ASSESSING STRUCTURAL HEALTH MONITORING ALTERNATIVES UTILIZING A VALUE FOCUSED THINKING MODEL

THESIS

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AFIT/GSE/ENV/09-M04

Abstract

Current Air Force operations are undergoing significant changes necessitated by increasing fiscal constraints, increasing aircraft age, and recent drawdown in personnel to perform maintenance, repair, and other necessary functions. In order to deal with these challenges, the Air Force must effectively improve current operations. This paper explores potential structural health monitoring (SHM) solutions to some of the challenges facing aircraft maintenance and repair operations. As with any problem, a variety of solutions exist and this paper explores the potential solutions and limitations of various options. Aircraft SHM is an intriguing concept with potential capability to revolutionize current Air Force maintenance operations. However, this capability needs to be balanced with the total life cycle cost associated with training personnel, and with developing, integrating, maintaining, and disposing of the SHM system. This thesis develops and implements a value-focused thinking model as a decision-making tool to analyze several potential solutions to SHM problems.

Acknowledgments

We would like to express our sincere appreciation to our faculty advisors, Dr. Som Soni and Dr. Joseph Carl, for their brilliant and insightful guidance and steadfast support throughout the course of this thesis effort. We would also like to thank Dr. James Blackshire from the Air Force Research Laboratory Materials and Manufacturing Directorate for sharing his knowledge and providing suggestions for our research effort. In addition, we would like to thank Dr. Mark Thomsen from Hill Air Force Base for providing us with tremendous insight to the challenges faced daily by the engineers and maintenance personnel responsible for keeping Air Force jets flying. Finally we would also like to recognize Dr. Jeffrey Weir from AFIT for the knowledge and direction he provided in the development of the value model presented in this research.

- Maj Marti Barker, Maj Jeremy Schroeder, 1Lt Fatih Gurbuz

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List of Abbreviations

ACC – Air Combat Command
AE – Acoustic Emission
AF – Air Force
AFIT – Air Force Institute of Technology
AFRL – Air Force Research Laboratory
AFSO21 – Air Force Smart Operations for the 21st Century
ALC – Air Logistics Center
ASIP – Aircraft Structural Integrity Program
CBM+ – Condition Based Maintenance Plus
CJCS – Chairman of the Joint Chiefs of Staff
COTS – Commercial Off-the-Shelf
D&SWS – Develop and Sustain Warfighting Systems
DA - Decision Analysis
DAU – Defense Acquisition University
DMAG – Depot Maintenance Activity Group
DoD – Department of Defense
DoDD – Department of Defense Directive
DOTMLPF - Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel and Facilities
EC – Eddy Current
FAA – Functional Area Analysis
FBG – Fiber Bragg Grating
FNA – Functional Needs Analysis
FO – Fiber Optics
FSA – Functional Solution Analysis
GAO – Government Accounting Office
HVM – High Velocity Maintenance
IAT – Individual Aircraft Tracking
ISHM – Integrated Structural Health Monitoring
ISHMS – Integrated Structural Health Monitoring System
JOC – Joint Operating Concept
MCO – Major Combat Operations
PDM – Programmed Depot Maintenance
RUL – Remaining Useful Life
SHM – Structural Health Monitoring
TRL – Technology Readiness Level
USAF – United States Air Force
TuAF – Turkish Air Force

ASSESSING STRUCTURAL HEALTH MONITORING ALTERNATIVES UTILIZING A VALUE FOCUSED THINKING MODEL

I. Introduction

1.1 Problem Statement and Objective

The United States Air Force needs to reduce Operations and Maintenance (O&M) costs by improving the efficiency of current maintenance operations. Implementing a Condition-Based Maintenance (CBM) concept may dramatically decrease maintenance costs and aircraft downtimes while maintaining or improving fleet safety. Enabling technologies, such as an Integrated Structural Health Monitoring System (ISHMS), must be developed to make the CBM model a reality. Structural Health Monitoring (SHM) is a key aspect of the CBM & ISHMS constructs as it increases the users' awareness of the aircraft structural integrity. Maintenance and logistic planners can make better use of limited resources by better understanding the current structural state of the aircraft. This thesis explores several options for implementing SHM and presents a value model to determine what measures offer the greatest opportunity and "bang for the buck" toward achieving CBM operations.

1.2 Research Approach and Methods

1.2.0 Introduction.

Generally speaking, the authors took a broad, holistic, systems approach to determine how an ISHMS could be implemented. This section details (in nearly chronological order) the research methods used to come up with the notional value model presented in Chapter 5, as well as the conclusions outlined in Chapter 6.

1.2.1 Literature Review.

1.2.1.1. Articles and Presentations.

The research and discovery journey traversed throughout this study began with a review of numerous articles and presentations on CBM and SHM. The list of references (pg 82) included herein is only a fraction of the material that was combed through to learn about the genesis and evolution of these topics and to gain a deeper understanding of the benefits and challenges they present. Much has been written and published on both concepts over the last 15-20 years that can be easily found via open-source media.

Fairly early in the study, the authors attended the ISHM Symposium to learn more about the latest research and development in health monitoring technologies. Sponsored by the AFRL's Air Vehicle Directorate, this forum revealed the wide range of application of system health monitoring concepts and technologies. From the automotive and aerospace industries to civil engineering, presenters demonstrated how health monitoring is being used across disciplines and domains to cut costs and improve customer service and safety. This forum reinforced the authors' impression that a wealth of research is being done in this area, making it quite difficult to narrow the team's focus for this project.

A bit later, fortunately, Dr. Jim Blackshire, a researcher at the Air Force Research Lab's (AFRL) Materials Directorate, shared a cache of literature on sensor technologies being evaluated for SHM application. The repository of articles, book chapters, and presentations he disclosed helped piece together a clearer picture of the current state of SHM technologies. Dr. Blackshire's mini-library covered results of several recent sensor tests and his own soon-to-be-published comparative analysis. Much of the discussion presented in Chapter 4 is based on the information he so graciously provided.

1.2.1.2 Previous Thesis.

In addition to a thorough survey of open source literature, theses written by former AFIT students were studied and revealed a surprisingly narrow focus on sensor technology as the preferred solution to accomplishing SHM. In their 2006 work, Albert *et al*., suggested a SHM system "could consist of a set of sensors installed on the components or the aircraft structure" [1:26]. In 2007, Bond *et al*. said, "An important part of an ISHM solution is the sensor selection, and from the various technologies currently available the group was guided towards methods using Lamb waves. The specific technology that the group was guided to use was the *M*onitoring and *E*valuation *T*echnology *I*ntegration *S*ystem (METIS) sensor" [3:4]. In addition to these two studies, Underwood emphasizes that "an embedded SHM system installed at the bulkhead location of the known fatigue cracks would prevent the lengthy inspection times, increasing the readiness of the aircraft and reporting the structural health of the aircraft" [5:1]. Each of the aforementioned theses is summarized for background purposes in Chapter 2.

1.2.2 Broad, Holistic Systems Perspective.

The authors of this thesis discussed the previous focus on sensors and known associated challenges with implementing a system that relies almost exclusively on this technology. During this discussion the question of "What other technologies or processes can/could be used to gain insight into the structural state of the aircraft?" was raised. In other words, if sensors are too costly and difficult to implement on the legacy fleet, what other options are available now—or could be available in a relatively short period of time—that would help maintenance personnel and engineers ensure the structural integrity of the aircraft.

By taking a broader, holistic perspective to achieving an enhanced SHM capability, the authors were able to come up with a wide range of promising alternatives in addition to, or perhaps even in lieu of, sensors. Options from various levels of technical complexity emerged. For example, the flight data that is already being collected, such as the information captured on the flight data recorder (also commonly referred to as "the black box"), could be merged with accurate, detailed maintenance records and post-flight debrief and operational environment reports. This multi-sourced, fused data set could then be fed into tail-number specific diagnostic and prognostic models that ideally would be robust enough to be trusted and relied upon for predicting when a critical failure will occur. This Information Management and Modeling (IM&M) concept would allow continued operation until the model(s) determines unscheduled maintenance on a particular tail-number is necessary to prevent unacceptable damage, in essence fully enabling a CBM concept.

At the other end of the technical complexity spectrum is an improved training program incorporated into current maintenance operations. Essentially SHM would be accomplished in the same manner it currently is but would be streamlined and carried out by technicians who are fully aware of the ramifications of improper maintenance actions—ramifications that include costs and downtime metrics related to scrap and rework due to personnel-induced damage. This effort would simply place a renewed emphasis on best practices for avoiding damage induced during routine maintenance and inspection teardown. Obviously, this option is less sophisticated and as such less expensive than the IM&M alternative but would likely produce far less dramatic cost savings and asset availability benefits not to mention its failure to meet the tenets of CBM.

In Dr. Carl's first lesson of AFIT's Introduction to Systems Engineering Processes and Design course he presented systems engineering as

> "… an interdisciplinary approach encompassing all … efforts needed to evolve, verify, deploy (or field), and support an integrated and life-cycle balanced set of … solutions that satisfy customer needs" [30].

In concert with this and other similar definitions, and as budding systems engineers, the authors quickly surmised that the optimal solution likely involves a system that integrates, in part or in whole, all the proposed alternatives (and perhaps even others yet to be considered.)

1.2.3 Interviews with Stakeholders.

To ensure this new integrated approach is feasible and acceptable to real-world stakeholders, the authors visited with *A*ircraft *S*tructural *I*ntegrity *P*rogram (ASIP) managers and other engineers at the Warner-Robins Air Logistics Center at Robins Air Force Base, GA. Their feedback reinforced the hypothesis that an ISHMS does not necessarily have to be based on a sensor technology solution, especially when faced with the unique challenges of installing a suite of sensors on the legacy fleet. As a matter of fact, one High-Velocity Maintenance engineer expressed his hope that a laptop-based IM&M concept would someday be implemented across the fleet. This capability has already been demonstrated on a limited scale by researchers at the Mercer Engineering and Research Center (MERC) near Robins, GA. Ideally, detailed records of tail-number specific maintenance actions, the operational environment, pilot post-flight debriefs, black box data, etc. would be entered and stored on a single laptop computer that stays with each individual aircraft as it flies to various locations in and out of the theater(s) of operation. All this data would be collated to refine the finite element analysis model of the aircraft structure, as well as diagnostic and prognostic models of other subsystems and components. The models would be automatically updated as new information is input and then maintained on that same laptop so that personnel at any given destination can easily access relevant analysis and records for the aircraft of interest, thereby radically streamlining the current data collection, analysis, and modeling process.

In addition to gaining confidence in the theory that an ISHMS ultimately will need to be an integrated system that may or may not include sensors, the authors also gained a richer appreciation for how labor-intensive and time-consuming some of the current usage-based inspections are. After touring the C-130 depot maintenance facility and seeing first-hand some of the problem areas that are driving up O&M costs and aircraft downtimes, the team is convinced that current SHM operations is incredibly inefficient. Indeed, a better way of accomplishing this desperately needed capability must be developed and employed. More on the need for more efficient SHM operations is presented later in Chapter 3, and a specific C-130 trouble spot example is detailed in Chapter 5.

Finally, while in the area, the authors took advantage of the opportunity to observe an ongoing sensor comparison test at the Mercer Engineering Research Center (MERC). This highlighted how extensive the interest in and research into a sensor-based SHM capability currently is. In fact, the observed test set up was being used for three separate research entities—one commercial company, one government laboratory, and the MERC itself—all conducting studies related to SHM sensor technologies.

1.2.4 VFT and Value Modeling.

The research team soon realized that choosing the best SHM alternative for a given area was highly dependent on the scenario in question. In particular, the best/right mix depends on the time required to tear-down for a given inspection location and how often the area needs to be inspected.

Therefore, the authors then met with Dr. Jeffrey Weir, an associate professor at AFIT who teaches decision analysis (DA) courses in the Operations Research department. Dr. Weir passed on his expertise on the latest tools and techniques being used in the growing field of DA. Dr. Weir was generous enough to share with the authors a model-building tool that he developed based on value-focused thinking (VFT) principles. The value model described herein enables systems engineers to take a holistic, integrated approach to ISHMS implementation by revealing which alternative(s) most satisfies the customers' needs based on what the stakeholders identify as being "valuable" in an ISHMS. More details about VFT and the value model built for this study are presented later in Chapter 5.

1.2.5 More Interviews with Stakeholders.

Once the value model was built, the authors again sought feedback from key stakeholders. The model was demonstrated to ASIP Managers, engineers, and equipment specialists at Ogden Air Logistics Center at Hill Air Force Base, UT. Their input on factors that they value in an ISHMS and the appropriate weighting of those factors were incorporated into the model.

Perhaps more important than the model feedback obtained from the folks at Ogden is the enlightening insight on the political environment they conveyed. In particular, they described the sensitivity surrounding the Service Life Extension Program (SLEP) and related topics. In some legacy platform communities, assessments of the feasibility/possibility of stretching out the SLEP for aircraft set for retirement has become a very unpopular and taboo topic of discussion. Such evaluations could produce results that may undercut the rationale for recapitalization of the fleet. And because SHM of legacy aircraft and any enabling technologies such as the proposed ISHMS are viewed as measures that provide greater long-term cost saving benefits, proponents of recapitalization fear that investing in these technologies may send the wrong signal to senior leaders and Congressional staffers.

1.2.6 Intelligent Maintenance Systems Center Annual Board Meeting.

The Intelligent Maintenance Systems (IMS) Center held its annual board meeting in Dec 2008 and invited the authors to attend. The IMS Center is a consortium of academic institutions and industry partners interested in, as the name implies, maintaining systems wisely. This notion echoes the Air Force Smart Operations for the 21st Century (AFSO21) mantra: "work smarter—not harder." During the annual meeting, student researchers and industry experts present new models for optimizing operation and maintenance systems used across a wide range of business domains. International representatives from the manufacturing and production industry as well as dynamic operating systems, like a European high-speed railway system, demonstrated how they are taking advantage of cutting edge technologies and robust modeling techniques to operate more efficiently—cutting costs, boosting productivity, and improving customer service.

The most surprising and alarming take-away from this diverse forum was the lack of US government representation. Despite being hosted in Cincinnati, Ohio, representatives from foreign companies along with international exchange students participating in the IMS Center's intern program comprised roughly half of the attendees. Almost no one representing the US government (with exception of one other Air Force person and the authors of this study) attended this eye-opening conference.

1.3 Outline of Thesis Content

The remainder of this thesis first introduces some background on the SHM studies conducted to date by other systems engineering students at AFIT in Chapter 2. This background lays the foundation for the capability needs analysis presented in Chapter 3. Then, the current state of certain relevant technologies and processes that could be employed to better satisfy the capability need is discussed in Chapter 4. Next, a notional value model that assesses how well these alternatives meet stakeholder needs is described in detail in Chapter 5. And finally, the authors' conclusions and recommendations based on the research conducted throughout the study are presented in Chapter 6.

II. Background

2.1 History of SHM

Aircraft structural health monitoring has been around since the advent of flight. In its infancy, structural health monitoring was performed by visual inspection of various aircraft parts. Maintenance personnel would inspect parts for damage and replace them if the damage was perceived to be significant enough to pose a threat to the aircraft. This visual only inspection method quickly became a limiting factor as aircraft design advanced and structural material changed to various metals. These changes necessitated advances in inspection technology in order to inspect aircraft parts and determine if flaws existed at levels beyond which the human eye could detect. Non-destructive inspection (NDI) instruments and techniques began to emerge which provided a capability for engineers and maintenance personnel to assess the aircraft structural state. Many of the NDI techniques (eddy current, ultra sonic, x-ray, etc...) developed over the past decades are still utilized today to inspect aircraft structures.

The current inspection techniques have proved to be reasonably reliable and accurate; however, they are extremely labor intensive and require a highly trained operator to perform the inspection. The escalating costs associated with manual inspections have forced the aircraft community to develop alternative methods of inspection that are more cost effective. It is this recent shift in focus that has led to a vast increase in the research and development of alternative SHM methods. As of today, extensive research and development efforts are being performed to develop sensors, prognostic models, and various other approaches to more cost effectively address structural health monitoring concerns.

2.2 Previous Thesis

2.2.1 March 2006 Thesis Summary.

In 2006, a group of AFIT Systems Engineering students responded to a request by the Office of the Undersecretary of the Air Force for International Affairs (SAF/IA) to "develop a systems engineering (SE) approach for an Integrated Structural Health Monitoring system (ISHMS) for Coalition Air Force aging aircraft." Their research and analysis produced a "generic SE process to describe the system definition for an ISHMS installed on a non-specific aging aircraft." The scope of the system definition was limited to the system level definition of the ISHMS design problem and the functional system architecture and stopped short of addressing physical architecture and system design, which would be highly platform-dependent. The study also used mathematical simulations to compare the failure rate and number of inspections required for scenarios *with* an ISHMS vs. *without* an ISHMS. The simulations revealed promising flight safety and maintenance cost benefits. [1]

The students also drafted user requirements based on two key assumptions:

1. A cost-benefit analysis would demonstrate that an ISHMS could reduce maintenance costs enough to warrant investing in the development, design, and fielding of the system.

2. An ISHMS would be used primarily to detect structural damage by monitoring crack growth.

This thesis addresses the latter of these assumptions. Chapter 5 details a value model based on input from subject matter experts within the user community, illustrating how users would/should in fact employ an ISHMS for a number of specified structural locations.

2.2.2 March 2007 Thesis Summary.

Two thesis projects were completed in 2007 on the topic of ISHM. Captain Jeffrey Crider's work [2] examined the ability to detect simulated cracks in a representative aircraft structure using piezoelectric transducers. A second thesis completed by Matthew Bond, Captain James Rodriguez, and 1Lt Hieu Nguyen [3] expanded on a previous ISHM thesis by attempting to apply systems engineering principles to develop an ISHM system for any generic aircraft.

Captain Jeffrey Crider completed a thesis in 2007 in which he examined the use of Lamb waves to detect cracks in both aluminum flat plates and a simulated F-15 bulkhead. Captain Crider's work was based on the theory that crack detection is possible by exciting a material with electromagnetic energy (Lamb wave) and measuring the response of the material. The experiments were performed with piezoelectric sensors. The sensors examined were the M.E.T.I Disc 3 sensor and an American Piezo Ceramics (APC) 850 piezoelectric transducer.

The first tests performed examined the M.E.T.I Disk 3 sensor on a small (608 mm x 102 mm x 1.6mm) undamaged aluminum plate. This experiment served as a baseline for proving the ability to generate and measure signals and compare those signals to the theoretical predictions. Results from this experiment proved the concept, but were inconclusive due to the limited geometry of the test specimen. Due to the size of the test article, there were difficulties measuring the reflected wave from the edge boundary conditions and the original wave being propagated. The same test was then performed on a larger (1220 mm x 610 mm x 1 mm) flat-plate aluminum test article. The results from the second test proved the ability to produce, measure, and compare experimental results to theoretical predictions. This same series of tests was conducted using the APC piezoelectric transducers and also proved the ability to generate, measure, and compare experimental results to theoretical predictions.

Once the methodology was established for collecting data, Crider collected data from a realistic aircraft part. He selected an F-15 bulkhead since it was a part that had a known cracking problem in operation. Crider could not use an actual aircraft bulkhead so he had a replica made from aluminum. The test article was made with three EDM notches cut into the material to simulate the cracking observed in the operational specimen. The actual bulkhead is made of titanium, but aluminum was chosen as a suitable substitute for purposes of the experiment. Testing on the simulated bulkhead could only be conducted using the APC piezoelectric transducers because the M.E.T.I sensors would not fit in the area of the simulated crack due to their size. The M.E.T.I sensor also had the limitation of only being able to operate in a pulse-echo mode.

Crider's results showed the ability to detect the EDM "cracks" in the bulkhead test article with a reasonable amount of repeatability using the piezoelectric transducers in a pitch-catch mode. These results show promise for the ability to detect cracks in aircraft structures, but are yielded from a very controlled laboratory environment.

