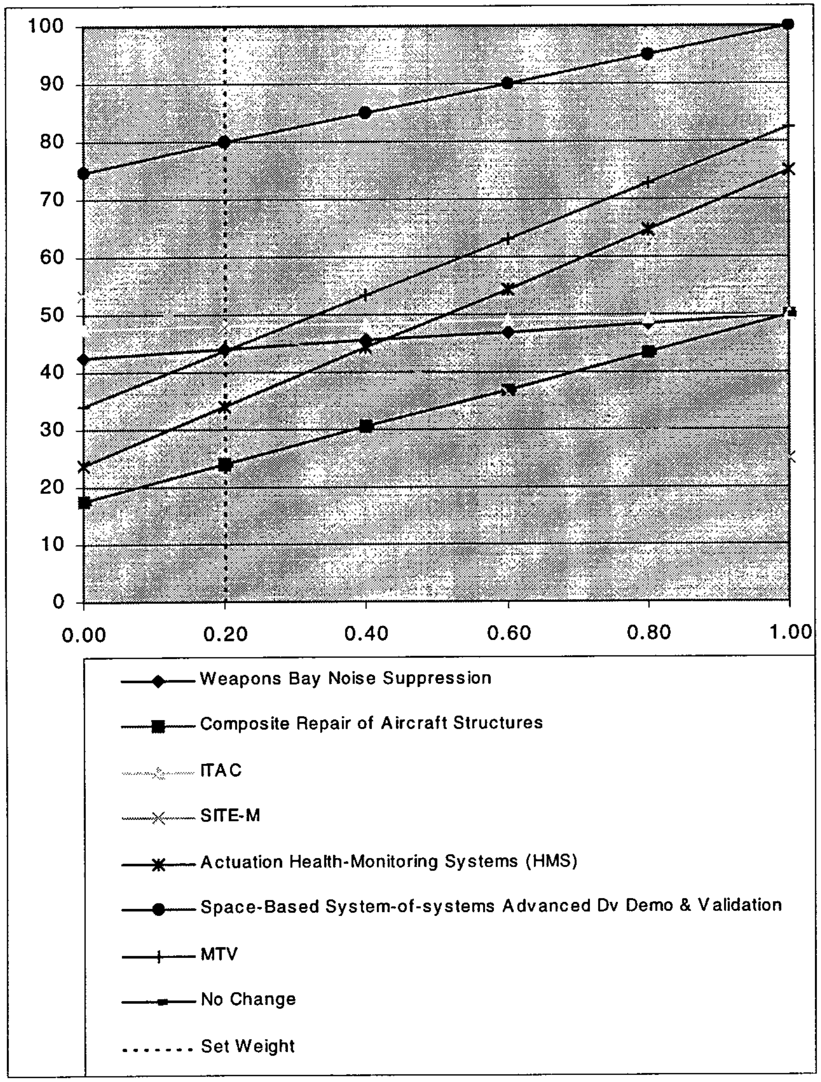


Figure 75: Sensitivity of Simplify Operations (Left) and Win (Right) under Technological Superiority



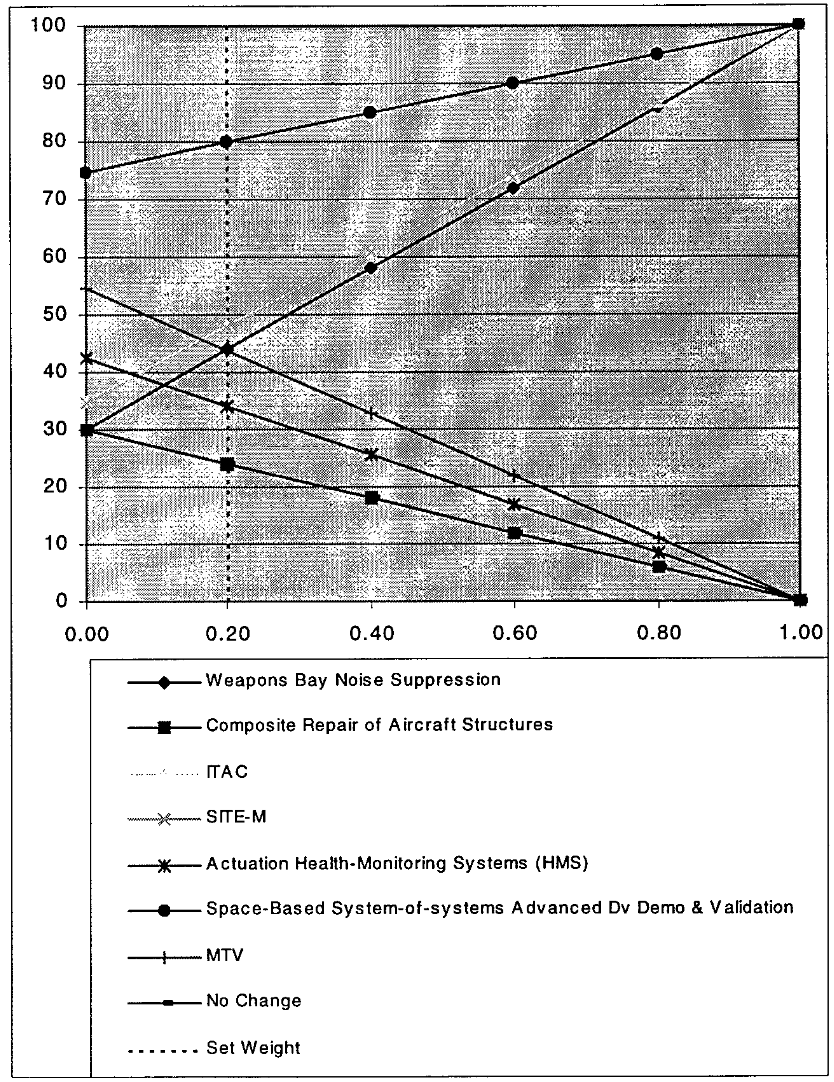
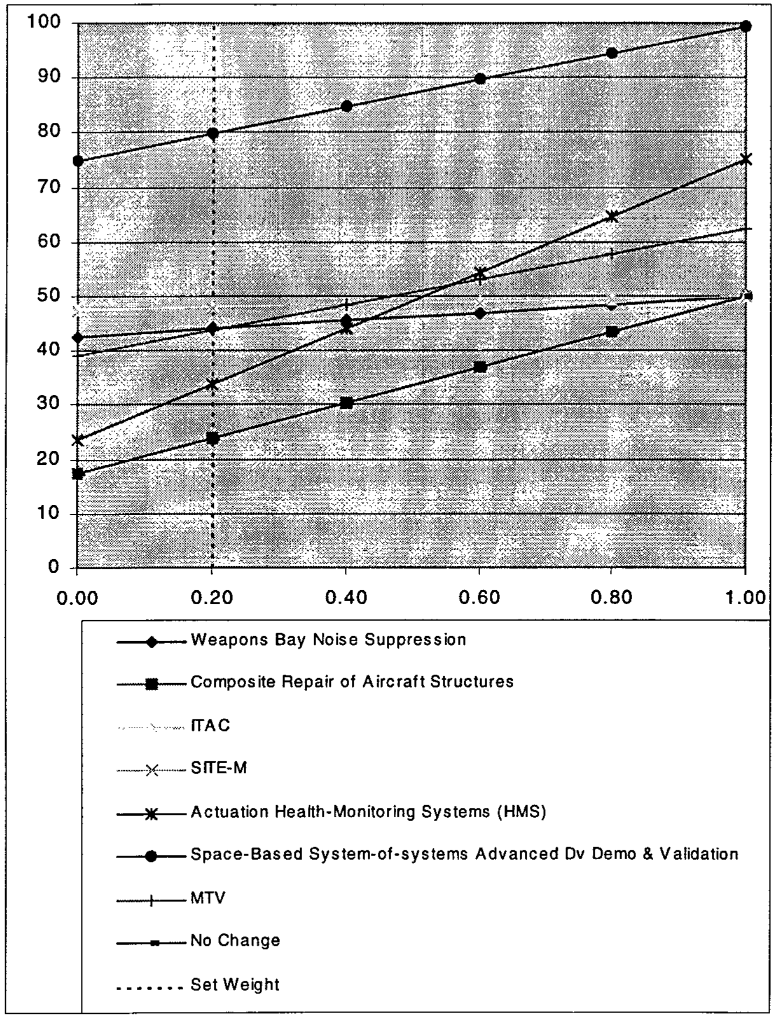


Figure 76: Sensitivity of Availability (Left) and Missions Enabled (Right) under Reach under Gain