Matthew Bond, Captain James Rodriguez, and 1Lt Hieu Nguyen conducted research which expanded upon previous AFIT ISHM thesis work completed in 2006. They applied systems engineering principles to analyze an ISHM system and its applicability to the F-15 bulkhead crack problem which was explored by Captain Jeffrey Crider.

Bond *et al*. began by creating architecture products (OV-1 and OV-5) which examined the operational need and then completed a functional decomposition. The main focus of this effort was to explore the requirements definition and how those requirements were used to design, install, and operate an ISHM system. Once the requirements definition and analysis was completed, the group performed experiments using the M.E.T.I. Disc 3 sensor. The experiments performed were similar to those conducted by Captain Crider, but with a different sized flat plate (21" x 42" x 1/4") and different frequency for wave generation. The group used wooden blocks placed on the aluminum plate to simulate damage. Tests conducted using the M.E.T.I. sensor and large aluminum plate produced very poor results. The group was not able to get repeatable results and theorized the reason was due to several factors including the dimensions of the aluminum plate, capability limitations of the transducer, and data processing methods and algorithms. They determined that they were not able to discern their wave signal from the background noise and hence could not make any conclusion from their experiments. The group decided at this point to cease testing with their current configuration and pursue testing with the second-generation M.E.T.I. sensor. When the group resumed testing with the second-generation sensor, results were still very inconsistent. The team was able to detect flaws in the material less than 50% of the time and with extremely limited repeatability. The results were very sensitive to the test configuration and material damage.

Bond *et al*. concluded that there is a possibility for sensors to detect damage to aircraft structures, but real-world factors such as background noise, complex structural geometry, and other environmental factors will make the technology challenging.

2.2.3 March 2008 Thesis Summaries.

Captain Jason Brown and 1Lt Travis Hanson completed a thesis [4] analyzing ISHM requirements and implementation. The thesis approaches the topic from a system engineering perspective to show the need for the Integrated Structural Health Monitoring System and discusses the technical feasibility of ISHMS. Cost benefit analysis, a comparison of true cost savings based on the current inspection methodology, and the development of the data processing requirements are included. The Joint Capabilities Integration and Development System (JCIDS) was explained, and an implementation of a JCIDS process to refine the requirements of ISHM was accomplished. A detailed review of the national documents was completed to identify the required capabilities and the capability gaps were accomplished along with the Functional Area Analysis (FAA), Functional Needs Analysis (FNA), and Functional Solutions Analysis (FSA). “This thesis attempts to show the need for an Integrated Structural Health Monitoring System, identifying how it may be implemented and the expected cost savings using a Systems Engineering (SE) approach." After providing some brief information about various types of sensor systems, the thesis details how an ISHM system could notionally be implemented. They analyze sensor cost estimates from design through disposal and provide comparisons between the various sensor solutions. The thesis also includes a needs analysis for ISHM system implementation. For example, "Any system must also be rigorously analyzed and tested to ensure that no negative side-effects occur, such as electric or magnetic interference of other systems and any chemicals" and current military standards must be met to ensure compatibility and interoperability. The thesis ends recommending studies on verification of cost savings from increased availability, determination of sensor accuracy, refinement of ISHM implementation costs and determination of optimal inspection intervals.

Captain Roman Underwood completed a thesis on specific technical issues regarding SHM and potential sensor applications [5]. He stated, "If we can know when an aircraft needs to be serviced- a.k.a. condition based maintenance- as opposed to servicing at a fixed interval, we could increase aircraft readiness while decreasing sustainment costs. An embedded SHM system installed at the bulkhead locations of the known fatigue cracks would prevent the lengthy inspection times, increasing the readiness of the aircraft and reporting the structural health of the aircraft." [5:1].

A goal of Structural Health Monitoring is to increase aircraft readiness through condition based maintenance (i.e., servicing an aircraft only when it is known to be necessary). The Piezoelectric Lead Ziconate Titanate (PZT) is a commonly used sensor that has shown potential to detect damage in aircraft structures without time consuming manual inspections. However, many locations identified by the USAF for SHM have restricted geometries, presenting difficulties using the PZT sensors. One known fatigue location in an aircraft bulkhead has been selected as a basis to evaluate some of the challenges of using PZT sensors for SHM. The United States Air Force (USAF) has aircraft with bulkheads known to suffer fatigue cracks. The goal of this research was to use analytical and experimental investigations to detect fatigue cracks in plates representing the restricted geometry of the aircraft bulkhead. To accomplish this task, Lamb wave characterization was done on a large flat plate made of 6061-T6 aluminum. Then, test plates cut from the same sheet of aluminum as the large flat plate are cyclically loaded to propagate fatigue cracks in them.

This thesis research showed the benefit of PZT sensors could be their ability to monitor a known crack as it grows, instead of trying to detect new cracks which may be emerging. The potential of detecting damage with PZT sensors and Lamb waves exists, but more research is required.

III. Requirements Analysis and Traceability

3.1 Capability Need

Why does the USAF need an ISHM system? The USAF is facing some serious challenges with respect to the health of their fleet of aircraft. Currently almost 1/3 of the aircraft fleet is over 30 years old with many aircraft such as the B-52 and C-130 over 50 years old. These aircraft have far exceeded their expected design life, and as such, are experiencing structural problems in the form of cracking and corrosion. In addition to the age of the aircraft, the operations tempo over the past ten years has also significantly contributed to accelerating the deterioration of aircraft structures. "The average age of military aircraft in 1973 during the Vietnam War was nine years, compared to today's average of 24 years. While the average age of aircraft is rising rapidly, the readiness to meet Air Force current missions, including Air National Guard readiness, has declined by 17 percent since 2001, primarily because of the high operations tempo" [6]. As a result, the USAF is facing increases in maintenance and repair operations. As Dave Montgomery reported in February 2007, "...maintaining older planes costs more money, and delayed modernization only leads to increased maintenance costs later. Maintenance costs increased 38 percent from 1996 to 2006; maintenance man-hours increased by 50 percent compared with flying hours; and the workload for heavy repairs rose 41 percent" [7]. The USAF cannot sustain maintenance cost growth at such a high level and must operate more efficiently in an increasingly constrained economic environment. A properly designed ISHM system can help reduce the maintenance burden and decrease the cost of maintenance operations. In addition, an ISHM system serves as a proposed method of filling the capability gap associated with the Major Combat Operations Joint Operating Concept and also through the AFSO21 construct.

3.2 JCIDS Perspective

The Joint Capabilities Integration and Development System (JCIDS) is the top-down Department of Defense (DoD) process that defines a capability-based approach for acquisition and evaluation of defense systems. The JCIDS process was established under Secretary of Defense Donald Rumsfeld through the Chairman of the Joint Chiefs of Staff (CJCS). On 24 June 2003, the CJCS issued the Chairman of the Joint Chiefs of Staff Instruction (CJCSI) 3170.01. This was established to address communications problems that arose during the first Gulf War. Under previous requirements processes, numerous shortfalls existed. Those shortfalls include not considering programs in the context of other programs, not sufficiently addressing joint warfighting needs, and insufficient joint service requirements prioritization. The primary focus of the JCIDS process is to address required capabilities as identified by combatant commanders. The change from a previous solution addressing specific threats, to a solution addressing specific capability needs has been a revolutionary shift in requirements ideology.

In addressing specific capability gaps, there is a more disciplined way to identify appropriate solutions that can interact with legacy systems. Whereas prior to JCIDS, requirements would be submitted for a specific weapon system, now the emphasis is on stating the capability need and the JCIDS process should identify the appropriate solution to fill an identified capability gap. This requires a disciplined look at multiple solutions to fill a capability gap and to choose the one that is most appropriate. JCIDS mandates the evaluation of both materiel and non-materiel solutions. This is important because previously a materiel solution was normally chosen as the first option, and materiel solutions tend to be the most expensive. JCIDS requires the services to address the full spectrum of the solution space including Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel and Facilities, or DOTMLPF for short. Given this range of opportunities to explore for appropriate solutions to filling a particular capability gap allows for a thorough, encompassing analysis process and discipline to attain the most appropriate solution. In the DOTMLPF spectrum, the materiel solution must be carefully considered in the context of the cost and time it takes to implement.

The JCIDS process, (Figure 1), encompasses several key analysis steps including the FAA, FNA, FSA and a post-independent review. This paper will not go into detail on each of these steps but will refer the reader to CJSI/M 3170. This thesis will focus instead on the top-level originating requirement and how an ISHM system fulfills a documented capability gap identified in the JCIDS process.

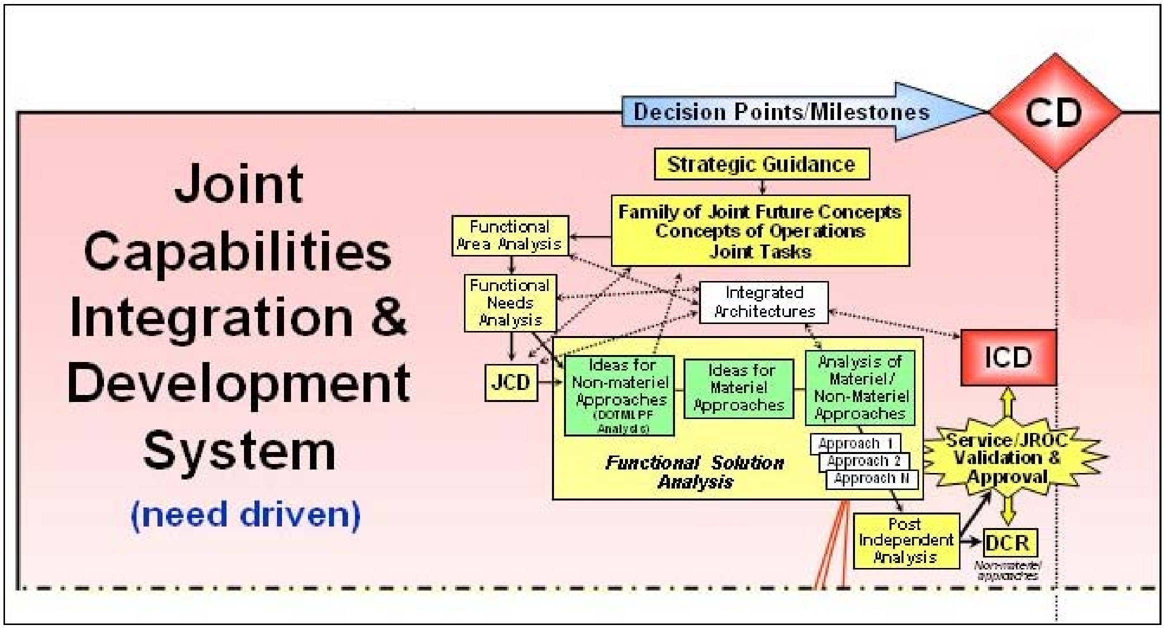


Figure 1 - Joint Capabilities Integration and Development System Process

The originating document that identifies a need for improved sustainment operations is the Major Combat Operations (MCO) Joint Operating Concept (JOC) version 2.0, December 2006. This document describes at the operational level how the future joint force intends to conduct combat operations in support of national military objectives and helps guide future joint force development by identifying the operational-level objectives and essential capabilities required to successfully implement the concept. The MCO JOC identifies broad capabilities required to fulfill required objectives. One of these capabilities is, "Reduce the need for sustainment pauses, enabled by improved commonality, reliability, maintainability, sustainability, and survivability in order to conduct relentless operations" [8:C-3]. An ISHM system can directly impact reliability, maintainability, and sustainability for DoD aircraft.

3.3 Air Force Smart Operations for the 21st Century

To meet the challenges of monitoring and improving aircraft structural integrity the Air Force and DoD are undergoing major transformations in the way daily operations are conducted. The Air Force has implemented a program termed the AFSO21 initiative. AFSO21 is the Air Force's overarching program guiding continuous process improvement in the Air Force [9]. The goal of AFSO21 is to "maximize value and minimize waste in all environments; operational, support and otherwise; to fully integrate continuous process improvement in to all we do across the Air Force" [9].

The AFSO21 initiative has defined four core key processes (Figure 2).

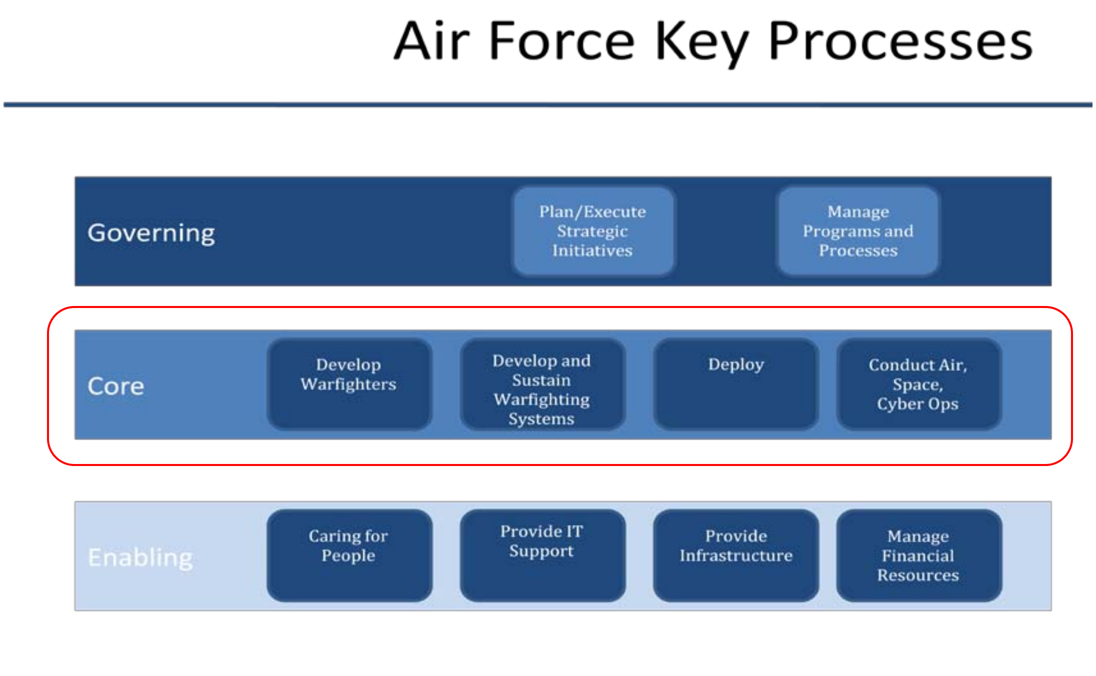


Figure 2 – Four Core Key Processes [10]

One of the four Core processes is Develop and Sustain Warfighting Systems (D&SWS). The Air Force Materiel Command Commander has been designated as the process owner for this effort and is responsible for designing, prioritizing, and leading Air Force-wide process improvement efforts in this core area. The vision for the D&SWS core process is “Streamlined and Integrated Life Cycle Management…One Materiel Enterprise”. In order to streamline and integrate life cycle management, the D&SWS effort has established several programs which trace their roots to DoD Directives (DoDD). Specifically, DoDD 4151.18, Maintenance of Military Materiel, March 2004 and DoDD 4151.22, CBM+ Policy, December 2007. These directives identify the need for "System health monitoring and management using embedded sensors; integrated data bus" [11:6], and "Decision support and analysis capabilities; on and off equipment; appropriate use of diagnostics and prognostics; automated maintenance information generation and retrieval" [11:6]. The AFSO21 requirements traceability is depicted graphically in figure 3.

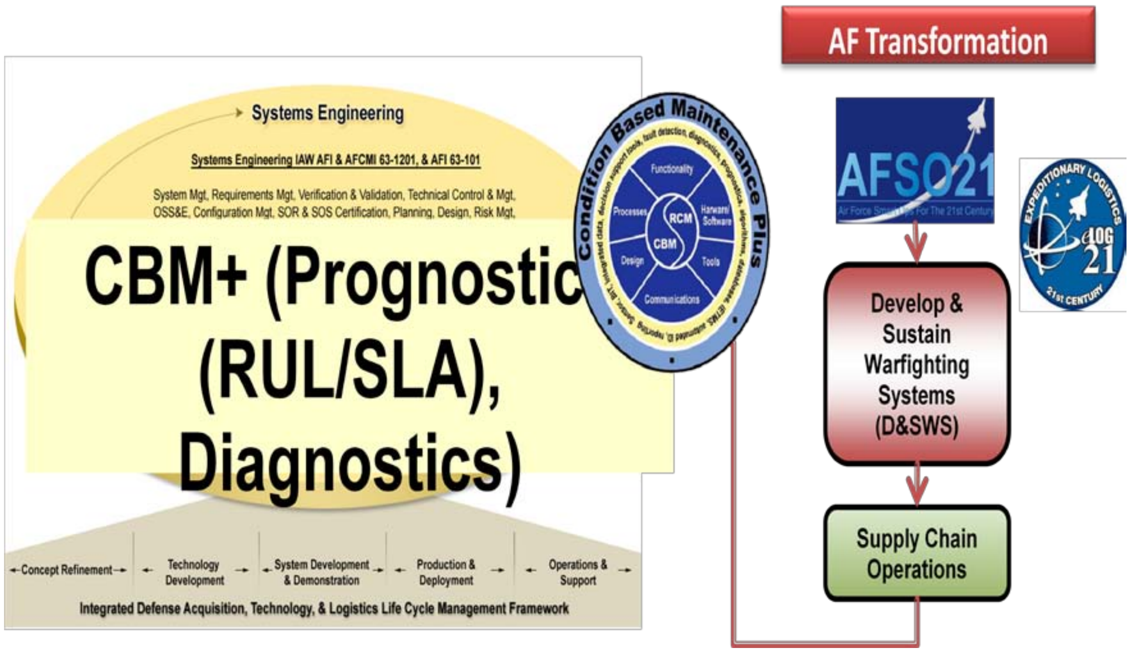


Figure 3 - AFSO21 CBM+ Construct

The capability gap associated with streamlining maintenance operations and sustainment activities can easily be traced to documented DoD directives and also through AF transformation initiatives. An ISHM system could be an integral piece of the solution to fill that particular capability gap.

IV. Analysis of Potential Solutions

4.0 Sensor Overview

The main reason for SHM is to continuously monitor and diagnose a structure's status and damage state. Sensors are an intriguing concept with the potential to save tremendous maintenance costs. Generally, sensors are intended to be placed at various aircraft inspection locations and utilized to determine if structural flaws (e.g. cracks, corrosion, etc...) exist. Since there is a large potential payoff for this technology, there has been a plethora of research and development efforts focused on sensor technology development. One area of research which is lacking however, is research focused on attaining "real-world" data. Much of the research to date has been conducted in laboratory environments under controlled conditions. Very little data is available on the performance of various sensor concepts in operational scenarios. Table 1 provides a short overview of some sensor technologies along with their basic physical principles, damage types, detection area, target materials and detection modes [13-14].

Currently, inspection of aircraft structures is accomplished by several means including visual, eddy current, x-ray, dye penetrant and ultrasonic applications. While these methods may be very labor intensive in some instances, they are proven solutions and have provided acceptable results. In addition to the labor burden associated with these methods, often times just getting to the inspection location induces collateral damage to the structure. This is another area where a distributed SHM sensor network can provide an advantage in the form of more frequent structural assessments and in turn, less labor and collateral damage leading to a much lower overall cost.