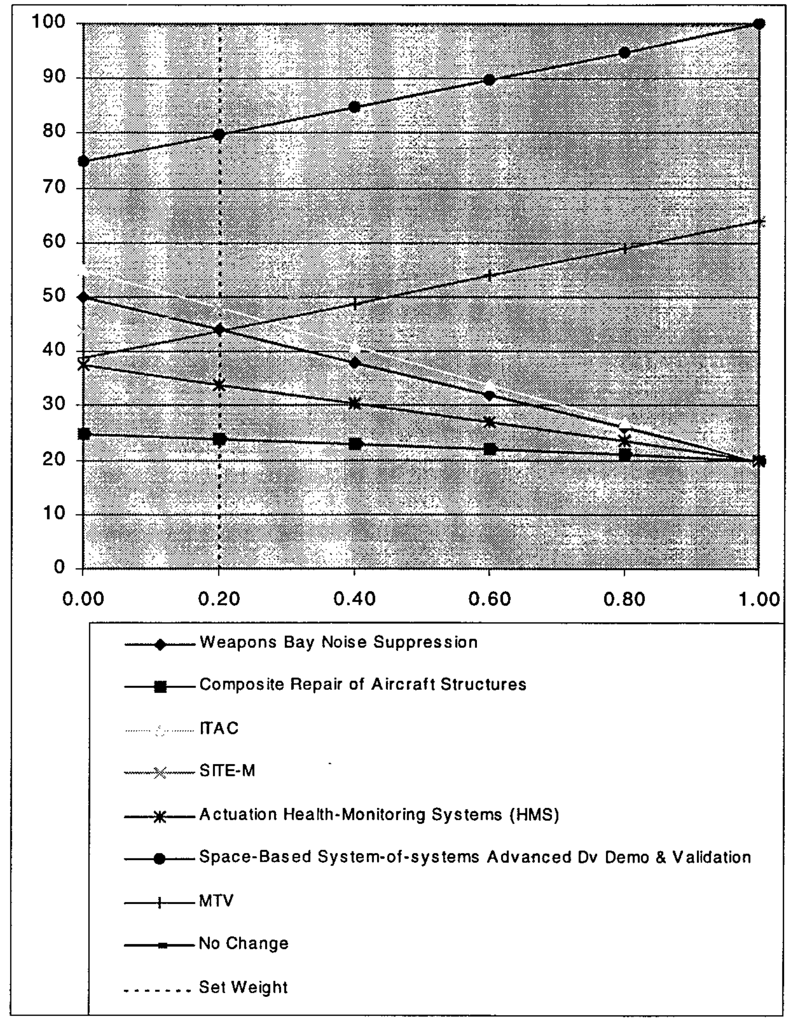


Figure 77: Sensitivity of Regeneration (Left) and Response Time (Right) under Reach under Gain

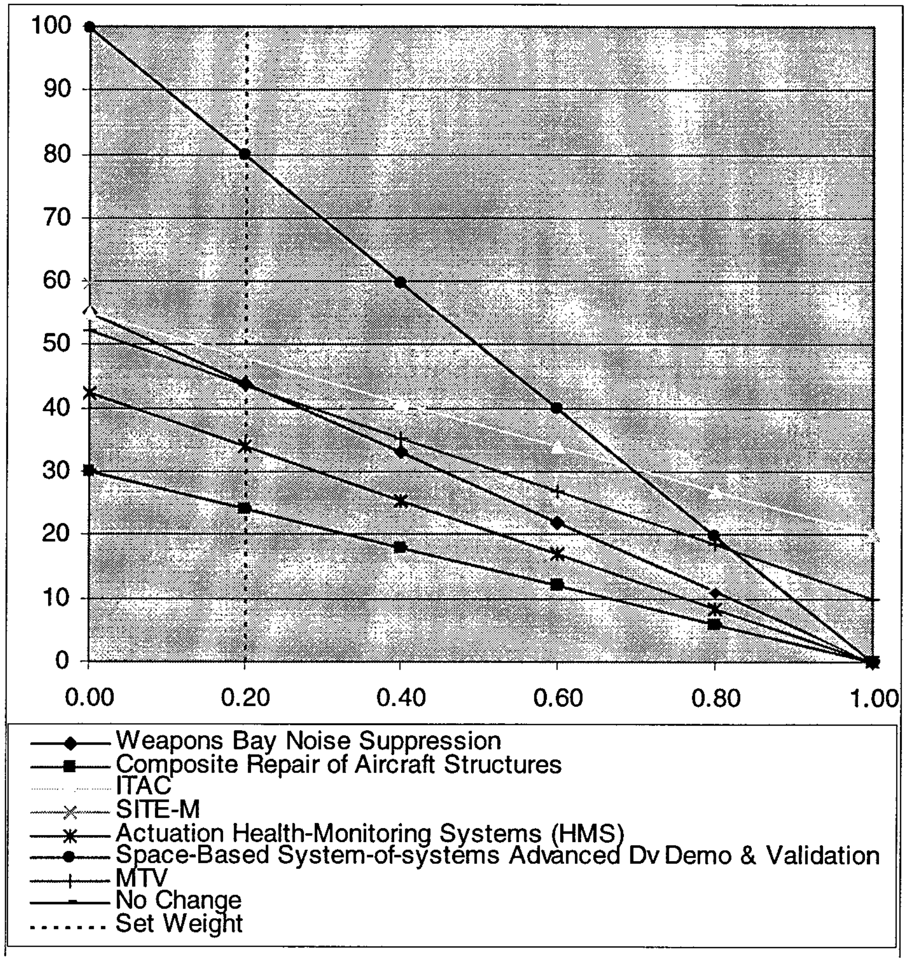
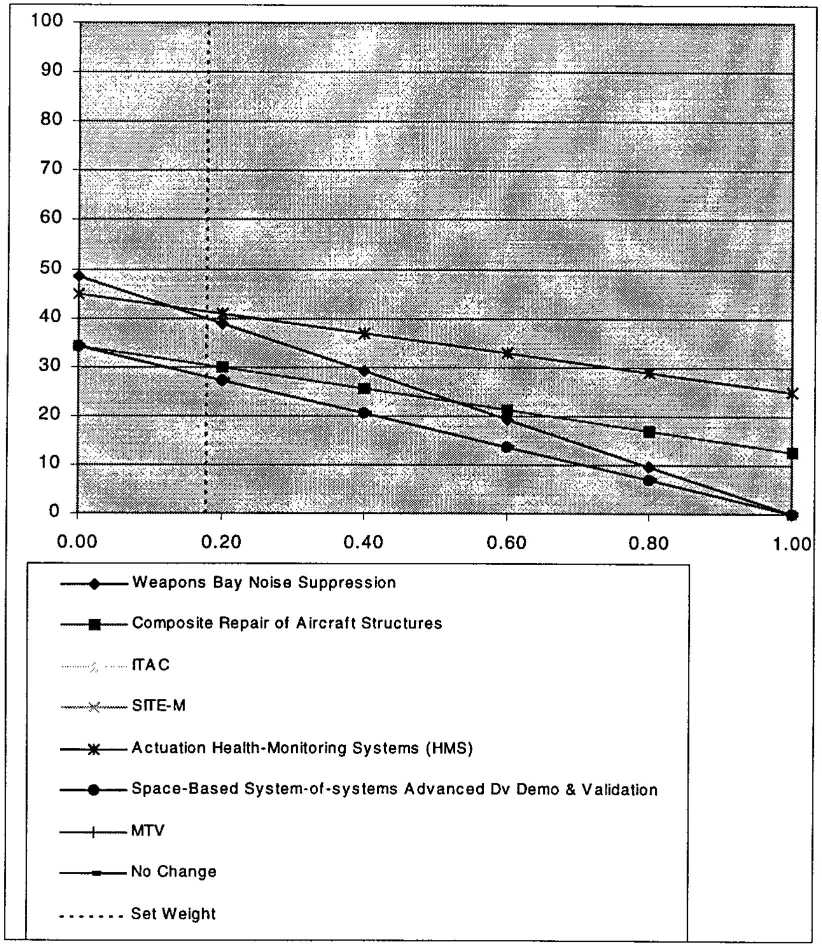


Figure 78: Sensitivity of Payload-Range under Reach under Gain



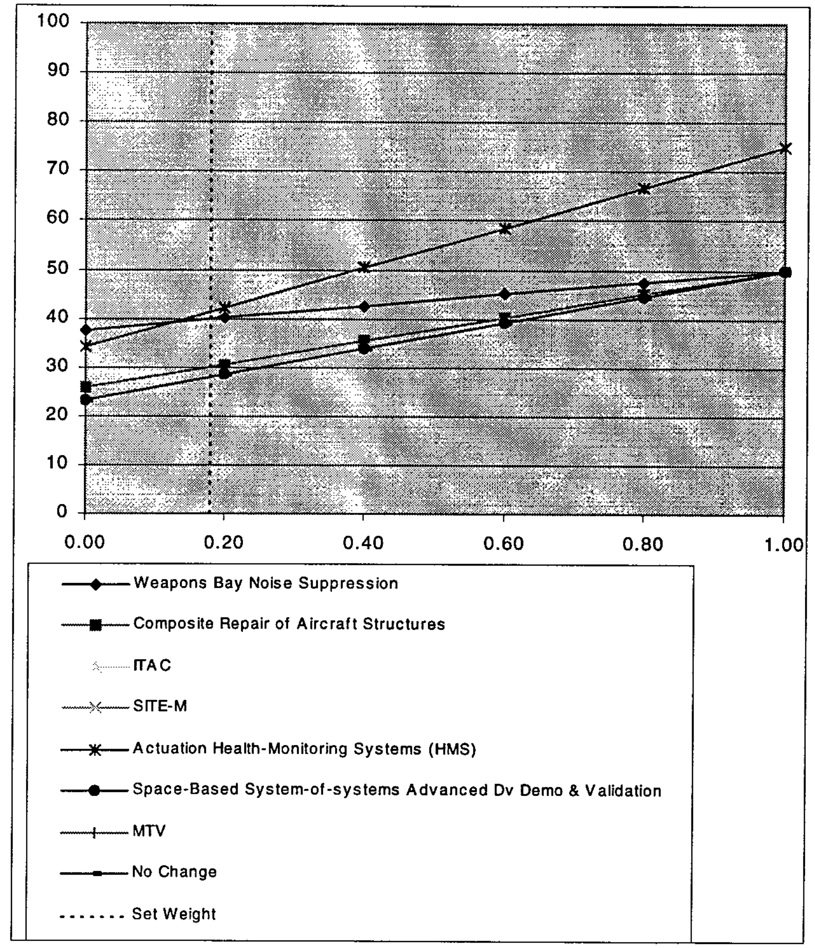
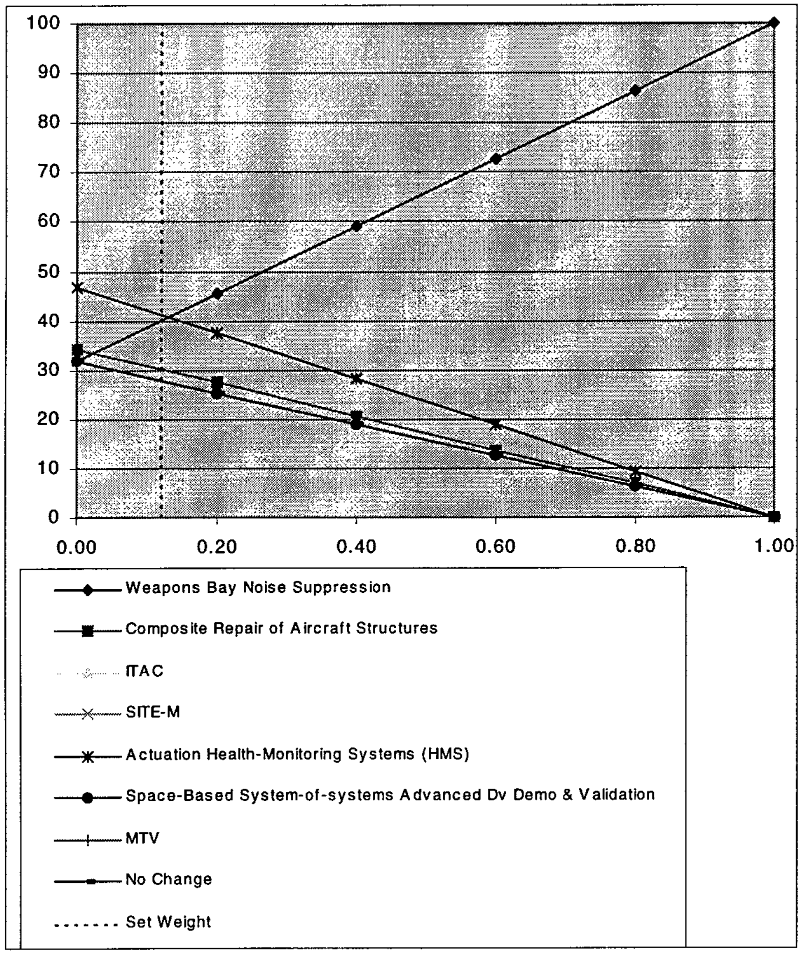


Figure 79: Sensitivity of Achieve/Extend Life (Left) and Availability under Reach under Sustain



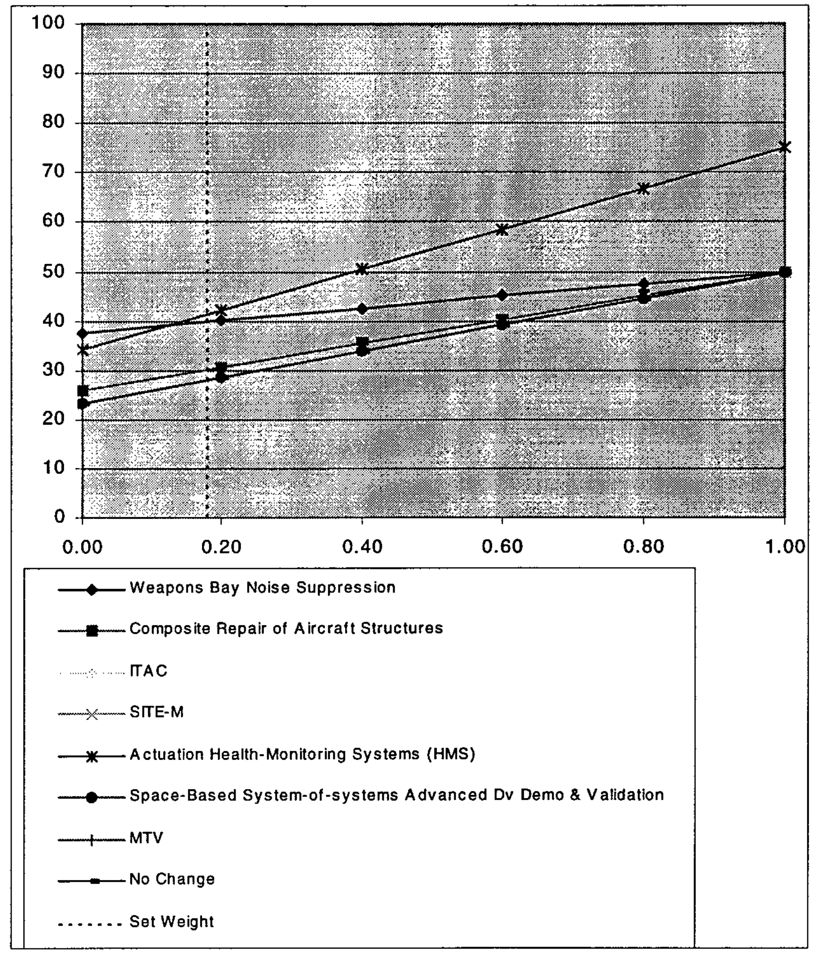
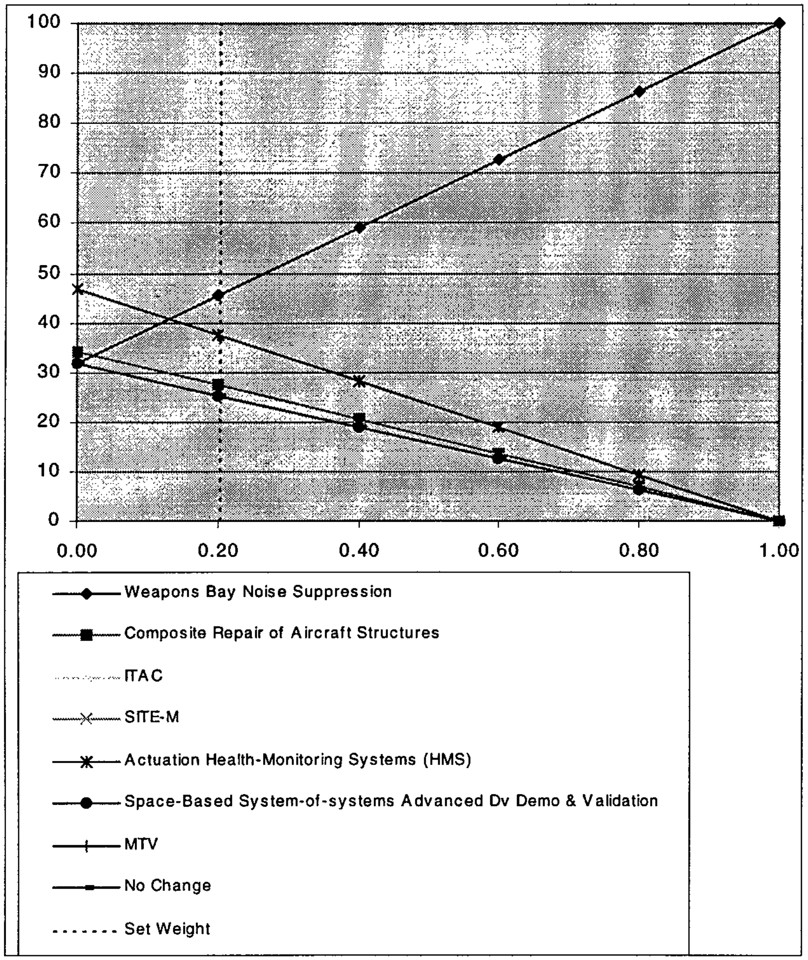


Figure 80: Sensitivity of Missions Enabled (Left) and Regeneration (Right) under Reach under Sustain