Table 1 - Short Overview of Some Technologies [14]

Technology	Basic Physical Principle	Detectable Damage Types	Detection Area	Target Materials	Detection Mode
Fiber Bragg Gratings (FBG)	Gratings written on the fiber core are subjected to strains (variation in length), which are caused by temperature changes (temp. sensor), or by local material strain, transmitted to the fiber.	Loads Impacts Delaminations	Local	Metallic and composites	On-line
Acousto-Ultrasonic's (AU)	Acoustic waves are sent through the material and received by specific transducers. A change in the material local behavior (and hence a damage) can be picked up and localized by an array of such sensors.	Delaminations Cracks	Global	Metallic and composites	Off-line
Comparative Vacuum Monitoring (CVM)	Open cracks generate leaks in a series of galleries bonded to the structures. A remote monitoring device tracks the pressure drop.	Cracks Corrosion Debondings	Local	Metallic and composites	Off-line
Acoustic Emission (AE)	Acoustic waves generated by small structural events (impacts, crack initiation, crack growth, delamination) are recorded by specific transducers when they occur.	Impacts Cracks Delaminations	Global	Metallic and composites	On-line
Sensitive Coatings (SC)	Coatings with integrated piezo- and ferro-electric elements being directly able to be bonded on a component surface or even integrated into a composite.	Corrosion Cracks	Global	Metallic and composite	Off-line

Technology	Basic Physical Principle	Detectable Damage Types	Detection Area	Target Materials	Detection Mode
Environmental Degradation Monitoring Sensors (EDMS)	Multifunctional sensors capable of monitoring parameters such as temperature, humidity, time of wetness and pH. In conjunction with a corrosion model, corrosion prediction and detection is possible.	Corrosion	Local to sensor position	Metallic and composites	On-line
Micro Wave Sensors (μW)	Micro waves are send and received in a pitch-catch mode inside the material, and provide a picture of the water content	Water ingress	Local	Composites Sandwich	Off-line
Imaging Ultrasonic (IU)	Classical ultrasound 2D images generated by newly developed integrated and miniaturized sensor networks	All damages caught by ultrasonic methods	Local	Metallic and composites	Off-line
Foil Eddy Current sensors (ET)	Eddy currents are generated in the structure. Their pattern and frequency distribution varies according to the presence of crack or other damages.	Cracks, Corrosion	Local	Metallic	Off-line

For any given SHM problem there is not just one factor that determines which sensor system is the best one to choose. Inspection locations will vary (e.g. materials, type of damage, environmental conditions, etc...) and therefore, sensors must be selected based upon the individual area to be monitored. Reliability, durability, affordability, survivability, dependability, applicability, detectability and simplicity are all important factors to consider when selecting an appropriate sensor solution. Many of the above sensor systems listed in Table 1 may satisfy some of the -ility requirements just mentioned, but it is very difficult to satisfy all of the issues with any one sensor system.

To meet all of the requirements, combinations of various sensor systems may be required [13]. Sensors are typically designed to detect a particular type of structural flaw and it may be possible to leverage the strengths of individual sensor types to form a network of different sensor types which is greater than the sum of its parts.

The reliability and durability of SHM sensor systems depends to a great extent on how the different component materials perform and degrade with time and usage. With respect to aircraft structures; mechanical effects, electrical effects, thermal effects and chemical effects are four of the main environmental effects encountered by SHM sensor systems [13]. These issues highlight some of the sensor-related problems and may dictate which SHM sensor system is applicable to various scenarios. Vibrations and stresses due to aircraft loading can cause mechanical effects. Components close to the engine section may be affected by hot temperatures while body/wing surface sections may encounter very cold temperatures. There may be electrical short circuits, electromagnetic interference or electrical conduction/insulation loss caused by various electrical effects. Chemical effects include corrosion, moisture, and fluid susceptibility [13]. To overcome these negative effects, SHM sensor systems should be chosen with careful consideration and account for all environmental factors. In addition, the geometric complexity of the inspection area must be considered. Decisions must be made regarding the types of sensing methods that can be used to achieve the most efficient detection capability while simultaneously providing a high level of reliability and dependability [15]. The next two sections examine the two types of the sensor systems which are evaluated in the value model.

4.1 Piezoelectric Transducers (PZT)

One of the leading SHM sensors being developed is the PZT sensor. These sensors are typically bonded to the surface of a structure. They operate by sending out and receiving energy in the form of elastic waves. PZT sensors typically operate in two modes; pitch-catch mode in which one sensor sends waves to another sensor, or pulse-echo mode where only one sensor is implemented and acts as both the sender and receiver of the waves. In order to determine if damage exists, the sensors determine if there has been a change in the amplitude, phase, or frequency, of the elastic waves [13, 5]. If the received wave is different from the wave which was originally propagated, then there is some sort of flaw in the material. PZT sensors are thin wafers that can be attached easily to different surfaces. Because PZT sensors are small, they may be useful in extremely tight inspection areas [15].

A typical PZT sensor disk as shown in Figure 4, consists of piezoelectric material between two layers of conductive material. The sensor is then attached to the substrate material of interest by using an adhesive bond layer [13].

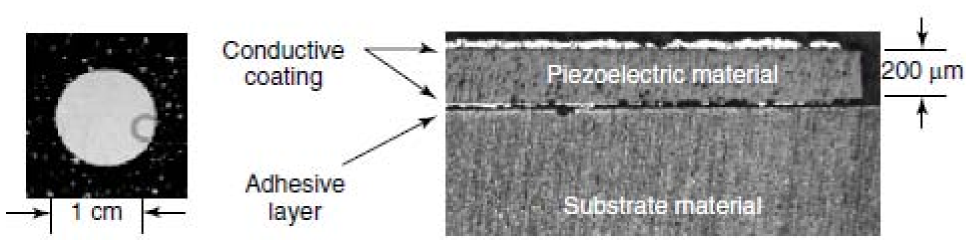


Figure 4 - Digital Image and Cross-Sectional Cut Through PZT Sensor Disc [13]

Typically, a PZT sensor system needs to have more than one sensor to locate the damage by using the triangulation method; therefore, a network of sensors is normally implemented. Figure 5 shows how a PZT sensor network could be implemented to detect and locate a structural flaw [4].

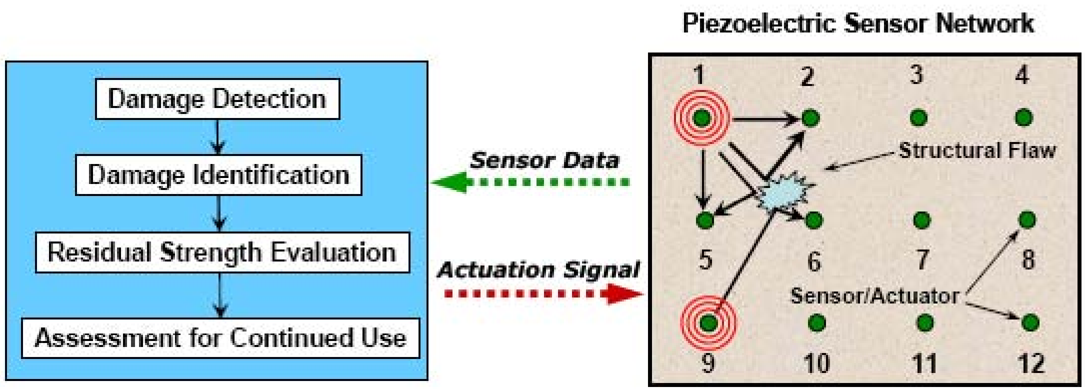
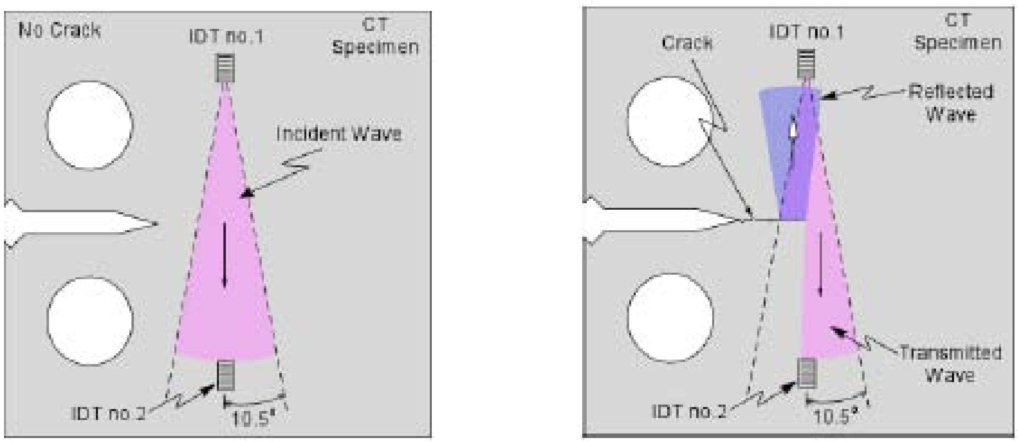


Figure 5 - PZT Sensor Methodology [4]

Since these sensors can both transmit and receive signals they are called smart materials. There are advantages and disadvantages to using PZT sensors in both the "pitch-catch" mode and pulse-echo mode. In pitch-catch mode, there is an inherent redundancy to the system. If one sensor fails, there is a second sensor which may still be able to perform the job. A disadvantage is the increase in cost and maintenance of the extra sensors. The reverse is true of single PZT sensor systems operating in only pulse-echo mode [13, 4, 5].

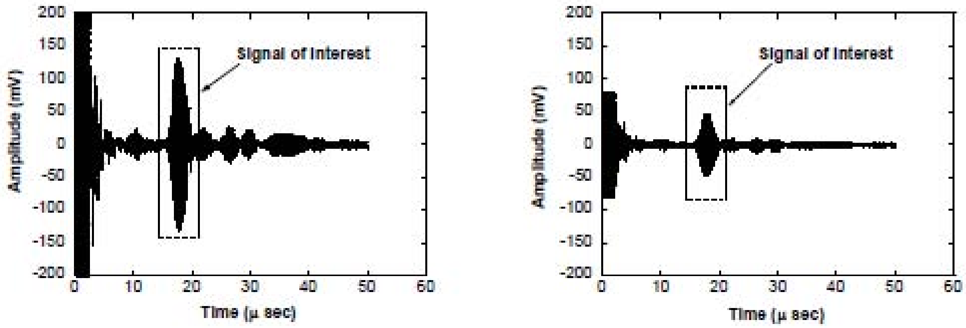
A case study done by Blackshire *et al.* depicts how the sensors work and how the signals are affected by a crack. Figure 6(a) illustrates how a PZT sensor pair operates in a pitch-catch mode with no flaw present in the material. Figure 6(b) illustrates how the same pitch-catch pair operates with the presence of a crack in the material. It is evident that the not all of the signal sent from sensor one reaches sensor two due to the interference from the crack.



(a) Before crack formation (b) During crack growth

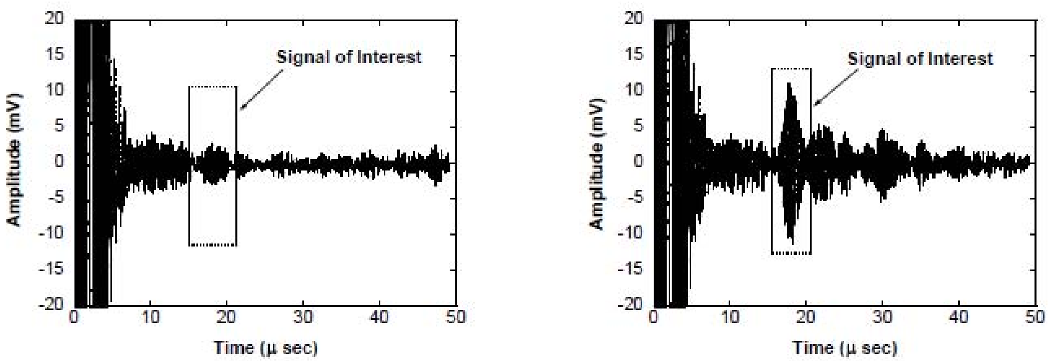
Figure 6 - Drawings Showing Propagation of Surface Waves Specimen [15]

Figure 7 shows the amplitude of the signals when the sensors operated in "pitch-catch" mode. It is evident that there is a change in the amplitude of the received wave due to the crack. Figure 8 depicts the amplitude of the signals when the sensors operated in "pulse-echo" mode. In both figures it can readily be seen when the crack is present versus when it is not [15].



(a) Before crack formation (b) During crack formation

Figure 7 - Surface Wave Signals Detected with the Receiving Sensor, in Pitch-catch Mode.



(a) Before crack formation (b) During crack formation

Figure 8 - Surface Wave Signals Detected with the Transmitting Sensor, in Pulse-Echo Mode

Surface bonded PZT sensors are inexpensive, lightweight, and can be applied relatively easily for SHM applications [13]. There are many environmental conditions however, that can cause degradation and damage, ultimately resulting in sensor failure. According to test results from Blackshire *et al.*, disbonded PZT sensors have serious degradation problems [13]. Various types of bonding agents to attach the PZT sensor to the substrate material have been evaluated; however, the results are still inconclusive as to which material holds up better with respect to various environmental conditions [13].

4.2 Comparative Vacuum Monitoring (CVM)

One of the most promising technologies existing today is Comparative Vacuum Monitoring (CVM). In contrast to most other sensor types, CVM sensors have been tested during long-term testing programs in actual operating environment. These sensors have been installed on different types of aircraft (B757, B767 and DC-9) in the fleet of Delta Airlines and Northwest Airlines for functional evaluation. CVM sensor durability testing was also conducted by the Australian Defense Science and Technology Organization (DSTO) and Airbus. No loss in sensor functionality due to temperature, chemical and ultraviolet exposure has been noted [13, 4, 16].

The CVM sensor consists of self-adhesive, elastomeric material, which has fine channels laser machined along the bottom surface to form alternating pressurized and vacuum galleries. Figure 9 shows a picture of a CVM sensor.

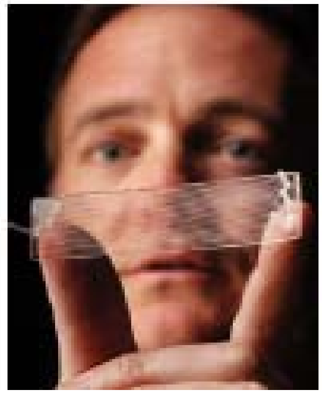
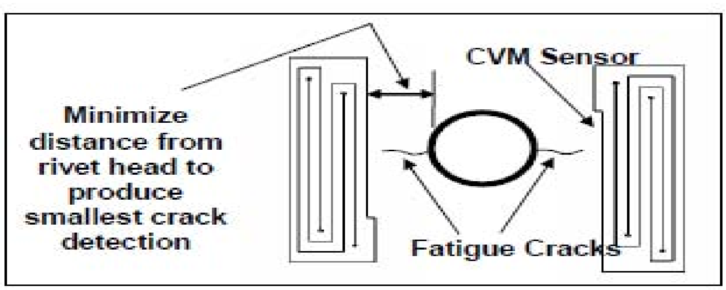
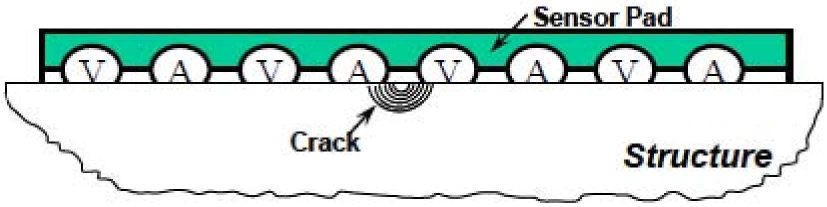


Figure 9 - CVM Sensor [16]

The basic premise behind CVM technology is that if a crack occurs and ruptures one of the vacuum channels, a leakage path forms between the atmospheric and vacuum channels. This leak produces a measurable change in the vacuum state, which is a positive indication that a crack exists under the sensor. Figure 10 shows the CVM sensor detection methodology.



(a) CVM sensors placed on both sides of rivet



(b) Cross-sectional cut through CVM sensor

Figure 10 - CVM Crack Detection Methodology [16]

One limitation of the CVM sensor is that once a crack is detected due to the change in pressure of the sensor, the sensor is no longer able to function. This means that crack growth cannot be determined, only that a crack exists. This may be acceptable in situations where the presence of any crack is a concern but could lead to false alarms if the crack length is not of concern until it reaches a specified critical length. Tests show that CVM sensors can accurately detect cracks from 0.04” – 0.07” under loaded conditions. For many aircraft inspection locations, this meets or exceeds the requirement for critical crack length. Table 2 shows the crack detection capabilities of CVM with 90% Probability of Detection [4].

Table 2 - CVM 90% Probability of Detection for Various Materials [4]

Material	Thickness	Coating	90% POD for Crack Detection
2024-T3	0.040"	bare	0.049"
2024-T3	0.040"	primer	0.021"
2024-T3	0.071"	primer	0.042"
2024-T3	0.100"	bare	0.272"
2024-T3	0.100"	primer	0.090"
7075-T6	0.040"	primer	0.026"
7075-T6	0.071"	primer	0.033"
7075-T6	0.100"	primer	0.023"

The use of load-bearing elastomer materials and flexible/compliant adhesives will enhance the CVM sensor ability to withstand high loading stresses and temperature changes in the aircraft environment [13].

4.3 Prognostic Modeling

An intriguing concept to SHM is the use of prognostic models to predict crack or corrosion growth. Essentially, this amounts to developing software with the ability to accurately predict the structural state at specific aircraft locations. This concept is not new and has been utilized for years in the aircraft design and maintenance communities.

In fact, many of the current maintenance inspection intervals in practice today were determined using various forms of component life analysis (prognostic modeling).

There are numerous limiting factors to the current analyses being conducted today. One major limiting factor is that the vast majority of models are being populated with notional aircraft load data generated using simulated flight profiles. Using that type of analysis, it assumes every aircraft experiences the same loads and stresses which obviously is not the case. Each aircraft experiences flight profiles unique to that particular aircraft. When this type of analysis is combined with conservative risk assumptions to establish inspection intervals, the result is that the inspection intervals established are often conservative, leading to unnecessarily short inspection intervals.

This research proposes that if the same analysis was performed utilizing the actual flight stresses and loads for each individual aircraft, a more accurate assessment would be produced. Currently the aircraft profiles are captured and logged, but there is nothing done with them after that. Should engineers and analysts use data already available and apply it to a software package tailored to perform structural life analysis, the result would be a more accurate assessment of individual aircraft structural health. This would facilitate scheduling aircraft for maintenance only when deemed necessary by individual aircraft flight profiles.

Through the course of the research team's analysis and interviews with various depot maintenance engineers, they realized that this type of approach was just beginning to be pursued at the various Air Force depot maintenance locations.

V. Value Model

5.0 Value Model

The value model developed in this section is derived from the processes developed by Ralph Keeney [18] and Craig Kirkwood [19]. The intent of the model is to serve as a value-focused framework for decision makers to use in assessing various SHM options. The model is predicated upon a systems engineering analysis of the SHM issues currently faced by the research and development community, the acquisition community, and the maintenance and logistics community. The values utilized in this model were attained through literature searches, subject matter expert input, or educated assumptions if no other data was readily available. Given this fact, the presented results of the models should only be used as demonstrations of the types of insight and information the model can provide. As further research is conducted in the area of SHM technology and more accurate data becomes available, the model can be refined to produce more accurate and representative results.

5.1 Value Model Definition/Development

5.1.1 Value-Focused Thinking Perspective and Development.

Value-Focused Thinking (VFT) is a methodology of establishing a hierarchy of values a decision-maker desires, with respect to a problem to be solved, and then applying those values to determine how well certain alternatives satisfy the overall problem. According to Keeney [18], the typical, but not desired, decision making process is alternative-focused thinking. Alternative-focused thinking, typically first considers the options available to the decision-maker, then determines what about each decision is desirable and finally selects an alternative. Essentially, VFT reverses two of the steps in the alternative-focused thinking process (Figure 11).