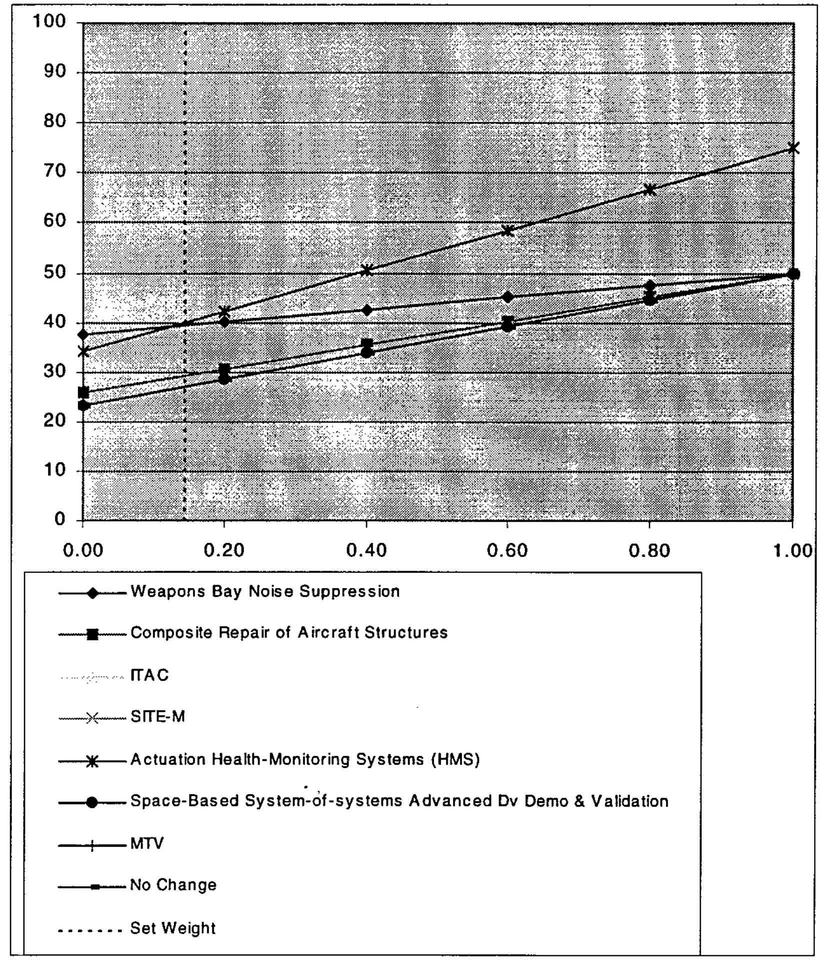


Figure 81: Sensitivity of Safety (Left) and Weight Reduction (Right) under Sustain under Reach

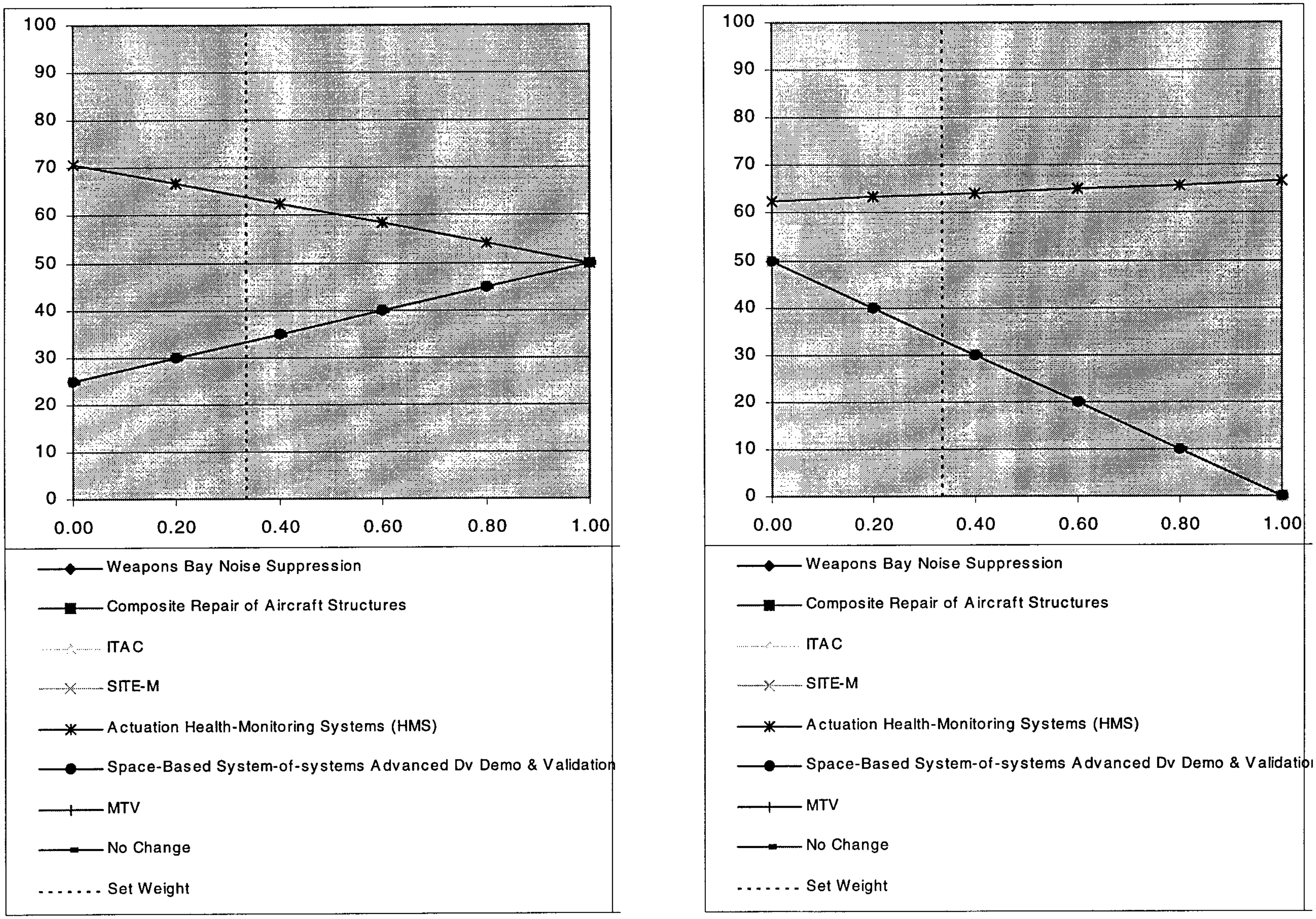


Figure 82: Sensitivity of Availability (Left) and Missions Enabled (Right) under Awareness under Gain

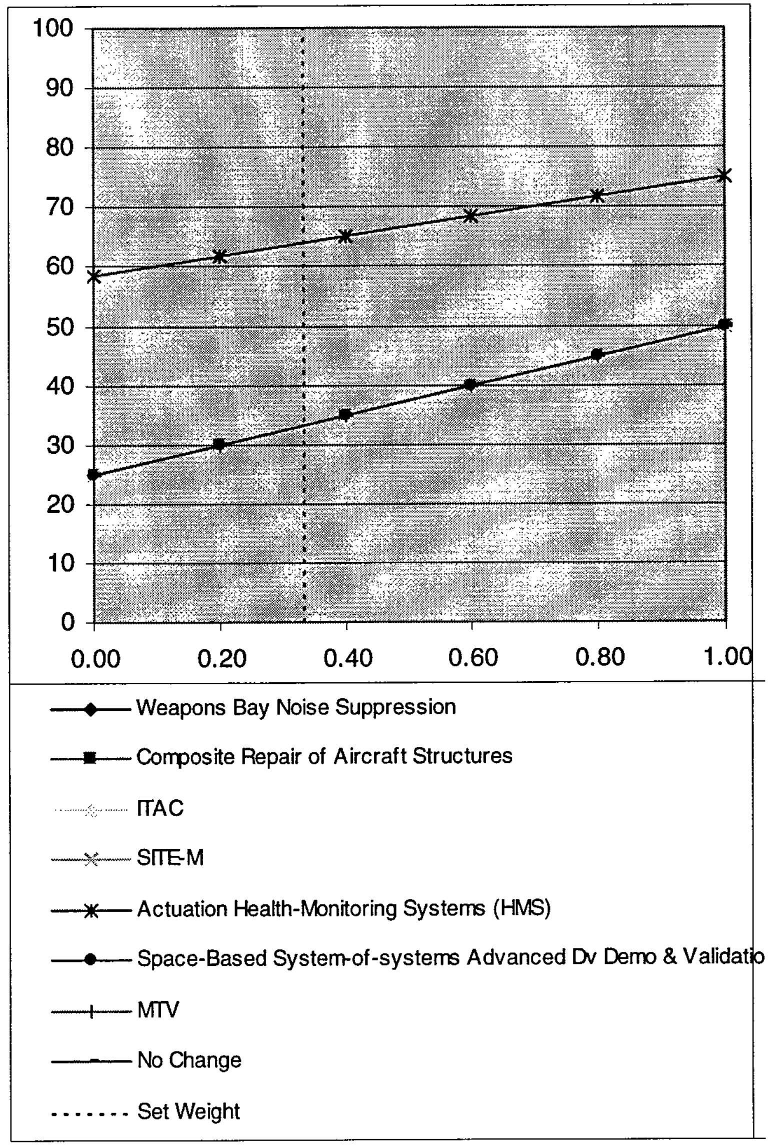
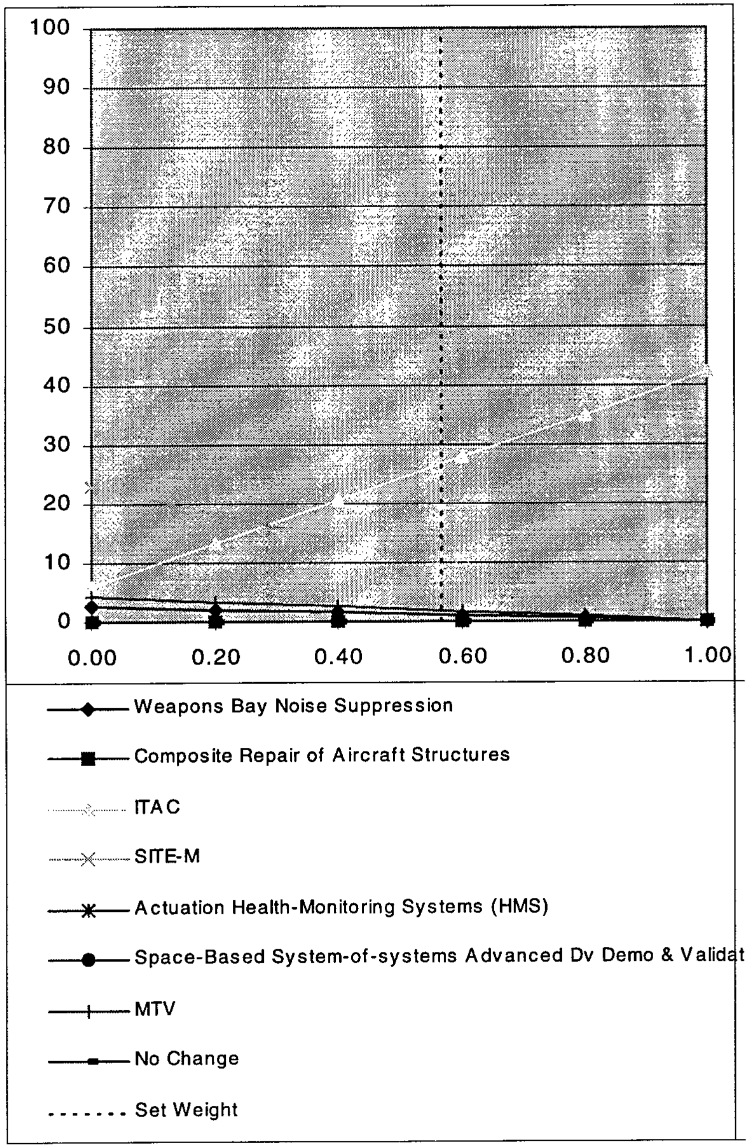