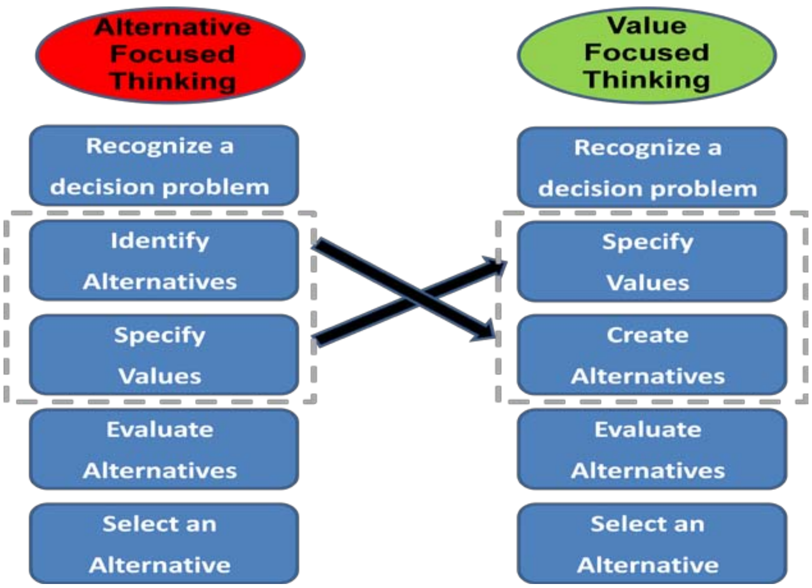


Figure 11 – Alternative-Focused Thinking vs. Value-Focused Thinking [18:49]

It is essential to first identify a decision opportunity when using the VFT framework. The decision opportunity often occurs because of dissatisfaction with current methods, or because the current solution may no longer be an option. Once a decision opportunity is identified, the decision-maker must determine what they value about the decision opportunity. "Values of decision makers are made explicit with objectives" [18:33]. An objective is a statement of something that one desires to achieve. When the set of values and objectives is established, some method of assessing the attainment of those values is needed. The method of assessing value attainment is called a measure. Measures are characteristics of each alternative that are assessed to determine how well the alternatives satisfy the overall value. Measures need to be quantifiable (e.g., they need to be able to be quantitatively measured) and independent from each other. Non-redundancy of measures ensures that there is no "double counting" [19:17] of measures in either a positive or negative manner. In addition, the values and measures identified should incorporate all of the key aspects necessary to evaluate the overall objective of the decision [19:16]. Once the values and measures are identified, they are then assigned weighting factors based upon input from key decision-makers and subject matter experts. These weighting factors determine the relative importance, to the decision-maker, of each value and measure identified. Finally, to implement a value measure, a single-dimension value function (SDVF) is created to score each measure. SDVF's establish the score-to-value function that, in aggregate, forms the overall score of each alternative. Because various values will require dissimilar measurements, an overall scoring requires the attainment of values to be standardized on a single scale. A SDVF accomplishes this need. The SDVF's are the lowest level of the hierarchy but are at the crux of the entire value model. It is at this level that each alternative's measures are scored to produce the overall score.

Upon completing the process just described, the value model can be implemented as a tool to aid decision makers in choosing the alternative which best meets the values they desire. The key advantages of a value-focused model over more traditional alternative-focused models are that the decisions are quantifiable, defendable, and repeatable. Because there is a definitive score and ranking for each alternative evaluated, and all alternatives are evaluated against the same measures, the value-focused thinking model helps eliminate the bias of many alternative-focused decision processes.

Figure 12 depicts a generic value-model for any decision problem. The overall decision problem is at the top of the hierarchy. The second level in the hierarchy is the values established by the key decision makers along with their relative weightings. Subsequent to the values, are the individual measures used to evaluate each characteristic of interest.

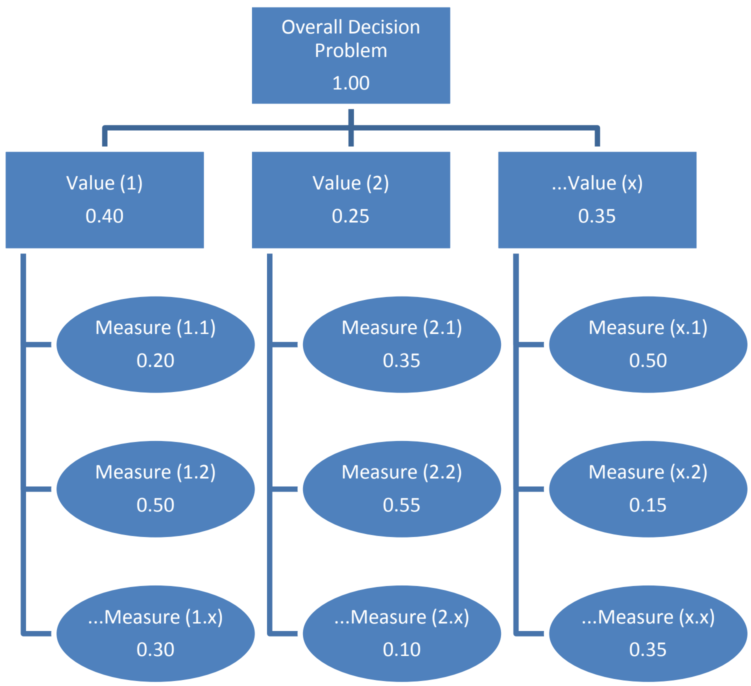


Figure 12 – Example Value Model Hierarchy

Each measure is scored based upon the SDVF developed for that individual measure. The score is essentially a measure of "goodness" ranging from zero to one. Each score is determined by evaluating the measure's independent variable (cost, performance, etc...) and determining the corresponding score. Figure 13 provides an example of measuring power. This example is used frequently if someone is purchasing a new vehicle and the decision maker chooses vehicle power as one of their values. The measure of power was chosen to be horsepower, and the SDVF was established with bounds from 109 horsepower to 175 horsepower. If the vehicle has 109 horsepower or less, it receives a score of zero (it is of no value to the decision maker). If the vehicle has 175 horsepower or greater, it receives a score of one (it completely satisfies the value of that measure). Any horsepower rating between 109 and 175 receives a score based upon the SDVF established for this measure.

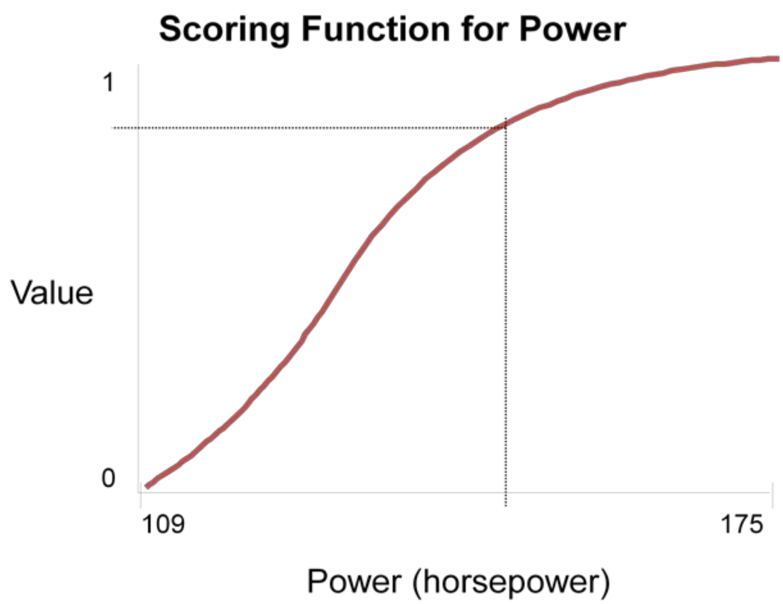


Figure 13 - Example SDVF [courtesy Dr. Jeffrey Weir]

The final product of the value model is a rank-order of all alternatives which were considered in the model. The rank-order is determined based upon the final "score" of each alternative. The score is determined by first taking the SDVF score for an individual measure (between zero and one), then taking the product of the score, measure weighting and value weighting. The following example illustrates how the score is determined.

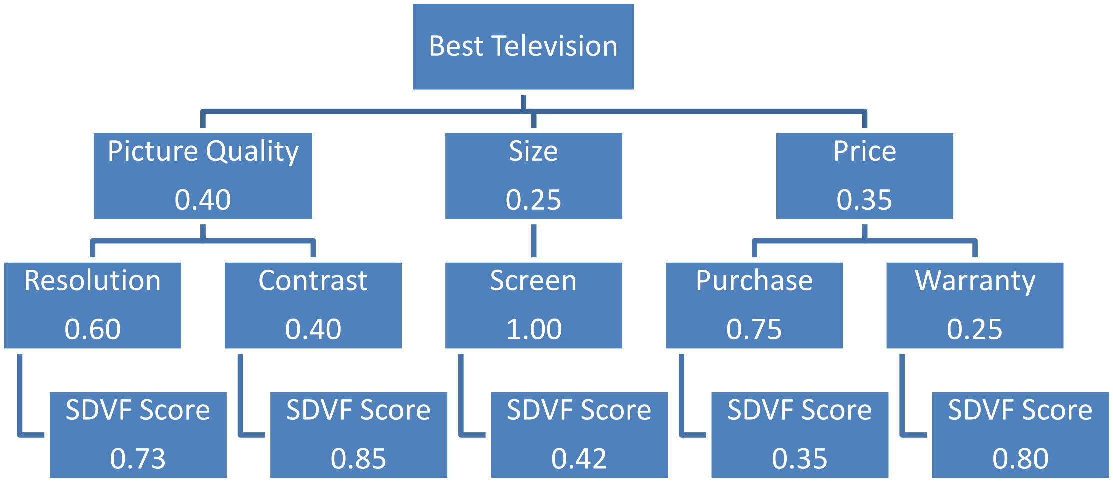


Figure 14 - Example Value Model Scoring

The alternative evaluated in Figure 14 would receive an overall value score determined as follows:

Value = (0.73)(0.60)(0.40) + (0.85)(0.40)(0.40) + (0.42)(1.00)(0.25) + (0.35)(0.75)(0.35) + (0.80)(0.25)(0.35) = **0.5781**

After scoring each alternative, a final rank-order of all alternatives considered is determined. The final rank-order can then be used by decision makers to determine which alternative best satisfies the overall value.

5.1.2 SHM Value-Model Development.

Currently, there are various SHM approaches being pursued by the Air Force and the DoD attempting to improve aircraft structural awareness. What is lacking however is a decision tool to aid decision makers as to which SHM approach is best for a given situation. As with any problem, there are multiple solutions, and no one solution is going to be best for all situations. This research utilized the value-focused thinking approach just described and applied it to create an SHM value model framework.

Stakeholders were identified by evaluating all aspects of a structural health monitoring problem from research and development through system retirement and disposal. The stakeholders identified were research and development engineers and scientists, program managers, acquisition personnel, maintenance personnel, sustainment personnel from Robins Air Force Base, Georgia, and Hill Air Force Base, Utah, and academic professors with backgrounds in structural health monitoring, systems engineering and operations research. The input gathered from this wide array of experts provided the key framework for constructing the value model.

A software add-in package for Microsoft Excel called Hierarchy Builder Version 1.01 [20] was utilized to create the value hierarchy and compute the values for the value model. This software add-in was written by Dr. Jeffery Weir, a faculty member in the AFIT/ENS Operations Research department.

Creating the value model began with first identifying the overall top-level objective. It was decided that the desired objective, or value, was to know the condition of the structure of interest. We classified this top-level objective as "Structural State Awareness" in our model.

The second tier of the value hierarchy depicts the values determined to be of significance to satisfy the overall objective and their respective weighting. The values and weighting factors for the SHM model were established by several methods. The research team conducted several brainstorming sessions, consulted with experts in SHM, logistics and maintenance, research and development, and searched open-source literature.

The final tier of the value-model depicts the measures considered and their relative weighting. The measures and weightings were determined in the same manner as the values. Figure 15 shows the overall SHM value hierarchy as determined and implemented in this research. A full-size figure is also located in Appendix A

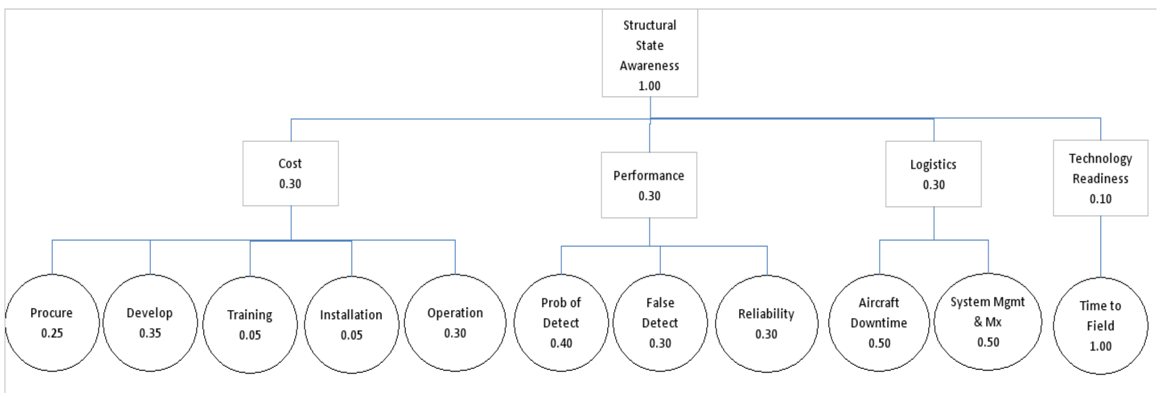


Figure 15 - SHM Value Model

5.1.3 Definition of Model Parameters.

Establishing the definitions for each measure takes a tremendous amount of thought and careful analysis. There are many different interpretations of a measure, so it is imperative to define the measures explicitly in order to minimize confusion and ensure the model is applied consistently. The values and measures categorized in Figure 16 are defined as follows:

COST

Procurement: Cost to buy a “finished” system. A “finished” system is one that the user deems acceptable for their use. It includes the cost of the system and any ancillary equipment necessary for operation. Essentially, this is the cost to purchase the system from the manufacturer. The procurement cost is determined for fleet-wide implementation, and then divided by number of aircraft intended for use to determine a per-aircraft cost.

Development: Cost to mature the system to specified technology readiness level (TRL) from its current state of readiness. Specified TRL is dependent upon what would satisfy a particular customer. Some customers will require a higher TRL than others. Development cost is also determined on a per-aircraft basis.

Training: Cost to train personnel on the proper use and maintenance of the system. The cost is determined based upon establishing training courses, materials, and time required to perform training. Training cost is also determined on a per-aircraft basis.

Installation: Cost to install the system on the appropriate platform. For example, cost to install sensors onboard aircraft, cost to install a new flight data recorder, or cost to install software model on computers. Installation cost is also determined on a per-aircraft basis.

Operation: Cost to operate the system for a given number of inspections. Includes cost to prepare the aircraft for inspection, perform the inspection, and put the aircraft back together following the inspection. Operation cost is dependent on the inspection location, method of inspection, and number of inspections performed in a five-year period.

PERFORMANCE

Probability detection/prediction: Probability of accurately detecting or predicting a flaw at a given aircraft inspection location at a predicted time. Establishing probability of detection for given SHM solution alternatives is very time intensive, so for this model POD numbers are assumed for each alternative.

Probability of false detection/prediction (Type I error): Probability of false detection/prediction. This includes the probability of a given SHM solution detecting/predicting a flaw when in fact no flaw exists. For this model, we include performing a manual inspection and not finding any flaw (e.g., current schedule-based maintenance inspections) as a false detection.

Reliability: Percent of time system operates correctly in a realistic operational environment. This area of SHM is extremely subjective and very little research has been accomplished to accurately assess SHM system reliabilities. For this model, reliability values will be assumed.

LOGISTICS

Aircraft Downtime – Number of hours an aircraft is down for the specified inspection. This includes number of inspections multiplied by the number of hours per inspection over an assumed five-year period.

System Maintenance and Management – Time required per year to maintain and manage the logistical aspects of the system. This measure is determined on a per-aircraft basis.

TIME TO FIELD

Number of years required to mature the technology to an acceptable level as determined by the user.

Table 3 summarizes the measures and SDVF's established in the value model. The graph of each SDVF can be found in Appendix B, D and F.

Table 3 - Value Model Measure Parameters

MEASURE	MEASURE UNIT	MEASURE TYPE	LOWER BOUND	UPPER BOUND
Cost				
Procurement	Dollars	Linear (decreasing)	0	Varies by inspection
Development	Dollars	Linear (decreasing)	0	Varies by aircraft
Training	Dollars	Linear (decreasing)	0	Varies by aircraft
Installation	Dollars	Linear (decreasing)	0	Varies by inspection
Operation	Dollars	Linear (decreasing)	0	Varies by inspection
Performance				
Probability of Detection	Probability	Linear (increasing)	0.90	1.00
Probability of False Detection	Probability	Linear (decreasing)	0	0.50
Logistics				
Aircraft Downtime	Hours	Linear (decreasing)	0	Varies by inspection

MEASURE	MEASURE UNIT	MEASURE TYPE	LOWER BOUND	UPPER BOUND
Technology Readiness				
Time to Field	Years	Linear (decreasing)	0	5

The measure input parameters used to populate the model must be determined for each alternative to be evaluated. For the SHM model in this research, the values were determined either through calculations, information provided by various manufacturers, or assumed values based upon the most relevant data available. Due to the fact that the model is predicated upon a specific aircraft, per inspection location basis, it was necessary to determine measure values which were representative of that fact. Procurement, installation and operation costs are functions of the number of systems required to adequately perform the inspection and expected number of inspections over the life of the SHM system. Measures for development and training were considered one-time expenses and were calculated as total costs, and then divided by the number of aircraft in the platform fleet. Table 4 summarizes the value model parameter calculations.

Table 4 - Value Calculations

Measure	Calculation
Procurement (dollars)	(Number of systems required) * (Cost/system) + Cost of support equipment
Development (dollars)	Development cost / Number of aircraft
Training (dollars)	$2.5M / Number of aircraft
Installation (dollars)	$240/hr * Number of systems required / Number installed/hour
Operation (dollars)	$240/hr * Inspection time required * Number of Inspections
Probability of Detect	varies by alternative (0.90 < x < 1.00)
Probability of False Detect	aries by alternative (0.00 < x < 0.50)
Reliability	varies by alternative (0.90 < x < 1.00)
Aircraft downtime (hrs)	varies by alternative
System Mgmt & Mx (hrs)	varies by alternative
Time to field (years)	varies by alternative

Several assumptions must be made in order to utilize this model. The following list details the assumptions made for the three inspection locations to be analyzed:

1. An assumed SHM system life of five years was used. This assumes the system under consideration operates for five years, and then must be replaced.
2. The alternatives considered are all applicable to the specified inspection location.
3. Procurement Cost: the cost of the SHM alternatives is assumed to be $10/sensor for PZT plus $15,000 for support equipment, $50/sensor for CVM plus $25,000 for support equipment, $50,000 for prognostic model, and zero for current operations. These values are on a per aircraft basis.
4. Development Cost: the fleet-wide development cost of the SHM alternatives is assumed to be $5M for PZT, $1M for CVM, $5M for prognostic model, and zero

for current operations. The actual value measure is determined on a per-aircraft basis.

5. Training Cost: it is assumed that the fleet-wide training cost for the PZT, CVM and prognostic model are all $2.5M, whereas the cost for current operations is zero. The actual value measure must be determined on a per-aircraft basis.
6. Installation Cost: an assumed labor rate of $240/hour [4:93] was used. The number of systems required varies by alternative and inspection location, and the number installed per hours was assumed to be four/hour for PZT, four/hour for CVM, 0.5/hour for prognostic model, and zero for current operations.
7. Operation Cost: an assumed labor rate of $240/hour was used. The inspection time required was determined by using current T.O. information for the specified inspection for current operations. The value for PZT and CVM was assumed to be 33% of current operations. This value was chosen based upon the assumption that the area of interest would still need to be manually inspected once every three inspection intervals to check the condition of the sensors and ensure their integrity. An assumed value of four hours was used for the prognostic model.
8. Probability of Detection: the values for POD were assumed to be 0.90 for PZT, 0.93 for the prognostic model, and 0.95 for CVM [21] and current operations [22].
9. Probability of False Detection: The values assumed for probability of false detection were 5% for PZT and CVM, 20% for prognostic model, and 30% for current operations.

10. Reliability: reliability was assumed to be 0.90 for PZT and CVM, 0.95 for current operations, and 0.99 for prognostic model.
11. Aircraft Downtime: downtime was calculated based upon the time required to perform the inspection. For PZT, CVM and prognostic model, it was assumed that the downtime would be 33% of that for current operations. This number was chosen with the expectation that the area of interest would still need to be manually inspected once every three inspection intervals to check the validity of the sensors or model. The value for current operations was determined from current T.O. data.
12. System Maintenance and Management: assumed values were determined on a per-aircraft basis. The larger the number of systems required for the inspection, the higher the assumed value.
13. Time to Field: the value for PZT was assumed to be four years, CVM was assumed to be one year, prognostic model was assumed to be three years, and current operations is zero.

5.2 Value Model Application and Results

5.2.1 Examples of Model application.

To demonstrate the model developed in section 5.1, an analysis of three specific aircraft inspection locations will be examined. The locations of interest selected for demonstration purposes are the C-130 center wing rainbow fittings; the A-10 engine thrust mount, and the F-15 vertical stabilizer torque box splice. These locations were selected because they provide a wide range of inspection times, are current SHM areas of concern, and they demonstrate the versatility of the value model in being applicable to any airframe.

5.2.1.1 C-130 Rainbow Fitting Example.

The C-130 rainbow fitting is a great area of concern for the C-130 airframe. Currently, the C-130 is experiencing fatigue cracks where the outer wings attach to the center wing box as depicted in Figure 16 and Figure 17. The area of concern is the upper and lower "rainbow fittings".

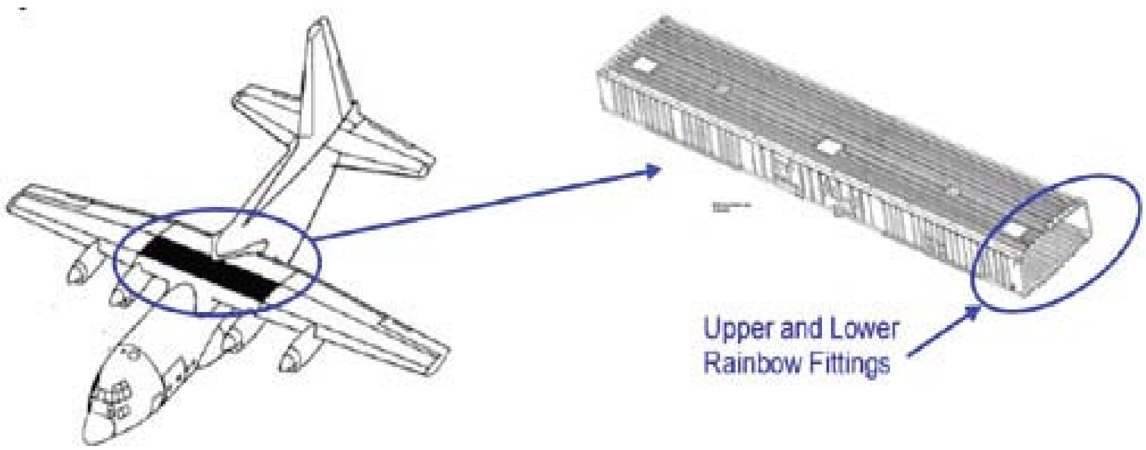


Figure 16 - C-130 Center Wing [23]

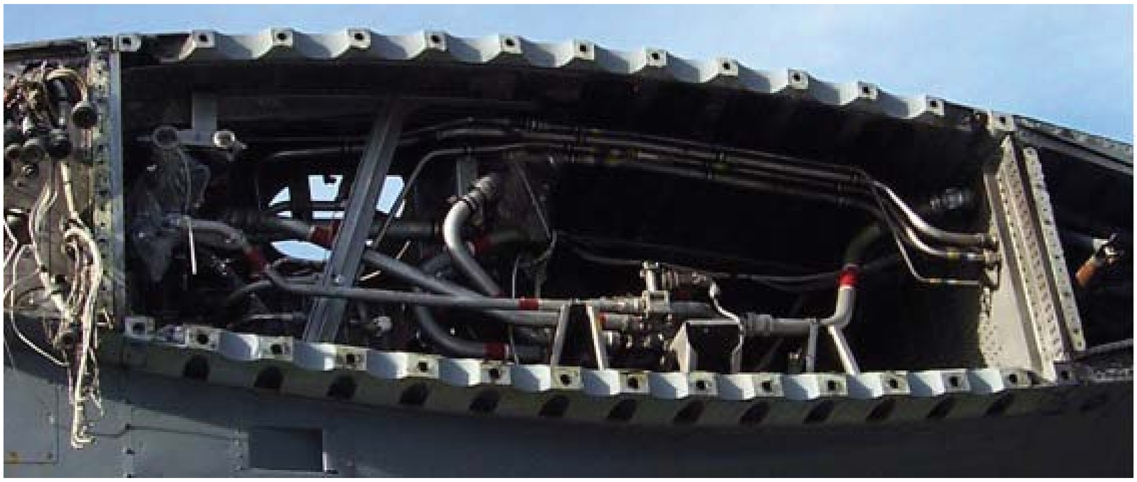


Figure 17 - C-130 Center Wing with Outer Wing Removed

This location is very highly loaded due to the fact that the outer wing contains fuel, engines, structure, etc, and is cantilevered out from the fuselage. An example of the fatigue cracks which are developing in the center wing attach points is depicted in Figure 18.

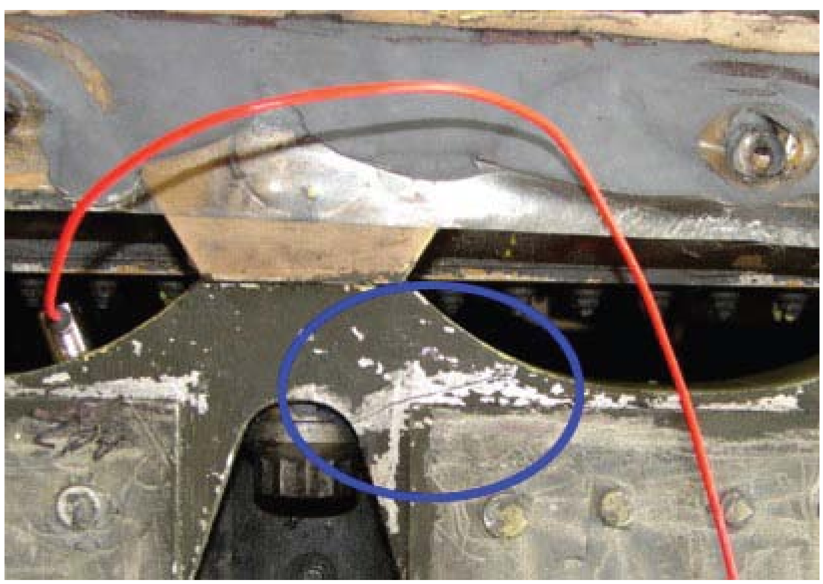


Figure 18 – Typical C-130 Rainbow Fitting Crack

The current method of inspection for the rainbow fittings is to remove a bolt, inspect the surface using bolt hole eddy current technique and replace the bolt. This is done for each of the 24 attach points on both the left and right side of the aircraft. The time required to perform this inspection using current methods is 360 minutes [23]. This time is for inspection only and does not account for aircraft preparation or putting the aircraft back together following the inspection. Time for aircraft preparation and putting the aircraft back together is estimated to be an additional 360 minutes. This location could also be monitored for structural health using a variety of sensors, through use of more accurate life prediction tools, or by manual inspections as they are currently being accomplished. Currently the inspection frequency for the rainbow fittings is determined by aircraft usage. Aircraft with less than 24,000 equivalent baseline hours (EBH) are inspected every 400 flight hours, whereas aircraft with more than 24,000 EBH are inspected every 80 flight hours [23:11]. For this example we will assume the worst case scenario of an inspection every 80 flight hours. An assumption must also be made as to the number of flight hours per year the aircraft accrues in order to determine the number of inspections required. For this example, it is assumed that the aircraft accrues 800 flying hours per year and therefore would require 10 inspections per year. Given an assumed SHM system life of five years, the total number of inspections is 50. The number of systems required to perform the inspection is estimated to be 192 for PZT, 192 CVM, one prognostic model, and zero for current operations. Aircraft down time was calculated as 600 hours (50 inspections multiplied by 12 hours/inspection) over five years, the assumed expected life of each SHM alternative. For this analysis it was assumed that the SHM alternatives would be implemented on the entire fleet of 435 C-130 aircraft [24]. Table 5 depicts the values used to assess this inspection location.

Table 5 - C-130 Value Model Input Parameters

Alternative Name	Procurement ($)	Development ($)	Training ($)	Installation ($)	Operation ($)	Prob of Detect	False Detect	Reliability	Aircraft Downtime (hrs)	System Mgmt & Mx (hrs)	Time to Field (yrs)
Piezoelectric Sensor	26920	11494	5747	11520	48000	0.9	0.05	0.9	200	17	4
CVM Sensor	34600	2299	5747	11520	48000	0.95	0.05	0.9	200	17	1
Prognostic Model	50000	11494	5747	1200	48000	0.93	0.2	0.99	200	7	3
Continue Current Ops	0	0	0	0	144000	0.95	0.3	0.95	600	0	0

Given the preceding values and assumptions, the VFT model generated the list in Figure 19, depicting how well each alternative satisfied our overall value of structural state awareness.

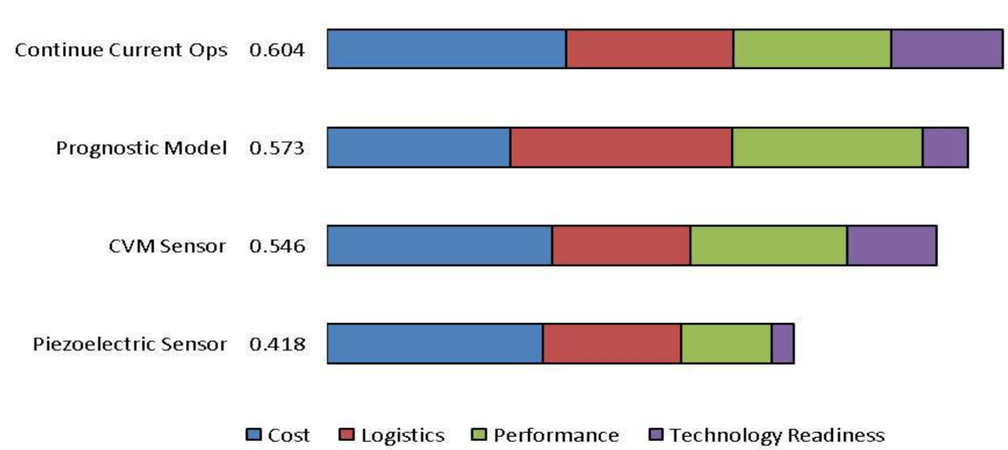


Figure 19 – SHM Value Model Results for C-130 Rainbow Fitting

Analyzing the results one can see that the SHM alternative of "Continue Current Ops" provides the most value (0.604). This means that this alternative satisfies 60.4% of our overall value of structural state awareness. This result indicates that even though continue current operations is our best alternative of the ones considered, it still does not provide a very good solution since it only satisfies ~60% of our desired value. The prognostic model which scored as the second best alternative considered, is close to the same value, within ~3%, as current operations. This indicates that this alternative could also be examined using a more thorough assessment to determine if it should be implemented. It is evident in our example that PZT sensors provide the least value to us currently because they score low in logistics, performance, and technology readiness. Not accounting for an entire system approach is a major factor limiting implementation of structural health monitoring concepts in today's environment.

A sensitivity analysis can be performed on any of the values or measures listed in the SHM value-model developed in section 5.1. The sensitivity analysis examines the effect on overall ranking of the alternatives if the weighting factors are adjusted. This sensitivity analysis helps solve conflicts when decision makers may have differing opinions of the weighting factors used in the analysis. For example, Figure 21 is the sensitivity analysis for cost for the C-130 rainbow fitting. Currently, the weighting factor for cost is 30%, indicated by the solid vertical line. If the weighting factor for cost were adjusted to zero percent (indicating the decision maker cared nothing about cost), while increasing the remaining value weights of performance, logistics, and time to field proportionally, the overall ranking of alternatives would change. In this case, the number one alternative would become the prognostic model and continue current operations would become the second best option. On the other hand, if the decision maker cared 100% about cost and zero about the other values of performance, logistics, and time to field, the continue current operations option would again be the best alternative, followed closely by the CVM and PZT options. This sensitivity analysis helps decision makers identify where changes in the overall ranking of alternatives occur for given changes in weighting factors. Looking at Figure 20, if the weighting factor for cost is anywhere between 15% and 100%, continue current operations remains the highest scoring alternative.

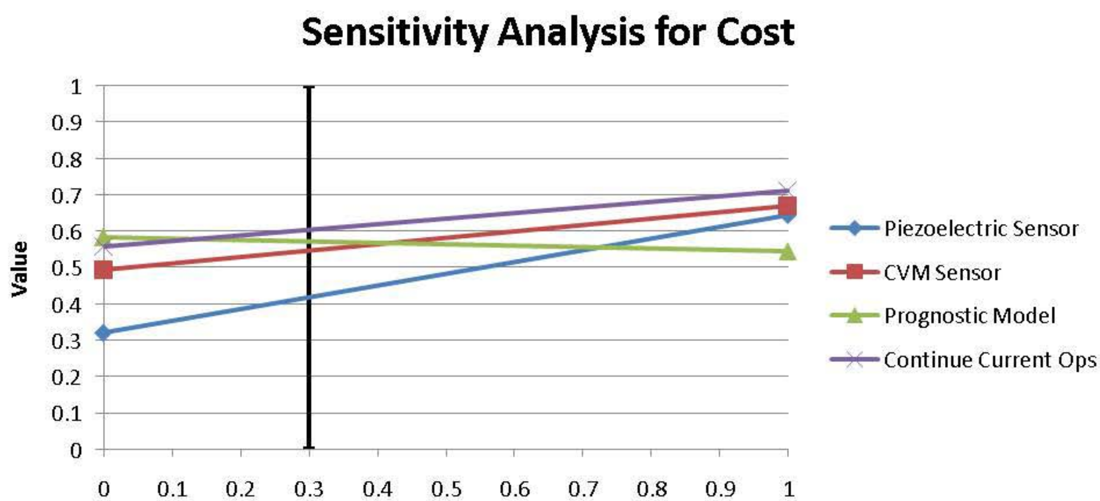


Figure 20 - C-130 Sensitivity Analysis for Cost

As long as the decision making group agrees that the weighing factor for cost lies somewhere between 15% and 100%, the highest scoring alternative in this case will not change, but there will be changes in the order of the remaining alternatives. A similar sensitivity analysis for performance and logistics was performed and the results are included in Appendix C.

5.2.1.2 A-10 Engine Thrust Mount Example.

For a second example of applying the value model to an SHM decision opportunity, an analysis of the A-10 engine thrust mount is examined. The specific location is depicted in Figure 21.

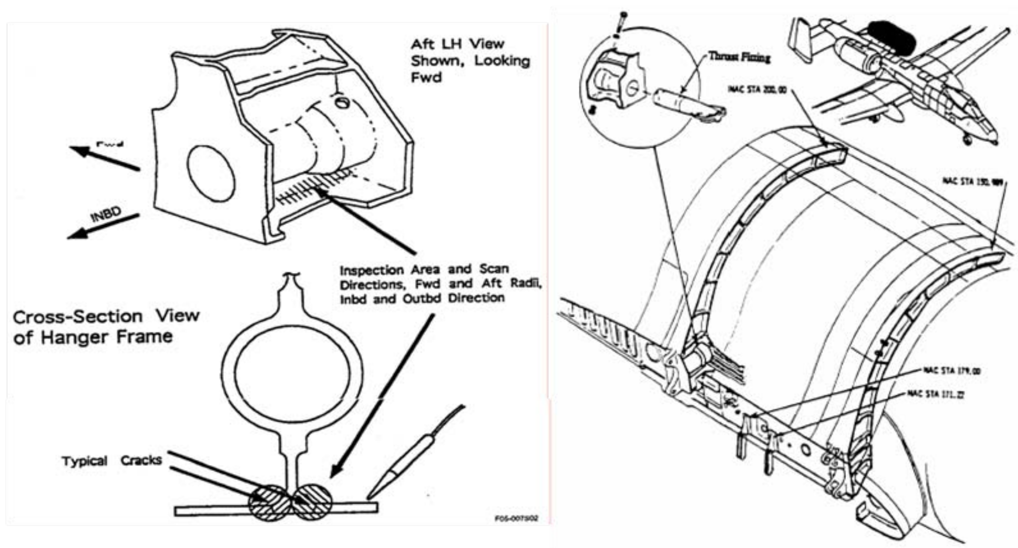


Figure 21 – Schematic of the A-10 Engine Thrust Mount [25]

This is a location of concern because if a failure occurs at this point, loss of an engine is possible. Due to its proximity to the engine, this location on the aircraft experiences severe vibration and heat. This location could also be monitored by using a variety of structural health monitoring techniques such as sensors, component life prediction tools, or by continuing to perform manual inspections as are currently done. For this example, it is assumed that all of the SHM alternatives considered would be applicable to this location, however due to the environmental conditions around the area of concern, significant improvements in current performance and durability characteristics of SHM sensors would need to occur for this to truly be the case. Current inspections are conducted via eddy current surface probe and take approximately 30 minutes to conduct and an additional 30 minutes for aircraft preparation and clean-up. For this analysis it is also necessary to assume the number of SHM systems required and anticipated number of inspections that will be conducted over the life of the SHM system. In this example, 32 PZT sensors, 16 CVM sensors and one prognostic model were chosen as necessary to monitor the area of concern. The inspection interval was assumed to be 250 flight hours, and an assumed flight-hours of 400/year were used. This leads to approximately eight inspections over the five year assumed SHM system life, and aircraft downtime of eight hours. Similar to the previous example, the authors assumed the SHM alternatives would be implemented on all 367 aircraft in the inventory [26]. Table 6 depicts the values used to assess the various SHM alternatives for this inspection location.

Table 6 - A-10 Value Model Input Parameters

Alternative Name	Procurement ($)	Development ($)	Training ($)	Installation ($)	Operation ($)	Prob of Detect	False Detect	Reliability	Aircraft Downtime (hrs)	System Mgmt & Mx (hrs)	Time to Field (yrs)
Piezoelectric Sensor	25320	13624	6812	1920	316.8	0.9	0.05	0.91	2.6	12	4
CVM Sensor	25800	2725	6812	960	316.8	0.95	0.05	0.91	2.6	10	1
Prognostic Model	50000	13624	6812	2400	7680	0.93	0.2	0.95	2.6	7	3
Continue Current Ops	0	0	0	0	960	0.95	0.3	0.95	8	0	0

Given the preceding discussion and values, the value model developed in section 5.1 was applied to the A-10 engine thrust mount location. Figure 22 displays the result of this analysis.