Figure 83: Sensitivity of Regeneration under Awareness under Gain



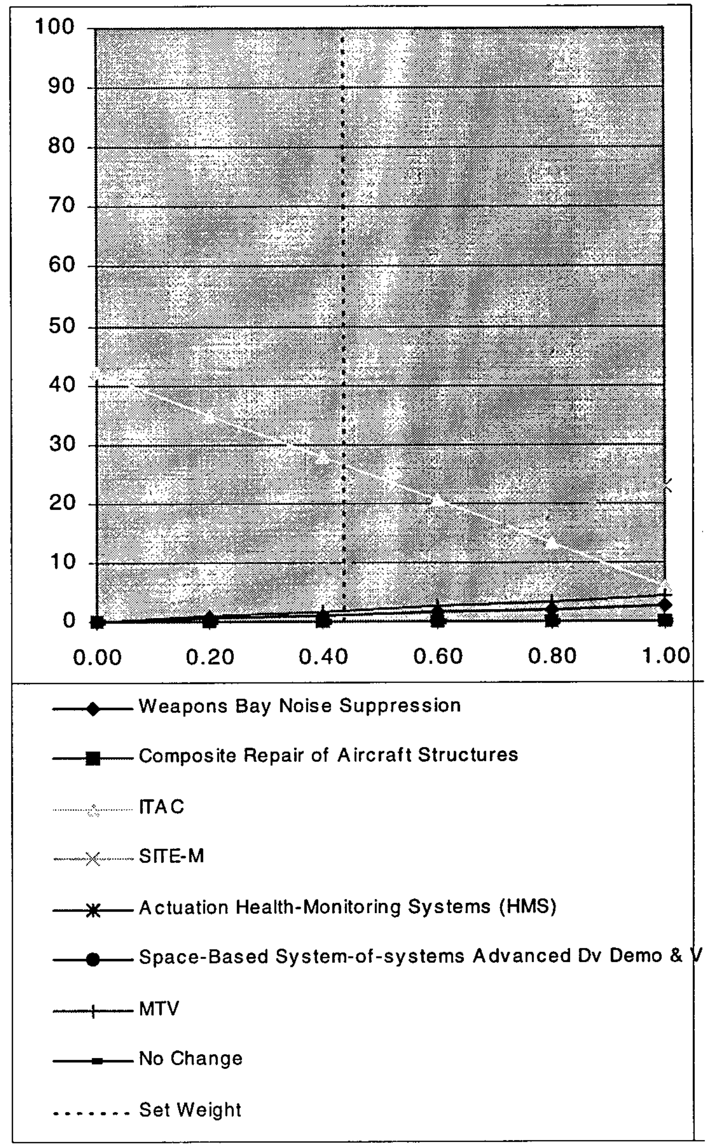


Figure 84: Sensitivity of Effectiveness (Right) and Survival (Left) under Power under Lethality

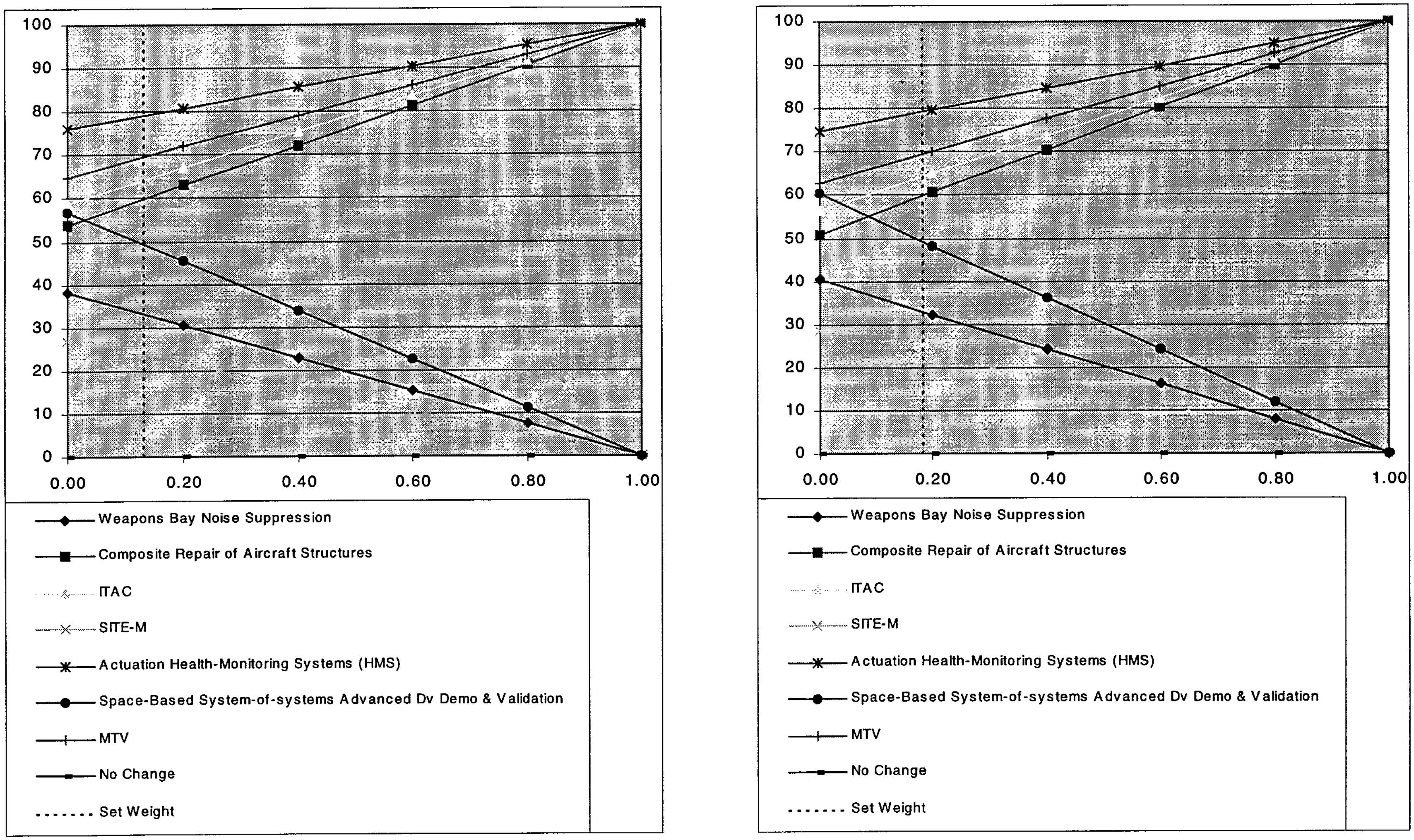


Figure 85: Sensitivity of Dual Use (Left) and Intermediate Products (Right) under Technological Superiority under Be Efficient