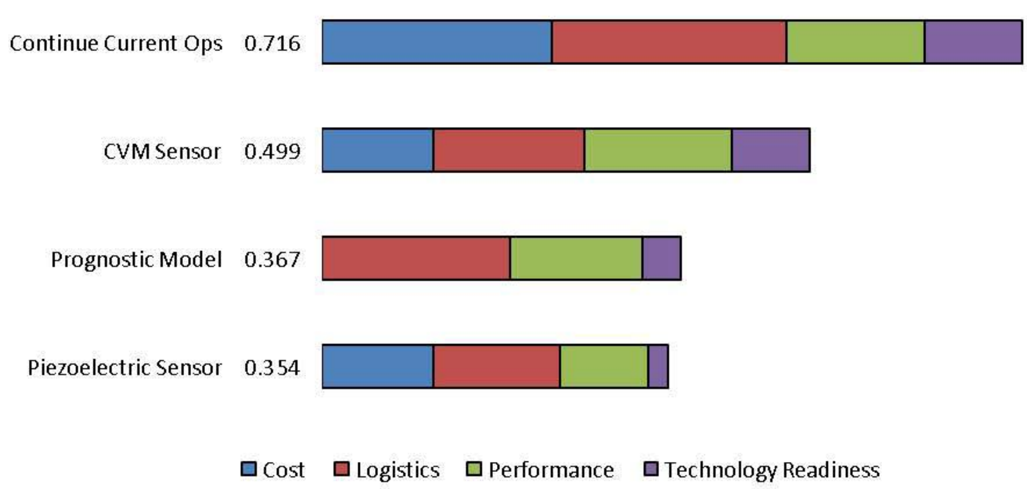


Figure 22 – SHM Value Model Results for A-10 Engine Thrust Mount

It is evident from Figure 22 that continuing current operations is by far the most valuable alternative. This makes intuitive sense as well because this inspection location takes very little time (~1 hour) to perform manually, so it does not make sense to utilize an alternative SHM system for such a simple inspection. The same sensitivity analysis performed for the C-130 example was also performed for the A-10 example. The sensitivity analysis for performance is shown in Figure 23.

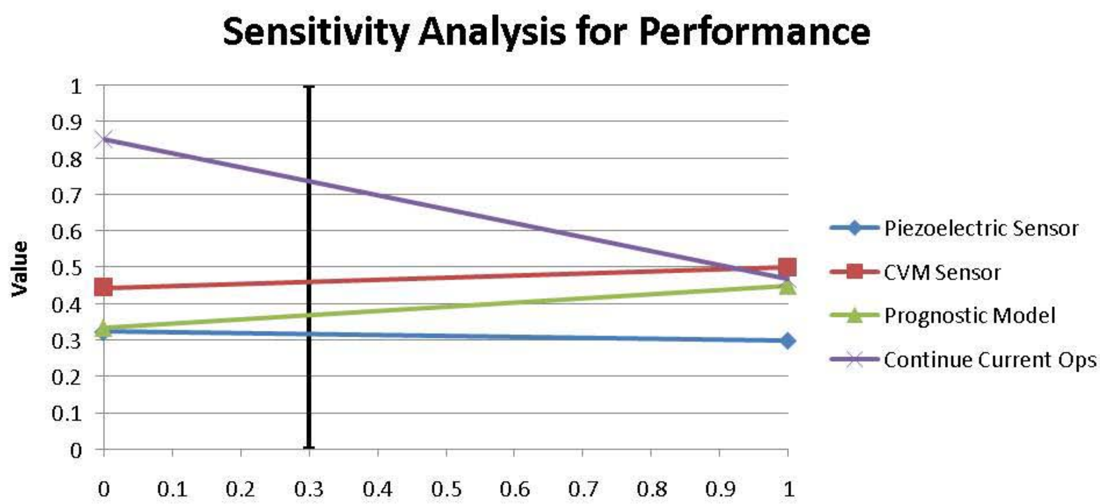


Figure 23 - A-10 Sensitivity Analysis for Performance

This sensitivity analysis indicates that continuing current manual inspection methods is the best alternative until performance is weighted at 90% or higher. As long as the decision making group agrees that performance will never account for 90% or greater of the overall decision, continuing current operations will remain the best option. Similar results were obtained for the sensitivity analysis performed for cost and logistics and can be found in Appendix E. In actuality, this inspection location would most likely not even be considered for alternative SHM techniques because it is such a simple manual inspection which takes very little time and expense; however, it was chosen as an example in order to demonstrate the versatility of the model.

5.2.1.3 F-15 Vertical Stabilizer Torque Box Splice Example.

The third and final inspection location this research examined is the F-15 vertical stabilizer torque box splice depicted in Figure 24 as IAT 7, and in more detail in Figure 25 [27:957]. This location is also a known structural health issue. The vertical stabilizer torque box experiences both shear and normal forces which over time fatigue the material and lead to a degraded structure. If left unchecked this structure will eventually fail with possible catastrophic results.

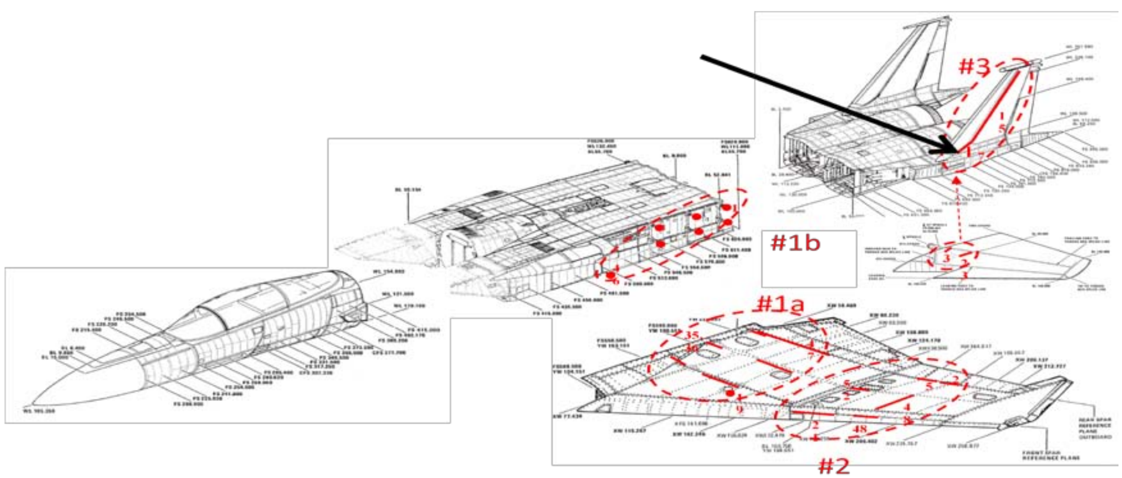


Figure 24 - F-15 IAT Locations [27]

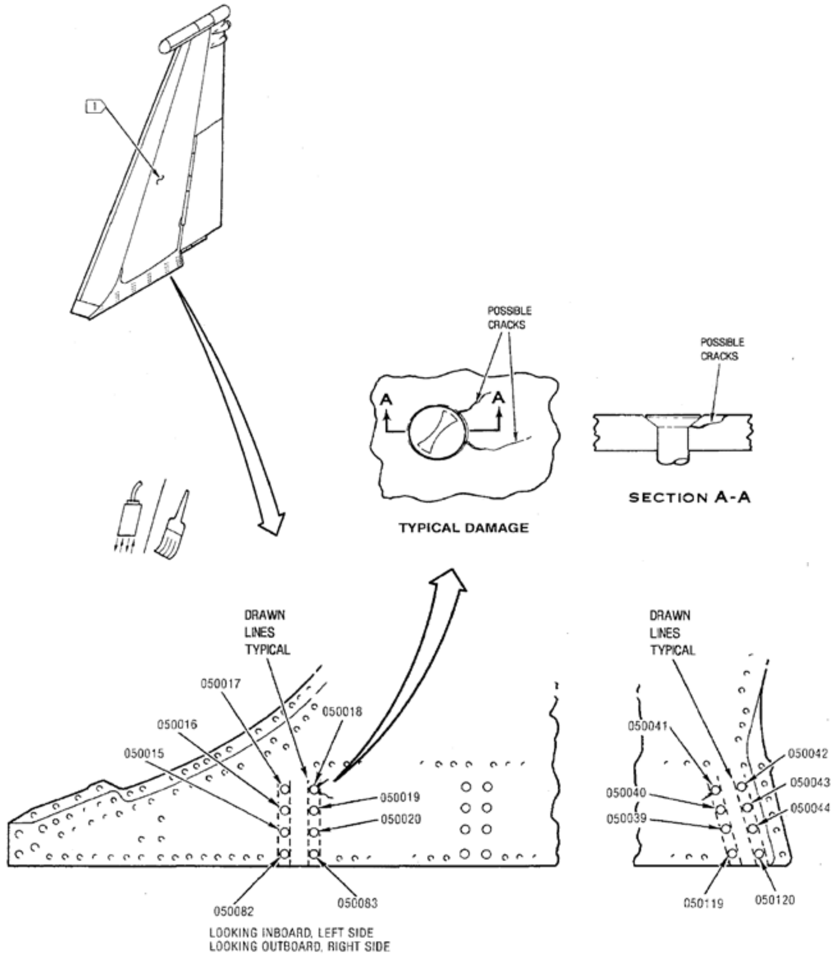


Figure 25 - F-15 Vertical Stabilizer Torque Box Splice [27]

Current inspection methods utilize eddy current probe measurements of fastener holes on both sides of each vertical stabilizer to determine if cracks exist. The time to conduct the inspection is approximately 210 minutes [28:243]. The required time for aircraft preparation and clean-up is assumed to be 150 minutes. The time between inspections is assumed to be 150 hours, and the estimated hours accrued per year are 200 hours. Given an assumed SHM system life of five years, this leads to a total of approximately seven inspections over the life of the system. The number of systems required to perform the inspections was estimated to be 128 PZT, 90 CVM and one prognostic model. The current inventory of F-15s is 522 [29], and this analysis assumes all will have the respective SHM system installed. Table 7 depicts the values used to assess this inspection location.

Table 7 - F-15 Value Model Input Parameters

Alternative Name	Procurement ($)	Development ($)	Training ($)	Installation ($)	Operation ($)	Prob of Detect	False Detect	Reliability	Aircraft Downtime (hrs)	System Mgmt & Mx (hrs)	Time to Field (yrs)
Piezoelectric Sensor	26280	9579	4789	7680	3360	0.9	0.05	0.9	14	10	4
CVM Sensor	29500	1916	4789	7200	3360	0.95	0.05	0.9	14	8	1
Prognostic Model	50000	9579	4789	1200	6720	0.93	0.2	0.99	14	5	3
Continue Current Ops	0	0	0	0	10080	0.95	0.3	0.95	42	0	0

Given the preceding discussion and values, the value model developed in section 5.1 was applied to the F-15 vertical stabilizer torque box location. Figure 26 displays the result of this analysis.

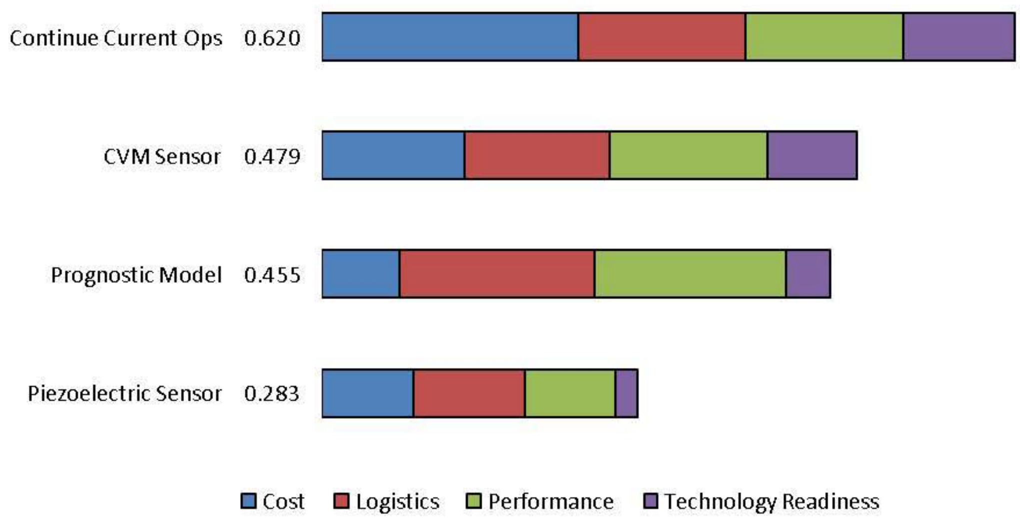


Figure 26 - SHM Value Model Results for F-15 Vertical Tail Torque Box

It is evident from the results that continuing with the current manual inspections provides the most value for this inspection location. This option was the most valuable because it was the most cost effective as indicated on the bar graphs. The SHM alternatives of the CVM sensor and the prognostic model were relatively close in value, and the PZT sensor alternative provided the least value. A sensitivity analysis was also performed for cost, performance and logistics and can be found in Appendix G.

5.2.2 A Case for Sensors

Given the three cases just presented, the result was the same in each: continue current operations was the most valuable option. This is consistent with current Air Force practices, however it begs the question; "What would it take for any other option to become the best?" There is no specific answer to this question, but there are several factors in any number of combinations that would lead to other alternatives being the best option. For example, cost could be decreased, performance improved, logistics footprint reduced, and technology readiness improved. The research team then re-examined the C-130 rainbow fitting case with several new assumptions.

The new assumptions for the C-130 rainbow fitting case were all cost parameters remained the same, probability of detection was increased to 0.95 for both PZT and CVM sensors, reliability was increased to 0.95 for both PZT and CVM sensors, system maintenance and management was decreased to 10 hours/year for PZT and CVM sensors, and finally, time to field was reduced to one year. Table 8 summarizes the updated measures used in this example.

Table 8 - Updated C-130 Measures

Alternative Name	Prob of Detect	Reliability	System Mgmt & Mx	Time to Field
PZT Sensor	0.90 → 0.95	0.90 → 0.95	17 → 10	4 → 1
CVM Sensor	0.93 → 0.95	0.90 → 0.95	17 → 10	1 → 1
Prognostic Model	0.95 → 0.95	0.99 → 0.99	7 → 7	3 → 3
Continue Current Ops	0.95 → 0.95	0.95 → 0.95	0 → 0	0 → 0

These new values are reasonable as they are consistent with the values utilized for the "continue current operations". Essentially, the research team is making the assumption that a sensor solution parameters are as good as current maintenance practices. Given these new values, Table 9 depicts the new parameters utilized as inputs for the value model.

Table 9 - Updated C-130 Value Model Inputs

Alternative Name	Procurement ($)	Development ($)	Training ($)	Installation ($)	Operation ($)	Prob of Detect	False Detect	Reliability	Aircraft Downtime (hrs)	System Mgmt & Mx (hrs)	Time to Field (yrs)
Piezoelectric Sensor	26920	11494	5747	11520	48000	0.95	0.05	0.95	200	10	1
CVM Sensor	34600	2299	5747	11520	48000	0.95	0.05	0.95	200	10	1
Prognostic Model	50000	11494	5747	1200	48000	0.95	0.2	0.99	200	7	3
Continue Current Ops	0	0	0	0	144000	0.95	0.3	0.95	600	0	0

The results of the value model with the updated inputs are depicted in Figure 27.

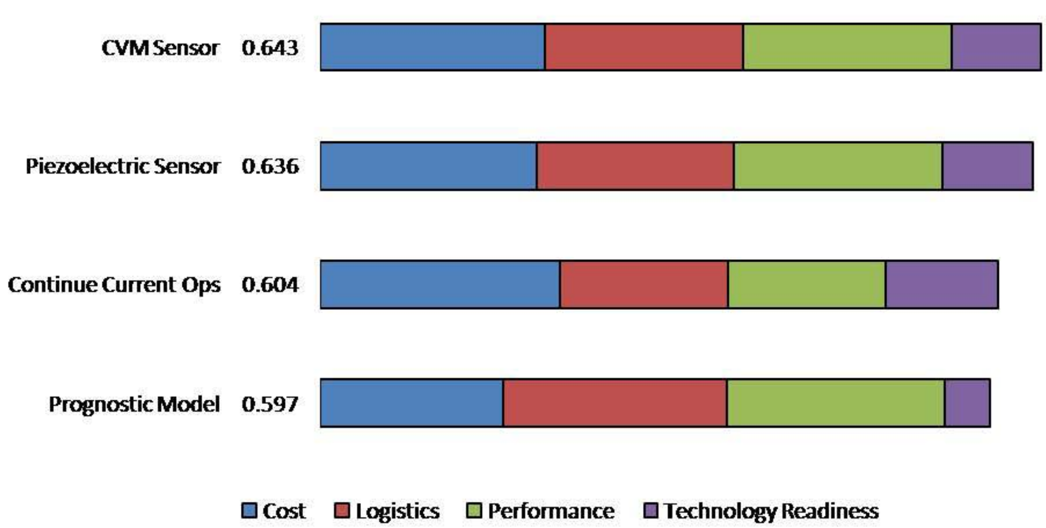


Figure 27 - Updated SHM Value Model Results for C-130 Rainbow Fitting

As evident in Figure 27, the top two options are now sensors (CVM and PZT respectively). This indicates that if sensors can improve in performance, reliability, and time to field as presented above, they provide the most value to solving our structural state awareness issue. These results can also help decision makers decide where it makes sense to focus research and development dollars. In the example just provided, decision makers now have some insight as to which parameters affect various SHM alternatives. With this knowledge they now have the ability to focus their efforts in a more cost-effective manner.

5.2.3 Summary of Results

The value model was applied to three different aircraft and three different inspection locations. This emphasizes the versatility and flexibility of the model to be applied to virtually any aircraft and inspection location. In all three scenarios examined, the SHM alternative that provided the most value as assessed by the model was to continue performing maintenance as is currently being done today. The reason for this is that even though alternative forms of SHM may provide a reduced operational cost in the form of fewer aircraft inspections and reduced aircraft downtime, those gains are often offset by the cost, performance, and logistics burden incurred with adding another system to the aircraft. This was substantiated by the discussions the research team conducted with program office engineers and maintenance personnel at Warner-Robins AFB and Hill AFB. In order to determine what it would take for any other SHM alternative to become the best option, the research team then re-evaluated the C-130 scenario utilizing new values for probability of detection, reliability, system maintenance and management, and time to field. The results utilizing these new parameters indicate that there are scenarios where it may make sense to utilize alternative forms of SHM. This result is predicated however, on the assumption that sensor technology advances to the point where it becomes on par with current operations.

In order for any alternative form of SHM to be widely implemented one or a combination of several things must happen. The overall cost of alternative SHM methods must be reduced, performance must be increased, the logistics impact must be kept to a minimum, and they need to be ready for operational use quickly. The overall cost (procurement, development, training, installation and operation) must be reduced to a point where they are an economically viable option. The performance must also be equal to or better than what is obtained with current NDE inspection methods. As the performance of alternative SHM system improves, they also become a more viable option. Finally, the increased logistics burden associated with adding any system to an existing aircraft must be kept to a minimum. The maintenance and logistics personnel currently operating today's aircraft are doing their best just to keep the aircraft flying, and adding additional workload in the form of additional system maintenance must be kept to an absolute minimum if any alternative form of SHM is to be accepted.

VI. Conclusions and Recommendations

6.0 Conclusions and Recommendations

Throughout the research conducted for this study, several conclusions emerged. Each conclusion then led to a recommendation(s) for near-term and/or long-term consideration. The authors hope that the accomplishment of the recommended actions will further the development of an integrated system that gives logisticians, maintainers, and engineers a better understanding of the structural state of each aircraft in the aging fleet and advance the ISHMS concept closer to implementation.

6.1 ISHMS—An Integrated Solution

By definition, an ISHMS must be developed using an integrated, holistic approach to accomplishing SHM. By incorporating elements from a wide range of options and enabling technologies, an integrated system captures the best features of each alternative and, in true "systems" style, leverages the synergies among them to produce a system that is more effective than the sum of the individual parts. From continued current operations, such as eddy current detection, to improved data collection and management to emerging sensor technologies and predictive modeling, each alternative presents its own benefits and shortcomings. To develop an optimal solution, an ISHMS must embrace the positive attributes of each aspect while minimizing the drawbacks.

Recommendation 1: Any future research and development of an ISHMS must take a broader, whole system perspective than just focusing on a technology solution. While sensors and models are likely a piece of the system solution, opportunities exist to improve current operations, training, and data collection and management. The question to be answered is, "How can we take advantage of simple, inexpensive—or even better no cost—process improvements and COTS technology to gain a better understanding of the state of the aircraft structure, as well as minimize damage induced by the inspection process itself?" Every aspect must be reviewed and scrubbed, and the entire scope of SHM practices and enabling technologies must be considered in order to achieve CBM and AFSO21 goals.