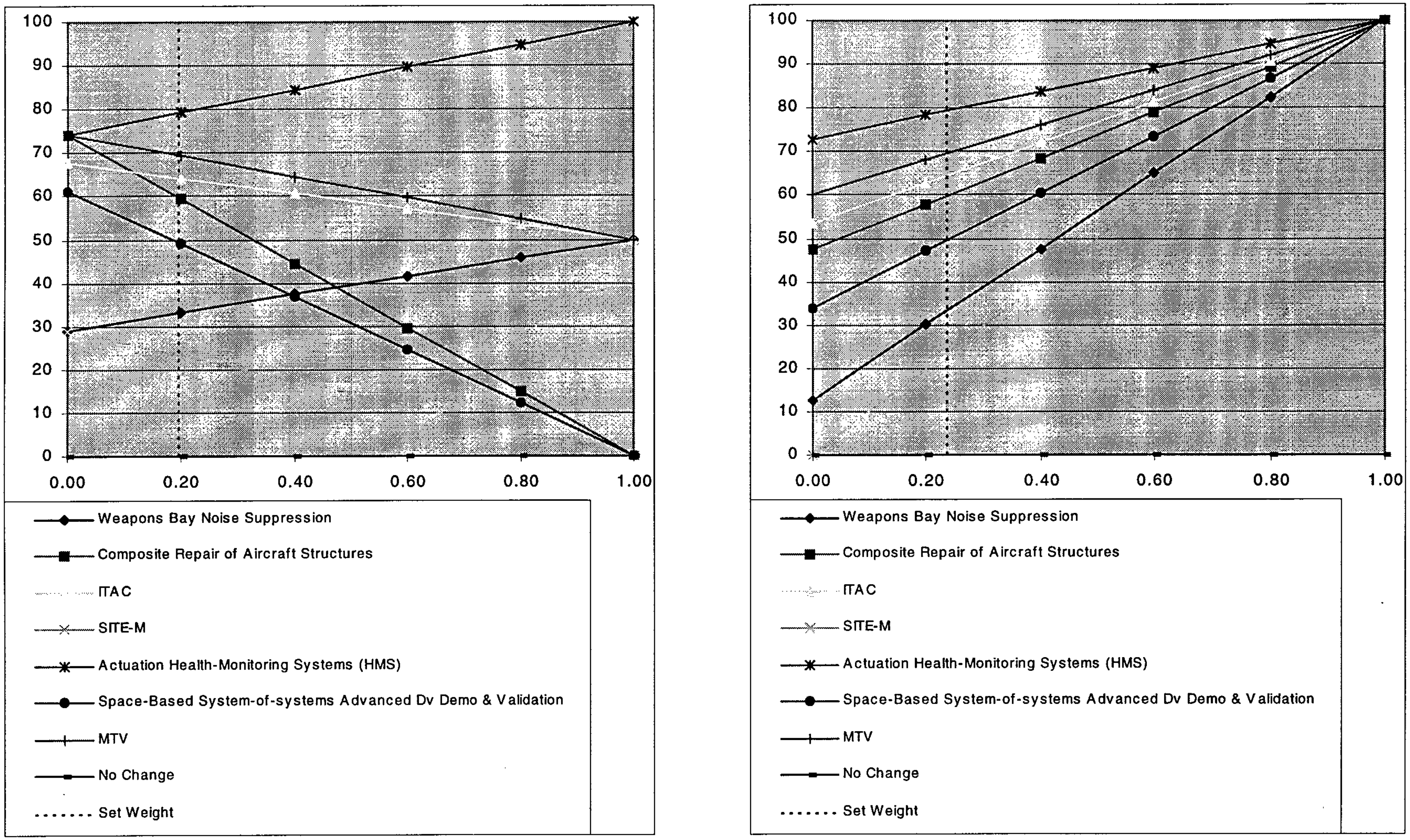


Figure 86: Sensitivity of Multiuse (Left) and Uniqueness (Right) under Technological Superiority under Be Efficient

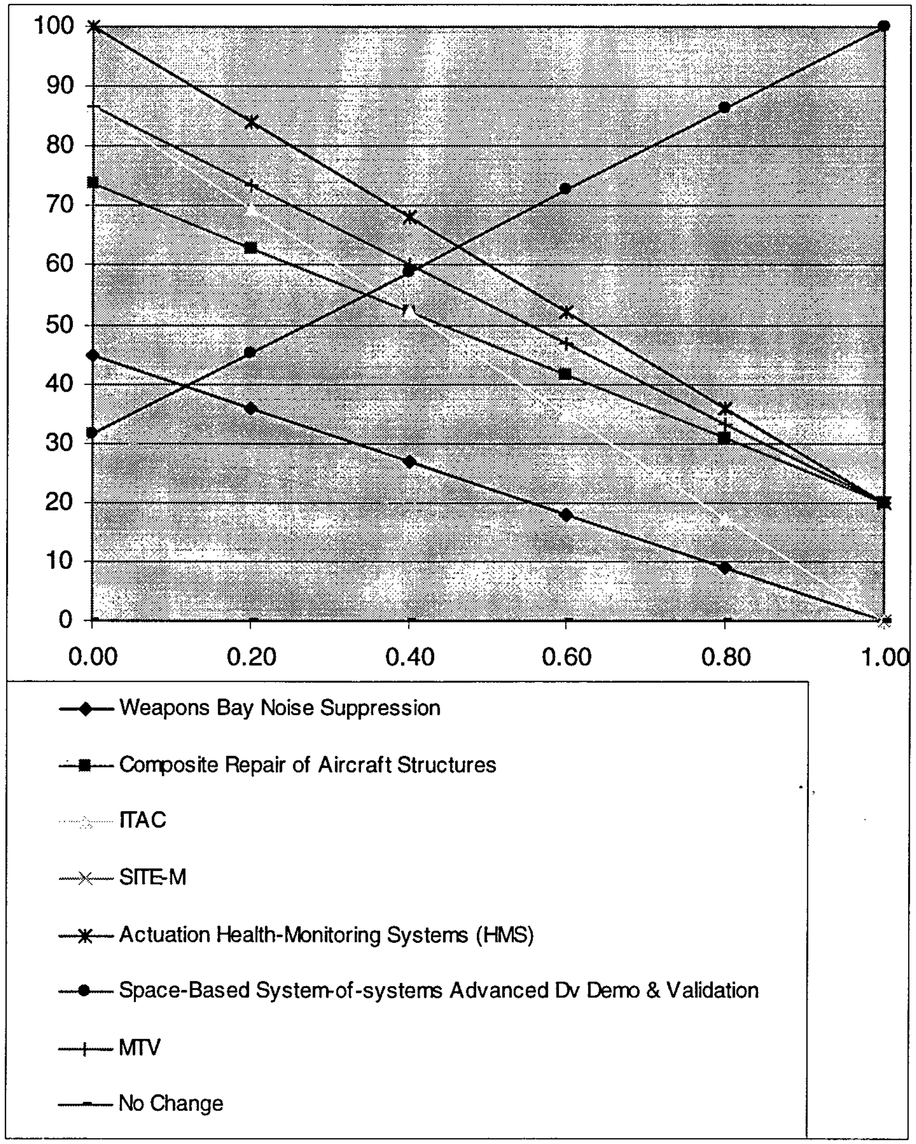


Figure 87: Sensitivity of User Rating under Technological Superiority under Be Efficient