6.2 Value Model

6.2.1 Tailored Solutions.

The value model presented herein is a flexible and scalable decision tool. It can be easily modified and refined for different platform types, individual tail numbers, or even particular locations on a particular platform to help users make informed decisions on the best alternative(s) for a given situation.

Recommendation 2: A follow-on study should be conducted that focuses on applying the value model to determine the best alternative(s) using validated inputs for a real-world SHM scenario(s). Given the appropriate set(s) of data, seemingly endless opportunities for using this model as a decision tool exist. These include, but are not limited to, using the model to tailor SHM activities and enabling technologies for not only individual tail numbers but specific locations on each aircraft.

6.2.2 Drive Future Efforts.

Of equal importance is the model's ability to highlight current weaknesses of each alternative. By identifying areas of greatest opportunity for improvement, researchers can better focus their efforts to advance certain technologies and overcome associated implementation challenges. Additionally, developers can use the model to lay out system requirements and determine cost and performance measures that must be demonstrated by each alternative in order to be a viable option for implementation.

Recommendation 3: Once validated inputs have been used to analyze a real-world SHM scenario, areas of weakness must be identified to drive R&D toward solutions that will be feasible to implement. This assessment should include system cost and performance requirements for each enabling technology currently under development.

6.3 Sensor Technology

6.3.1 Applicability.

Sensor technologies have broad applicability and utility for new aircraft, such as the F-22, F-35, and future KC-45, as they roll off the production line. However, implementation of sensors on the legacy fleet presents unique challenges that limit applicability. The value model can help identify where it makes sense to install sensors once the keys to implementation (discussed in the next section) are adequately satisfied.

Recommendation 4: Assuming these keys to implementation are met, proven sensor technologies must be evaluated for implementation on aircraft that are currently being produced and/or projected to be produced in the future. Platforms such as the F-22, F-35, and the proposed tanker are all excellent candidates for including crack- and corrosion-detecting sensors as part of an ISHMS design. And as key enablers of CBM, these sensors have the potential to significantly cut O&M costs over the service life of the aircraft.

Recommendation 5: Given the complex nature and associated expense of installing sensors on legacy platforms, the value model should be used to determine where/when to incorporate sensors into an aging aircraft ISHMS design. The unique challenges presented by retrofitting the fleet are too fiscally and logistically cumbersome to speculate on the potential benefits. In an objective, traceable manner, the value model can/should be used to clearly point decision makers toward installation of sensors on legacy jets before bearing the burdens of doing so can be justified.

6.3.2 Keys to Implementation.

6.3.2.1 Cost-Benefit Analysis.

However, before sensors are integrated into any ISHMS design, an in-depth, detailed cost-benefit analysis must reveal a compelling business case. In the case of existing aircraft, without clear evidence that a positive return on investment would be realized in a relatively short period of time, neither the operational community (ACC, AMC, AFSOC) nor the logistics centers will be able to justify the expense associated with developing and implementing sensor technology for SHM purposes.

Recommendation 6: A detailed cost estimate and cost-benefit analysis of sensor development and implementation must be completed. This study could be done as a stand-alone project or incorporated into the real-world scenario study previously recommended (ref. Recommendation 2.) If the results of the analysis indicate a favorable return on investment is likely to materialize in a suitable period of time (i.e., sometime before the aircraft is expected to be retired), continued research and development of SHM sensors is warranted.

6.3.2.2 Demonstrated Durability & Reliability.

In addition to a convincing business case, sensors must demonstrate they can be trusted. Maintainers cannot afford a significant number of false alarms which create more work, unnecessary downtime, and chew up valuable resources. Conversely, if the sensors are unreliable (i.e., fail to detect a critical flaw in the structure), safety of flight may be compromised. To date, results of sensor durability and reliability tests are inconclusive.

Recommendation 7: The test community should begin a flight demonstration on a variety of platforms, placing sensors in locations that have been identified by the value model as good opportunities for sensors to streamline current SHM operations. The C-130 center wing location that was examined in this study would be a prime candidate for this test program. The purpose of the demonstration would be to prove out the durability and reliability of one or more sensor types by exposing them to real-world operational environments.

Further it would serve as an initial phase in a 3-phase implementation plan. During this first phase, current inspections would continue as the sensors are being tested. Once confidence is gained in the sensors' ability to accurately meet SHM objectives, a second phase would begin and call for inspections to be skipped as was modeled in Chapter 5. Ultimately, after the sensors have been fully tested and prove to be durable enough and reliable enough to survive and operate properly in an operational environment, a third phase of implementation that transitions operations to a total CBM concept and eliminates scheduled inspection cycles would be appropriate. During this CBM nirvana, inspections only occur when a sensor indicates damage has been incurred, and thus the aircraft must be inspected and possibly repaired.

6.4 Information Collection & Management

Currently, a central database captures flight and maintenance action information to estimate remaining useful life. However, other technologies exist that could streamline data collection and improve the fidelity and effectiveness of the predictive models. For example, a simple, but robust flight data recorder that is used regularly in commercial airline operations offers engineers easy access to information related to the environment and loading to which the aircraft has been exposed. This information can then be fused with other clues to provide a clearer picture of the aircraft's structural state and perhaps yield enough insight to confidently stretch inspection intervals, thus reducing downtime and saving resources.

Recommendation 8: Readily available technologies that are intended to streamline data collection efforts and/or improve the fidelity of the existing models should be explored. Future technologies that enable the collating and analysis of multi-sourced data sets should also be pursued. Such advances can increase awareness of the aircraft's structural state without necessarily taking it out of service for inspection thus reducing asset downtime and saving O&M dollars.

6.5 Political Reality

Within the operational community (ACC, AMC, AFSOC), the contemplation of extending the service life of the aging aircraft fleet, particularly discussions of possible service extensions beyond official retirement dates that are currently on the books, carries a sensitivity that has hindered funding and advancement of ISHMS enabling technologies. Such hypothetical assessments are discouraged for fear that they may produce results that would negate the case for recapitalizing the fleet with new aircraft. This sensitivity also limits the timeline for seeing a positive return on investment and makes it very difficult to produce a compelling business case.

Recommendation 9: As fiscal constraints continue to tighten, the support and operational communities should engage in a dialogue aimed at assessing the risk associated with basing current operational, support, and budget plans on a couple of key assumptions: (a) Aircraft will actually be retired by the projected official expiration dates, and (b) those jets will actually be replaced with enough new assets to fully execute the warfighting mission. In addition to ascertaining the likelihood of one or both of these suppositions proving to be a false, a contingency plan must be agreed to that addresses how each functional community will deal with the predicament presented if either of these assumptions falls through. In which case, the legacy fleet will likely continue to carry the majority of the warfighting mission well into the future, making the case for investing in SHM technology development and process improvement much stronger and maybe even an absolute necessity.

6.6 Strategic Focus

6.6.1 SHM & ISHMS Development.

Currently, the USAF, and in particular the R&D and logistics communities within the AF (AFRL & ALCs, respectively), lacks a single focal point for SHM and the development of an ISHMS. Although a number of individuals and/or individual offices in both communities are working to develop solutions (or at least pieces of a solution), no one with appropriate authority has the taken on/been assigned the responsibility of defining a single vision for what SHM should be…. As the old adage goes, "You'll never get there if you don't know where you're going." This lack of vision and focused effort unfortunately seems to be a significant stumbling block for the development of a workable solution to SHM and implementation of an ISHMS.

Recommendation 10: A single focal point for SHM and the development of an ISHMS should be established. This office/IPT should be comprised of an interdisciplinary staff with representatives from the research, logistics, maintenance, operational, engineering, and acquisition communities. The organization would be responsible for guiding enterprise research and developing the most cost-effective "integrated system approach" solution to achieving aircraft structural state awareness.

6.6.2 Next Generation Maintenance & Support Systems Development.

From a broader, enterprise-level perspective, to date the authors are unable to identify a clear focal point within the USAF (R&D and logistics communities) that is responsible for tracking and developing technologies aimed at advancing maintenance and support operations. Sadly, it seems these extremely important and expensive mission areas are left to "fend for themselves" when it comes to improving the way the fleet is supported and maintained. The maintenance, logistics, and support communities must remain dedicated to accomplishing the mission at hand which leaves little time and resources for pursuing new technologies. As such, the Force, as an enterprise is failing to keep up with industry counterparts, as well as foreign entities, in equipping maintainers and support personnel with the latest, cutting-edge technologies available. More importantly, because of this neglect the Force is missing out on potential opportunities to improve efficiency, reduce downtimes, and cut O&M costs. Commercial airlines and manufacturers on contract to support them are taking on R&D efforts like those addressed by the Intelligent Maintenance Systems Center… Why isn't the USAF doing the same?

Recommendation 11: If the USAF is serious about AFSO21 and "doing things smarter," advancing the tools and equipment used to maintain and support the fleet must be made a priority and resources allocated accordingly. While industry is exploring cutting edge technologies to cut O&M bills in order to pad profit margins, AFSO21 initiatives like CBM should be driving the enterprise to cut costs and free up dollars for fleet recapitalization. Often in business it is said that "it takes money to make money." Likewise, cutting life cycle costs often requires an up-front investment. In this case, investing in the advancement of the software and hardware tools used to support and maintain the fleet may or may not result in reduced overall life cycle costs… But how can anyone know for sure if no one is responsible for following these technologies and evaluating their potential for cost savings? These important activities must be made the primary focus of an entity charged with researching and developing new and better support equipment and software tools. The USAF can ill afford to leave to chance that those in the trenches will eventually find the time and resources to discover the technologies needed to remain the most dominant air power in the world.

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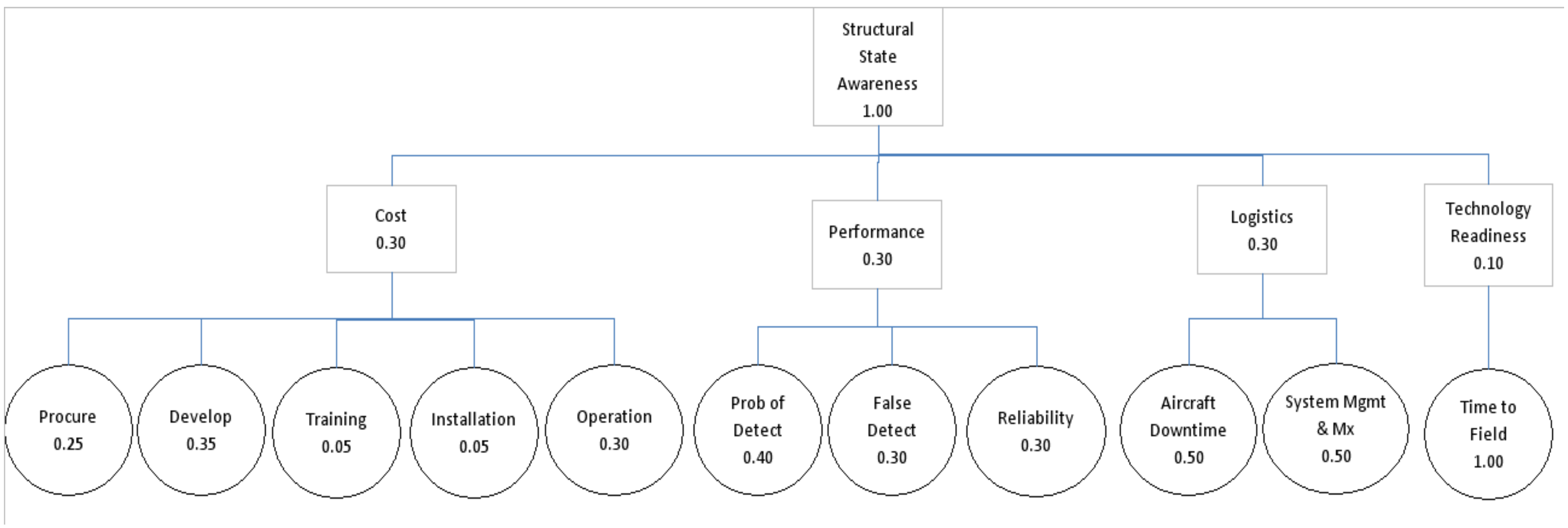
Appendix A - SHM Value Model