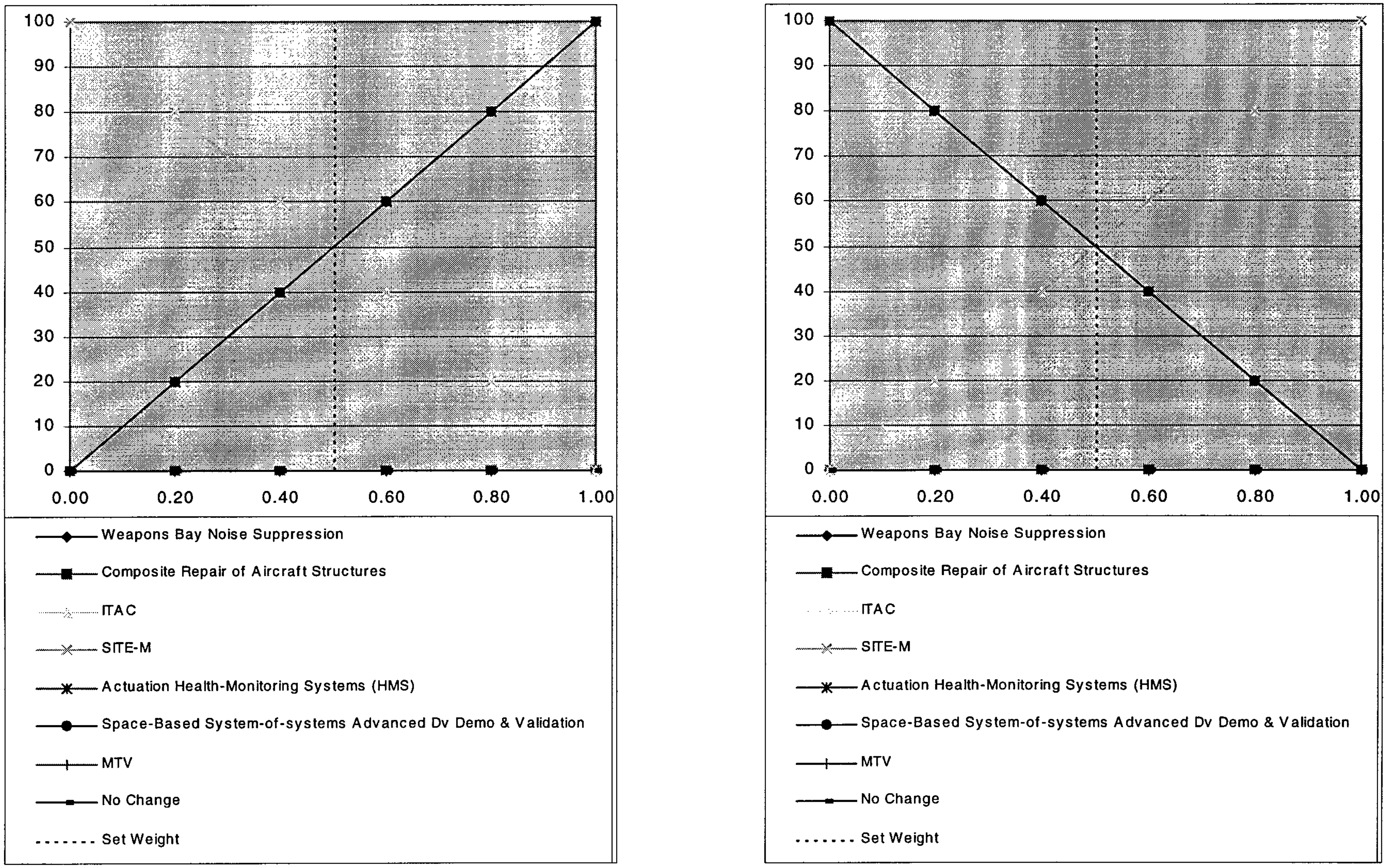
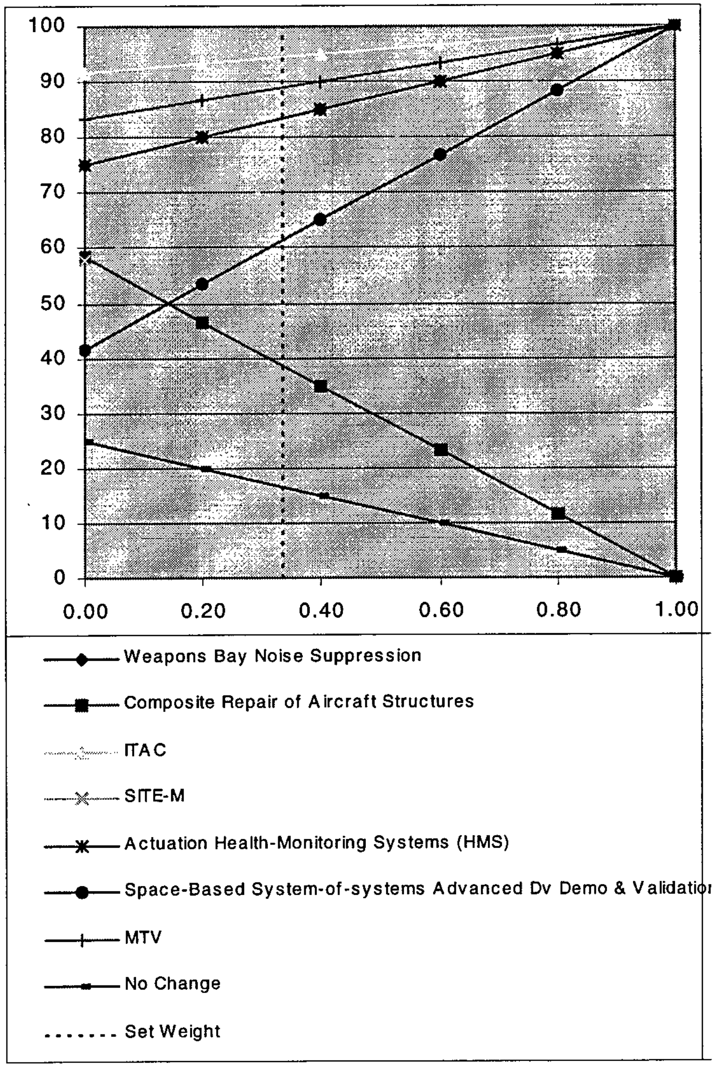


Figure 88: Sensitivity of Revolutionary (Left) and New Warfighting Spectrum (Right) under Technological Superiority under Expand our Frontier



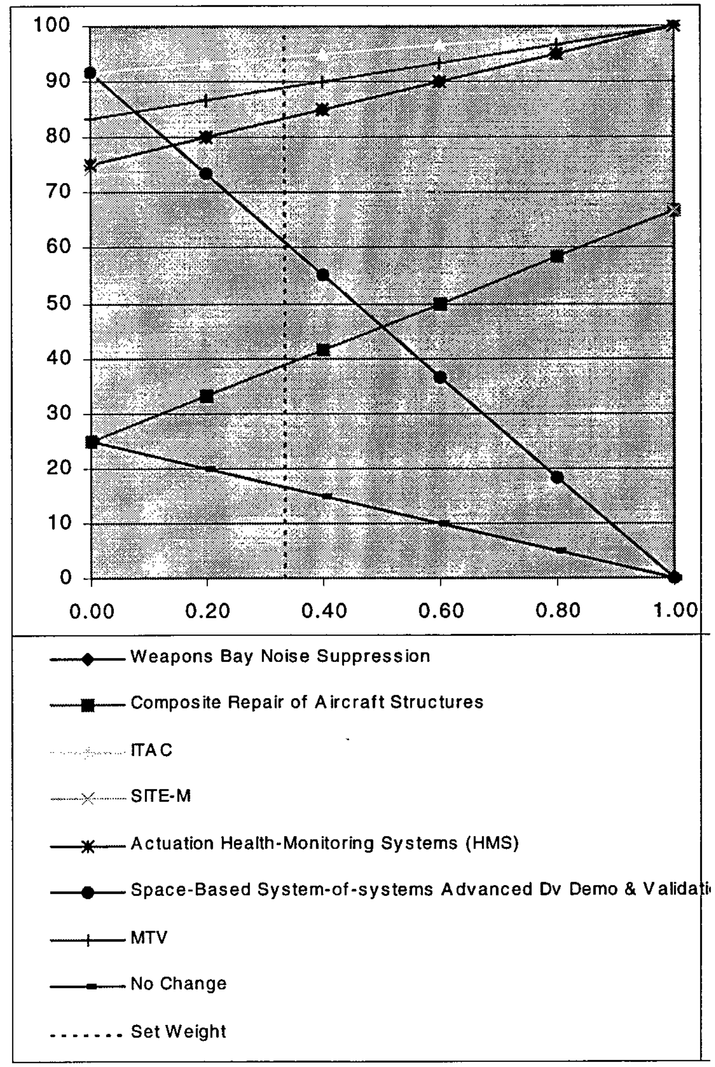


Figure 89: Sensitivity of Enables (Left) and Interoperability (Right) under Technological Superiority under Simplify Operations

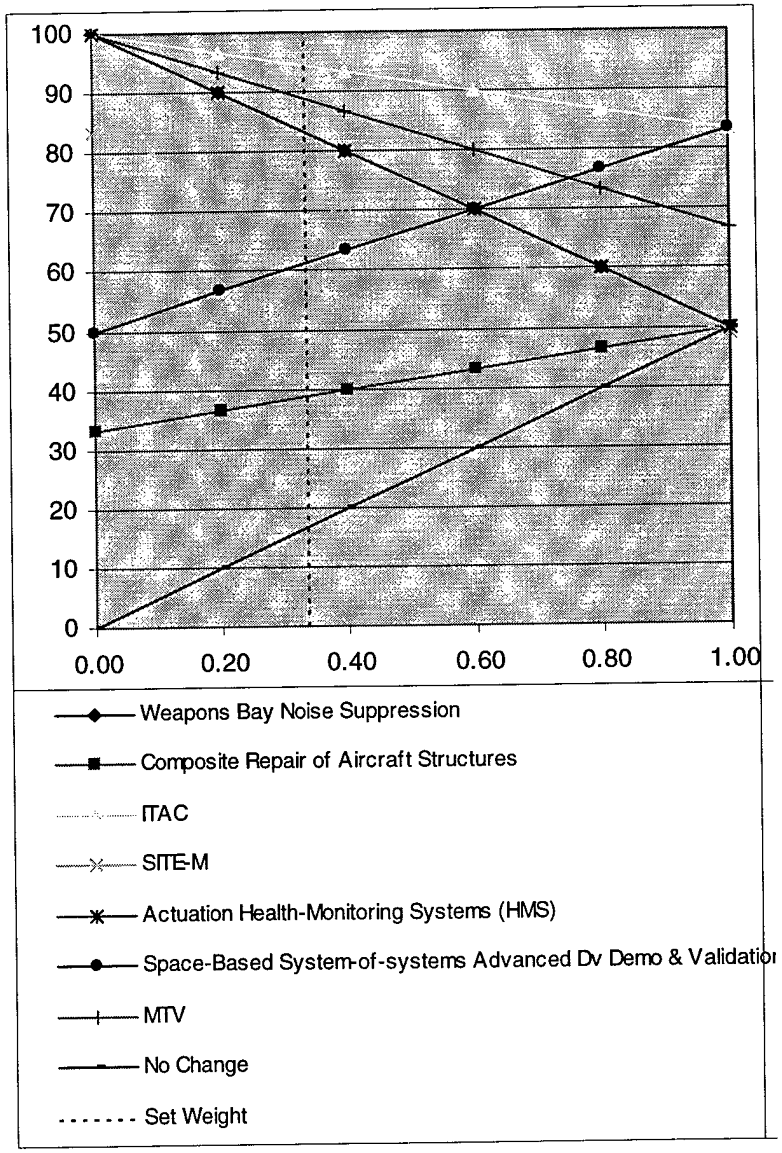


Figure 90: Sensitivity of Ratio of People under Technological Superiority under Simplify Operations

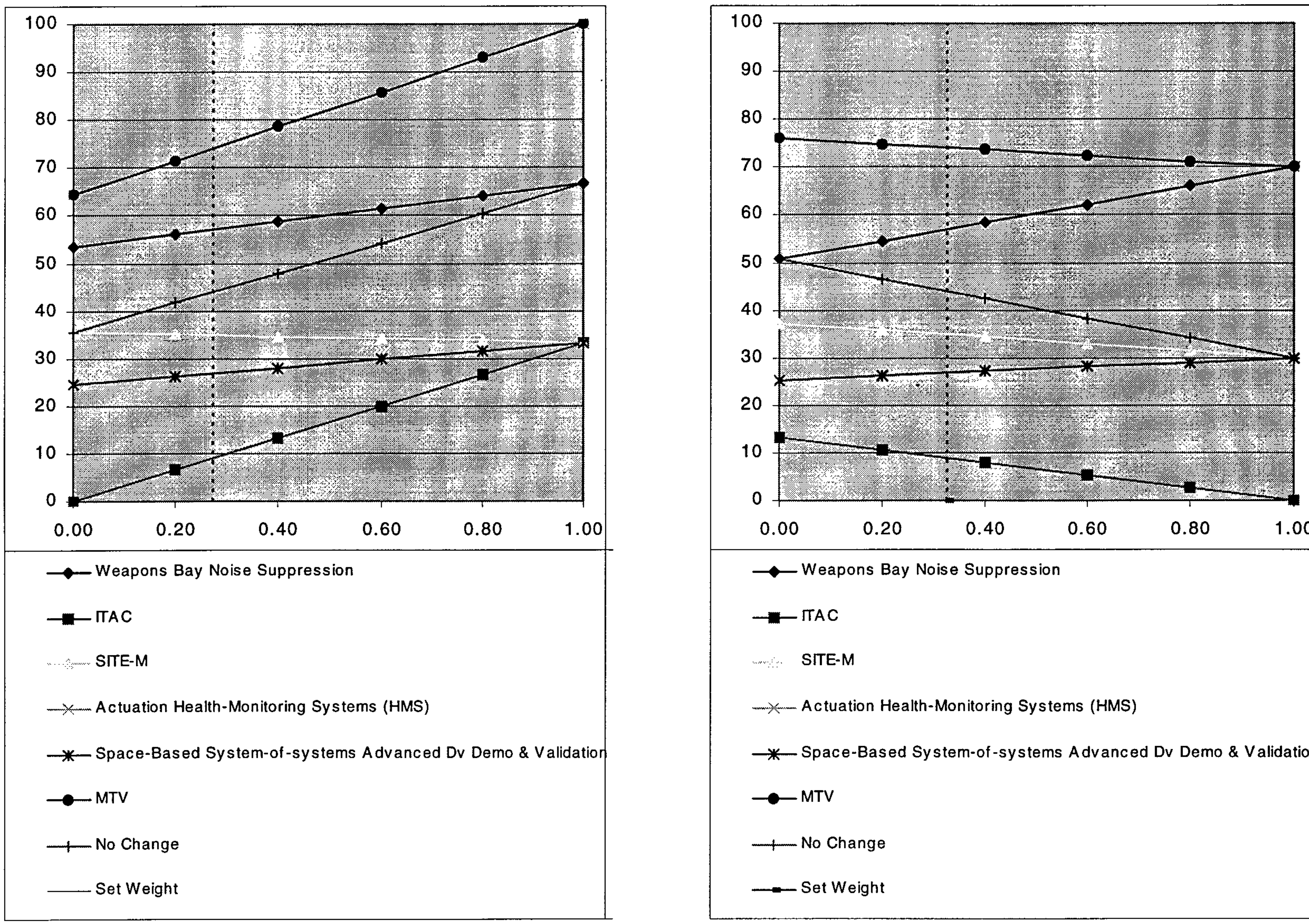


Figure 91: Sensitivity of Cost to Adversary (Left) and Lead (Right) under Technological Superiority under Win

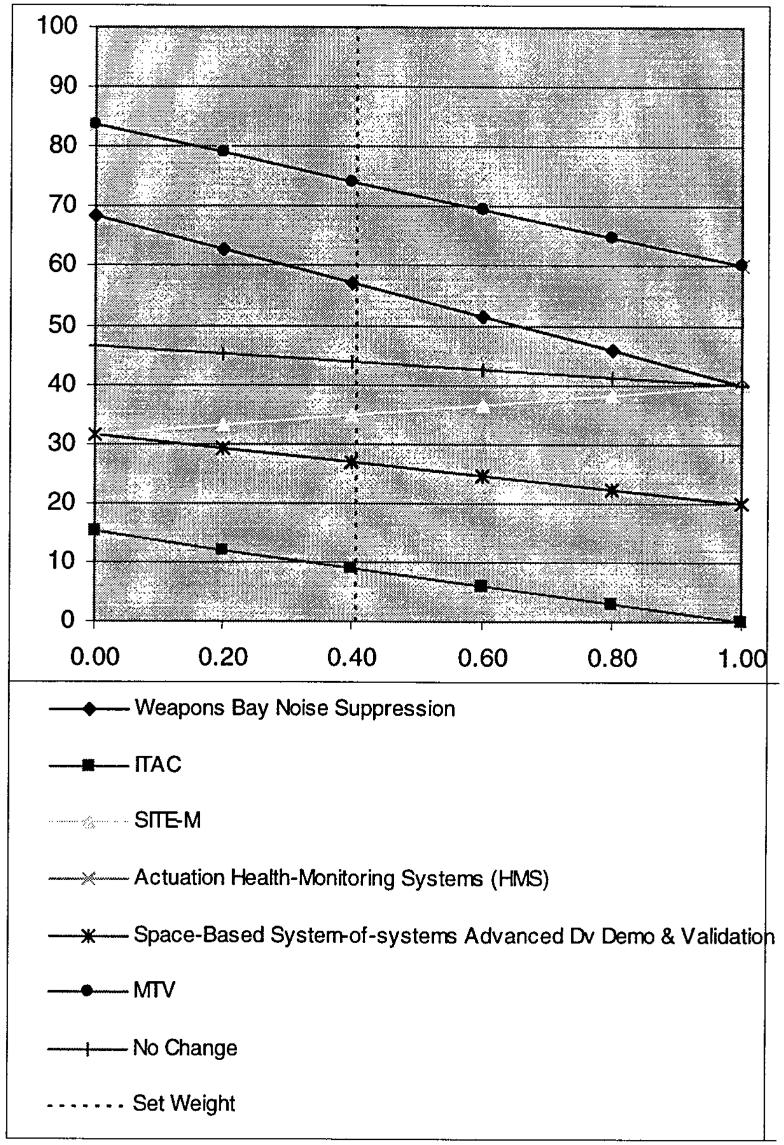


Figure 92: Sensitivity of Warfare Advantage under Technological Superiority under Win

Appendix K: Intensity of Change in Warfighter Support due to Technology

Intuitively, the change in warfighter technological intensity has a simple R&D interpretation. It is based on the idea that R&D should always improve over the current deployed state of the art. It is illogical to accomplish R&D to achieve the current existing deployed state of the art or to improve to some level below the current existing deployed state of the art. Therefore, the change in warfighter technological intensity is always a positive value, indicating an improvement in the deployed state of the art for technology.

At first, it was thought this parameter would be measured on a ratio scale, since the change in warfighter technological support is on a ratio scale and cost is also on a ratio scale. However, the parameter is not measured on a common ratio scale because for each program, change in warfighter technological support is divided by a different cost. This fails the allowable transformations for a ratio scale, which is multiplication by a scalar (Luce, Bush and Galanter, 1963: 8-13). The parameter would be only be on a ratio scale if change in warfighter technological support was divided by the same cost for every program.

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Vita

Capt Winthrop was born on 13 Apr 1967 at Tinker AFB, Oklahoma. He earned a Bachelor of Science in Astronautical Engineering from the USAF Academy in Colorado Springs, CO in 1989. On 23 Mar 1999, he earned a Masters of Science in Operations Research from the Air Force Institute of Technology.

From 1989-1993 he served as an Astronautical Engineer at Phillips Lab, Edwards AFB. He worked three major programs: the XLR-132 (an experimental upperstage rocket engine), lead development of a new test facility for testing hydrostatic bearings in rocket engine turbopumps, and worked to find new less toxic propellants for existing rockets.

In March 1994, Capt Michael F. Winthrop began working as a Wing Future Systems Planning Manager for 30th Space Wing, Program Requirements group at Vandenberg AFB, CA. The branch is responsible for working with new programs and marketing capabilities of Vandenberg AFB. Major programs Capt Winthrop was in charge of planning included the Airborne Laser Program and Evolved Expendable Launch Vehicle.

In Aug 1998, Capt Winthrop was accepted into the Master's program at the Air Force Institute of Technology. Capt Winthrop and his wife Barbara have two children, Phillip and Kaitlyn.

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13. ABSTRACT *(Maximum 200 words)*

A technology selection model was developed for the Air Vehicles Directorate of Air Force Research Laboratory. The model was developed and demonstrated to aid in addressing the question of what technologies Air Vehicles' should invest in to remain consistent with Air Force values. Both Value-Focused Thinking and optimization approaches were used to identify the value of Air Vehicles' technology, to provide insights to Air Vehicles' decision-makers, to determine where value gaps might exist with the scored alternatives, and to determine how sensitive the model was to changes. As a demonstration of the approach, seven technologies were scored, representing all three of the Air Vehicles' Integrated Concepts. In the process, the support to the warfighter due to technological change was quantified and analyzed.

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