Appendix B - C-130 SDVF's

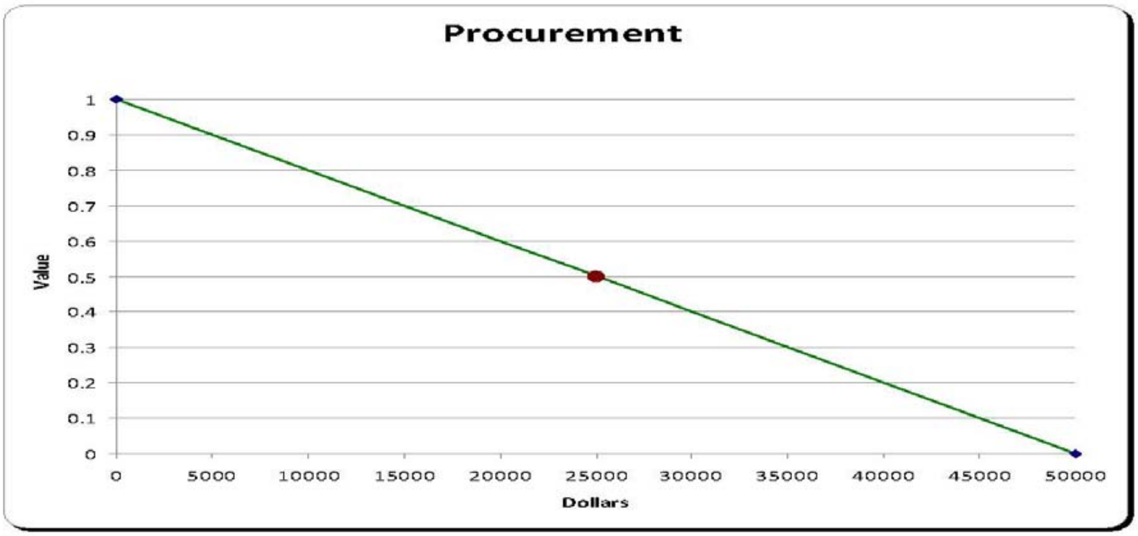


Figure 28 - C-130 Procurement SDVF

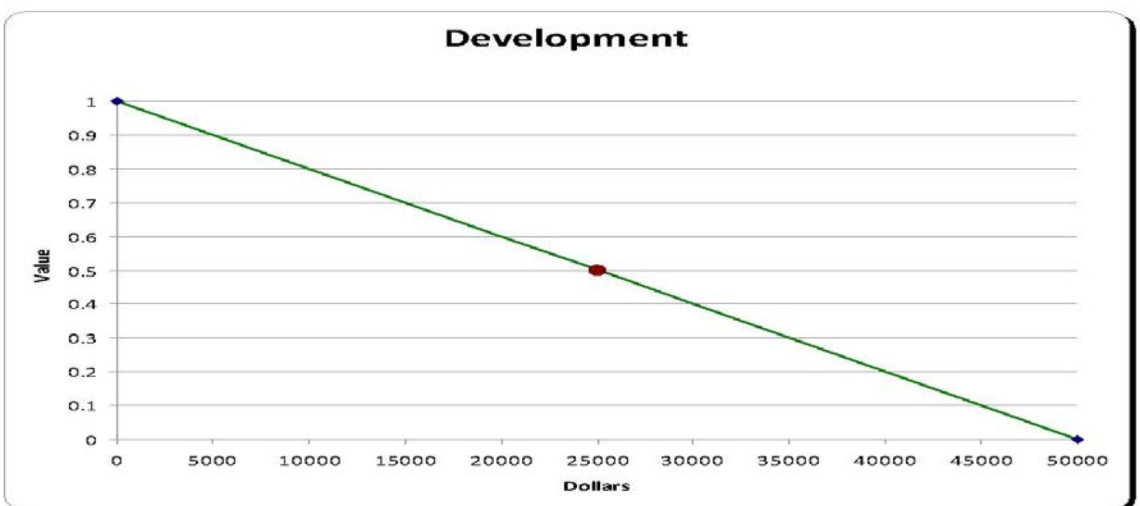


Figure 29 - C-130 Development SDVF

Figure 30 - C-130 Training SDVF

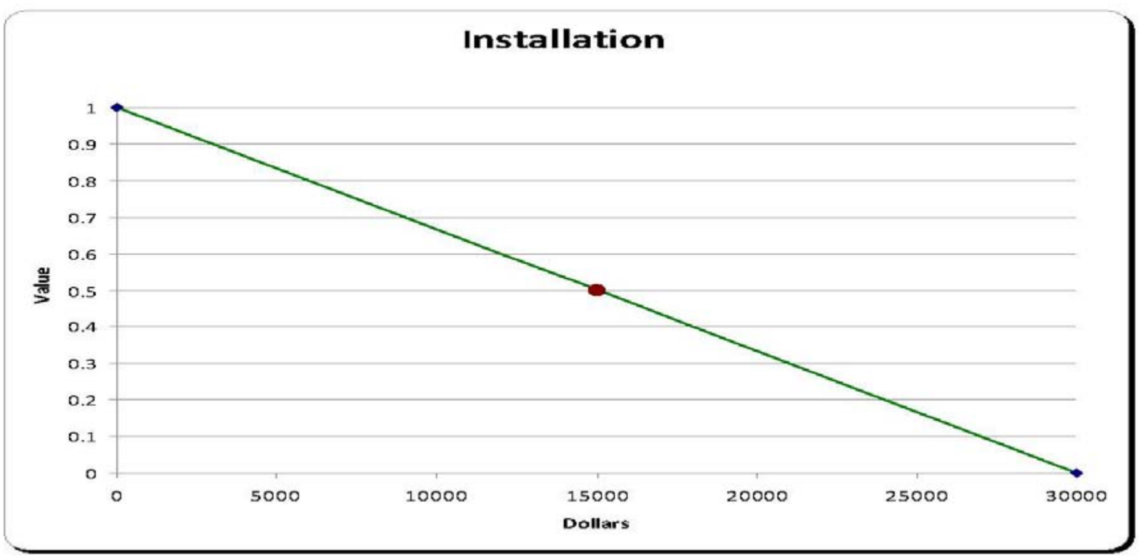


Figure 31 - C-130 Installation SDVF

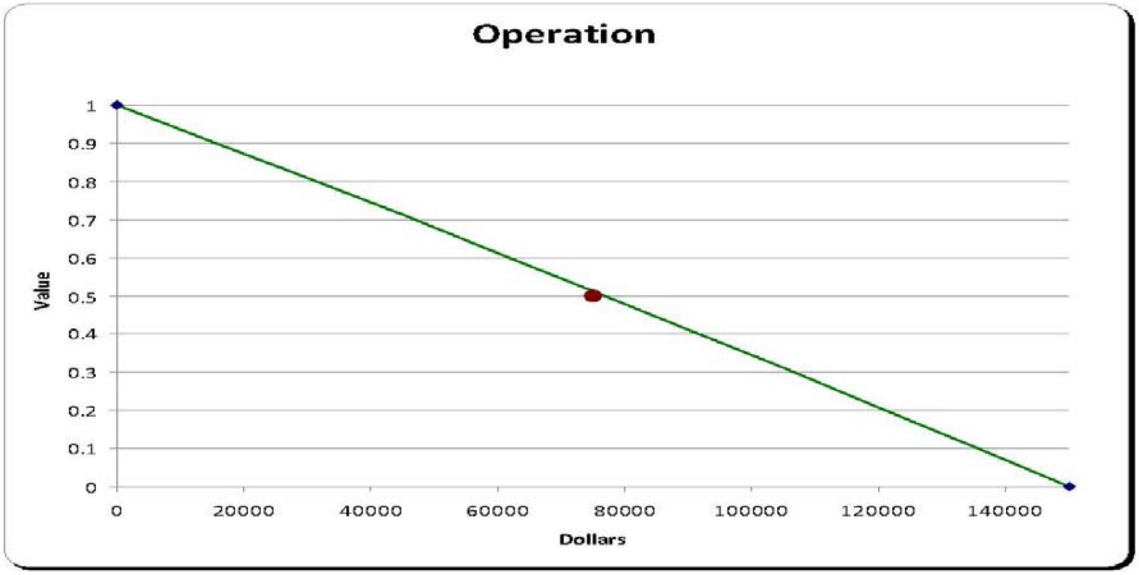


Figure 32 - C-130 Operation SDVF

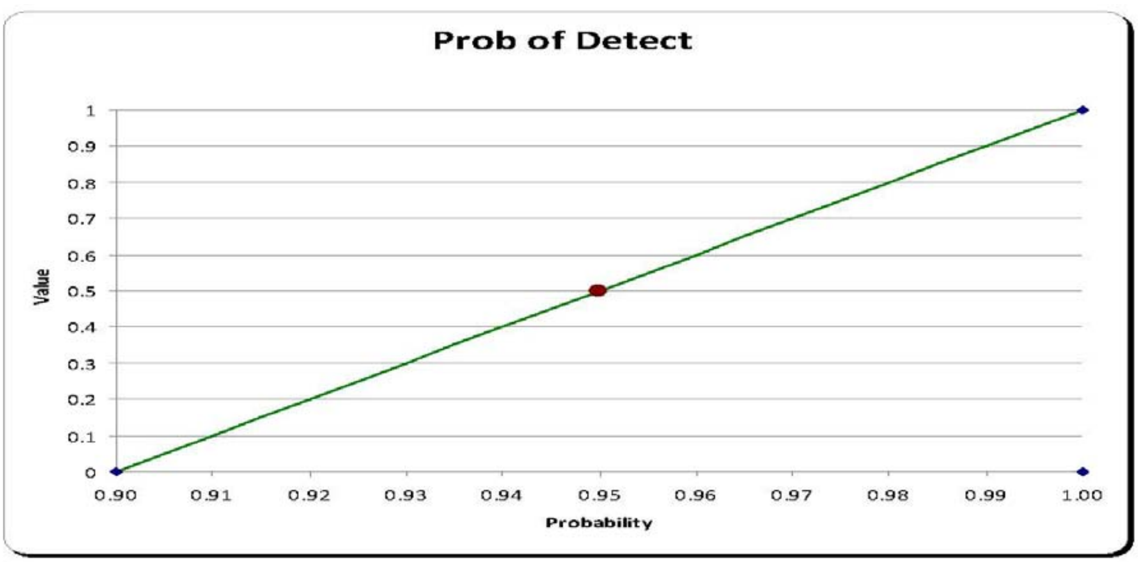


Figure 33 - C-130 Probability of Detection SDVF

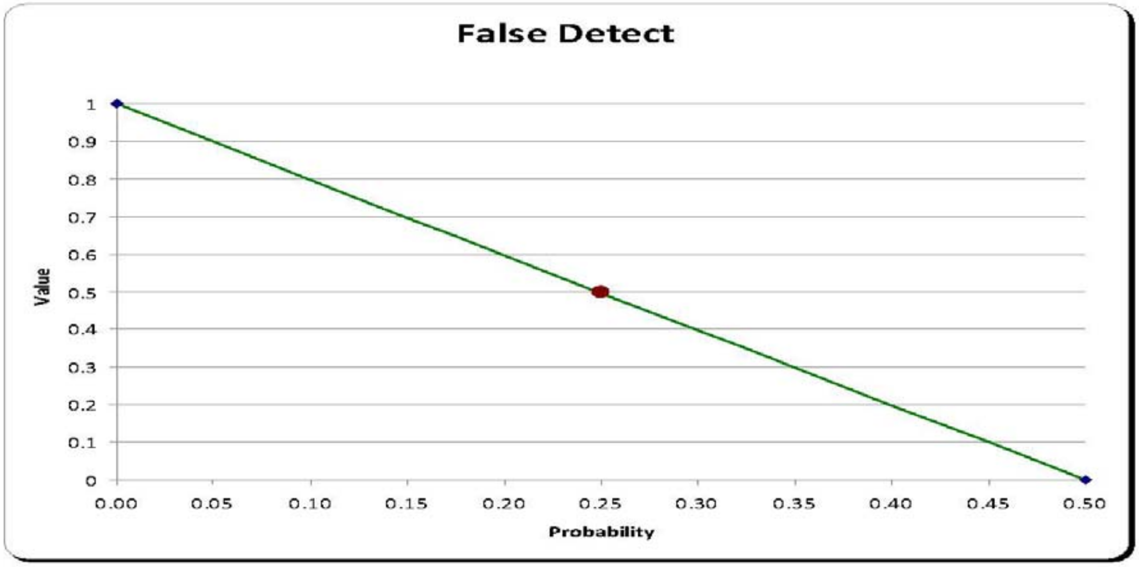


Figure 34 - C-130 Probability of False Detection SDVF

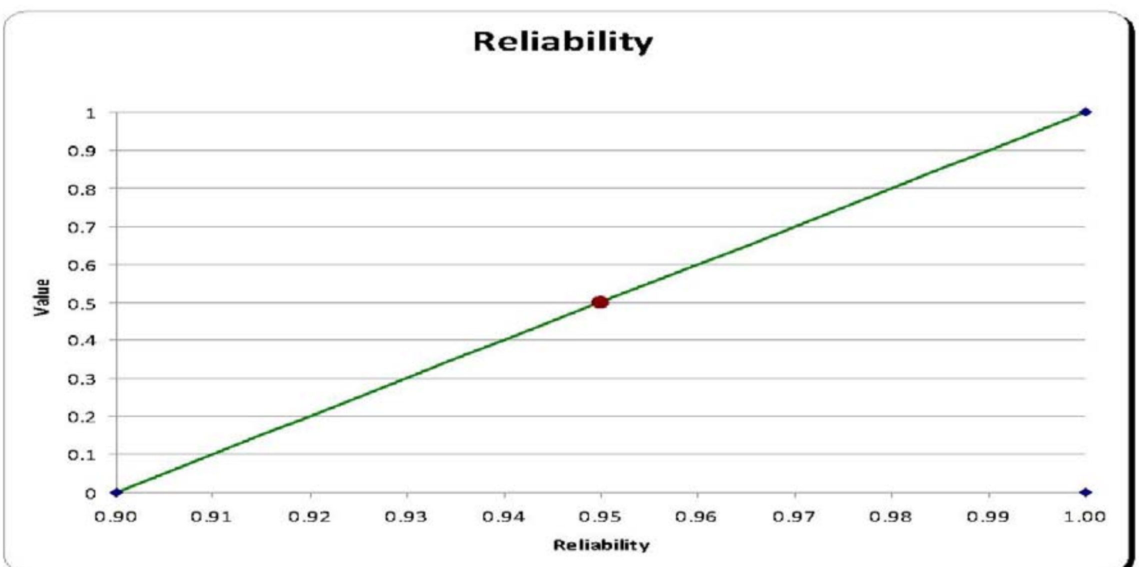


Figure 35 - C-130 Reliability SDVF

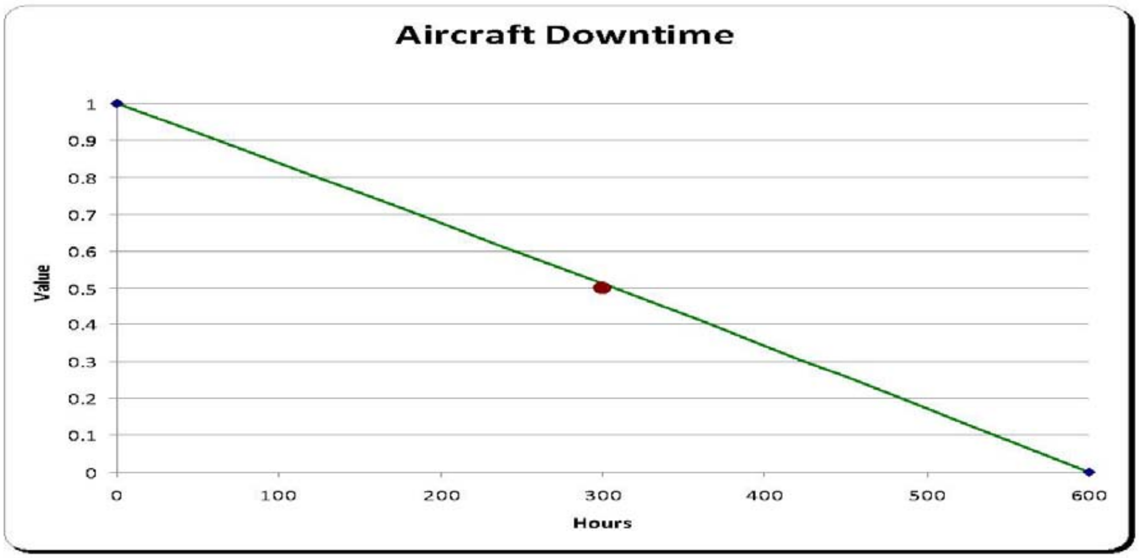


Figure 36 - C-130 Aircraft Downtime SDVF

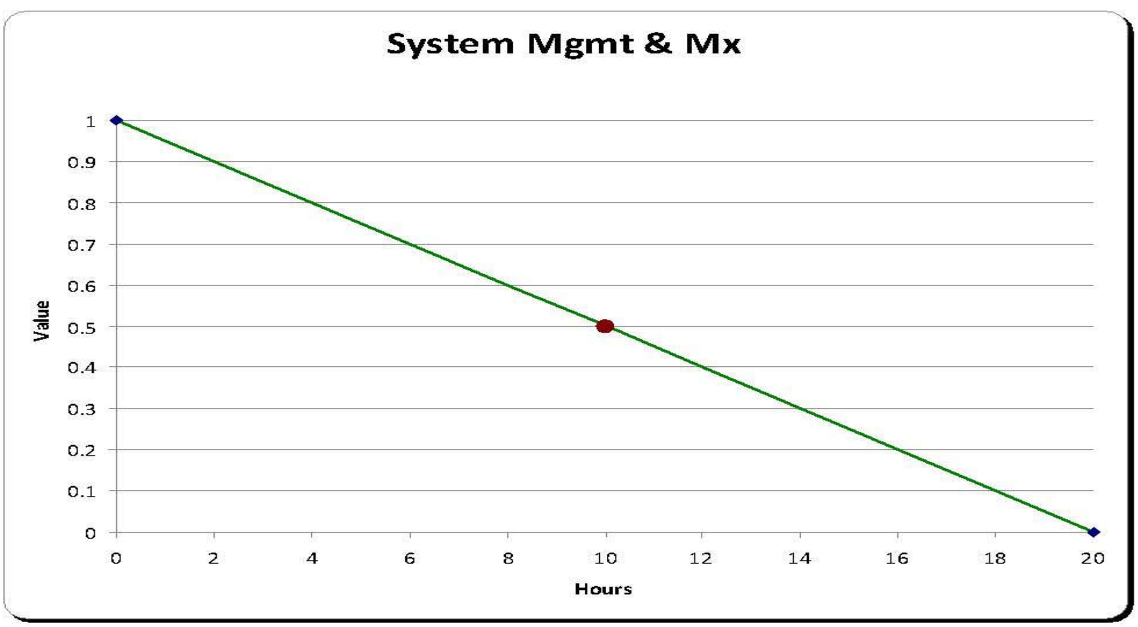


Figure 37 - C-130 System Management & Maintenance SDVF

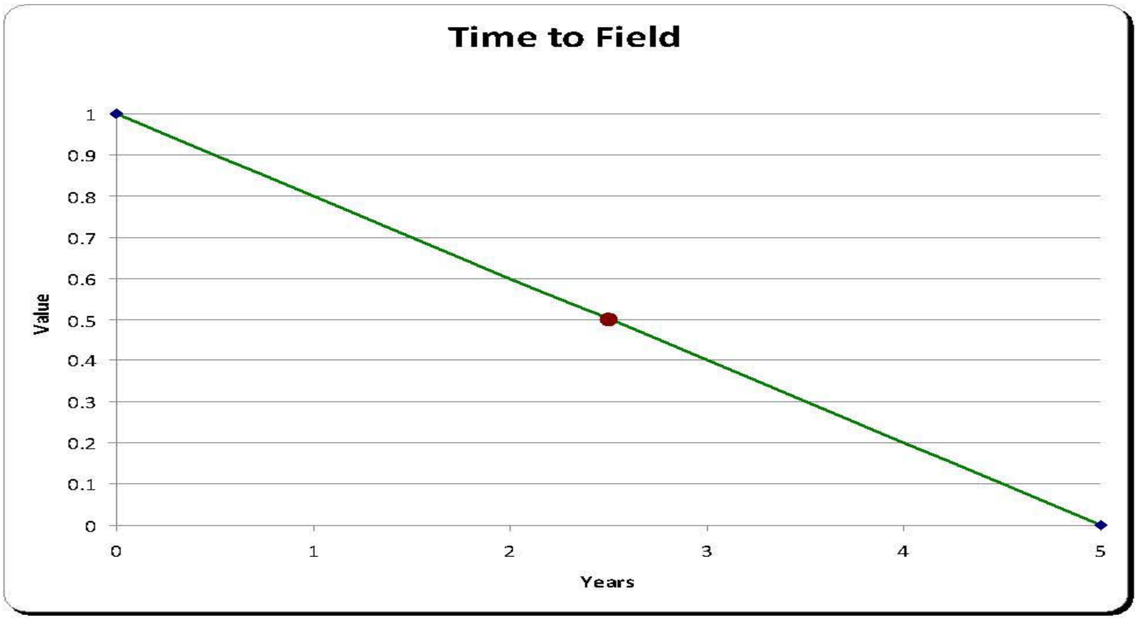


Figure 38 - C-130 Time to Field SDVF

Appendix C - C-130 Sensitivity Analysis

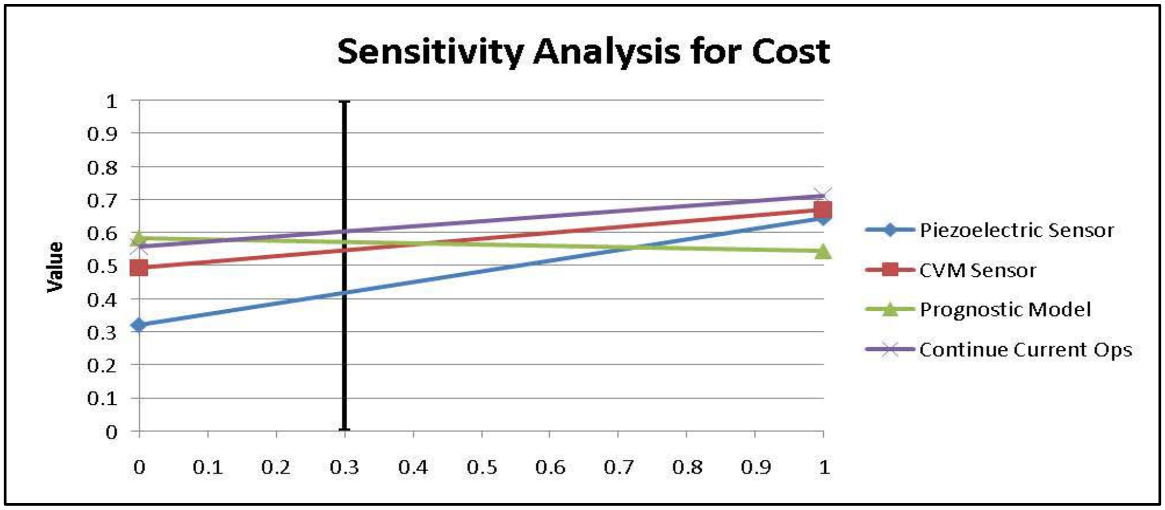


Figure 39 - C-130 Sensitivity Analysis for Cost

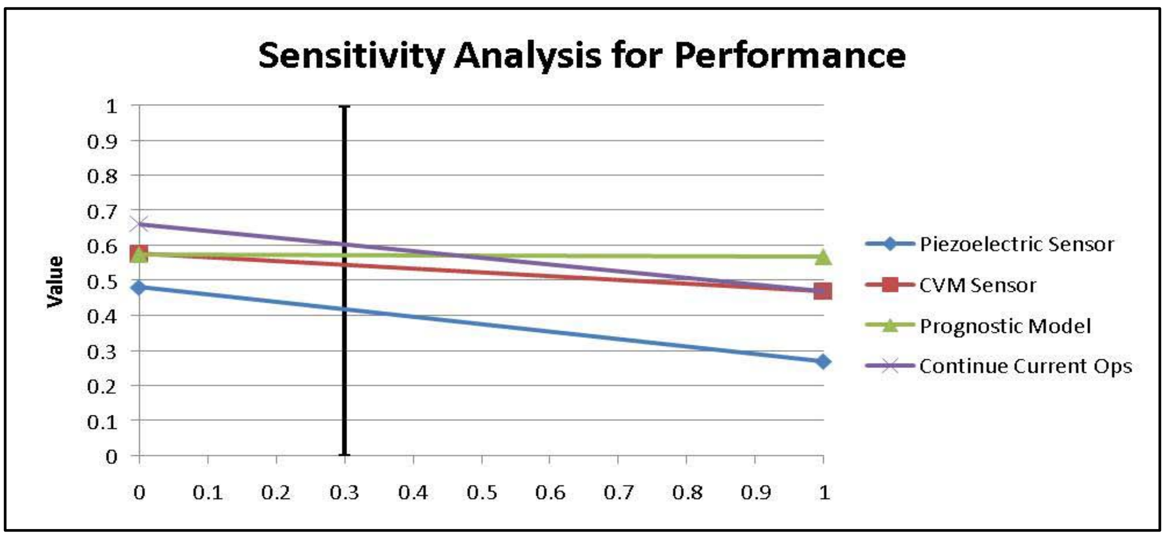


Figure 40 - C-130 Sensitivity Analysis for Performance

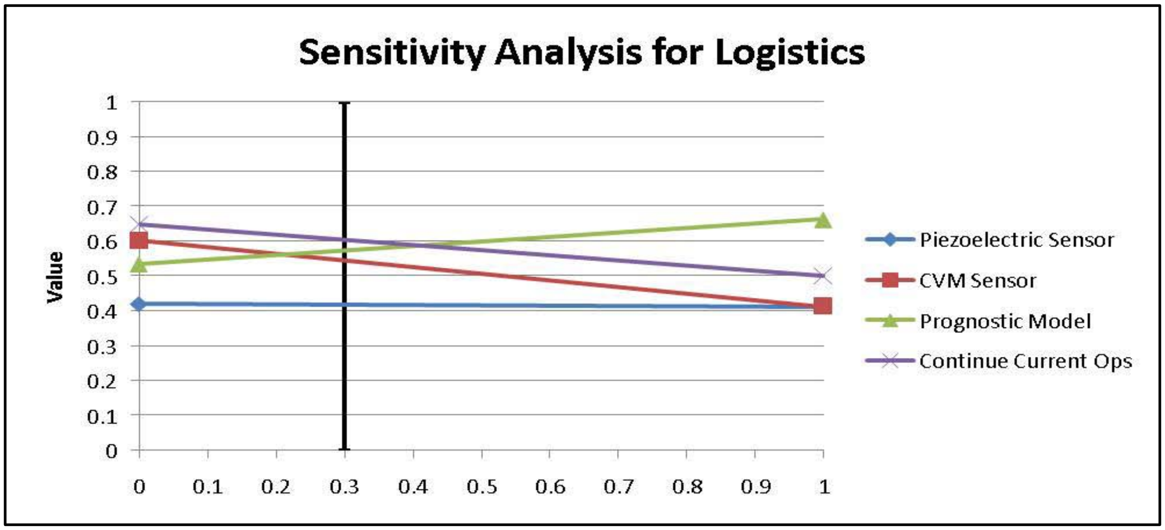


Figure 41 - C-130 Sensitivity Analysis for Logistics

Appendix D - A-10 SDVF's

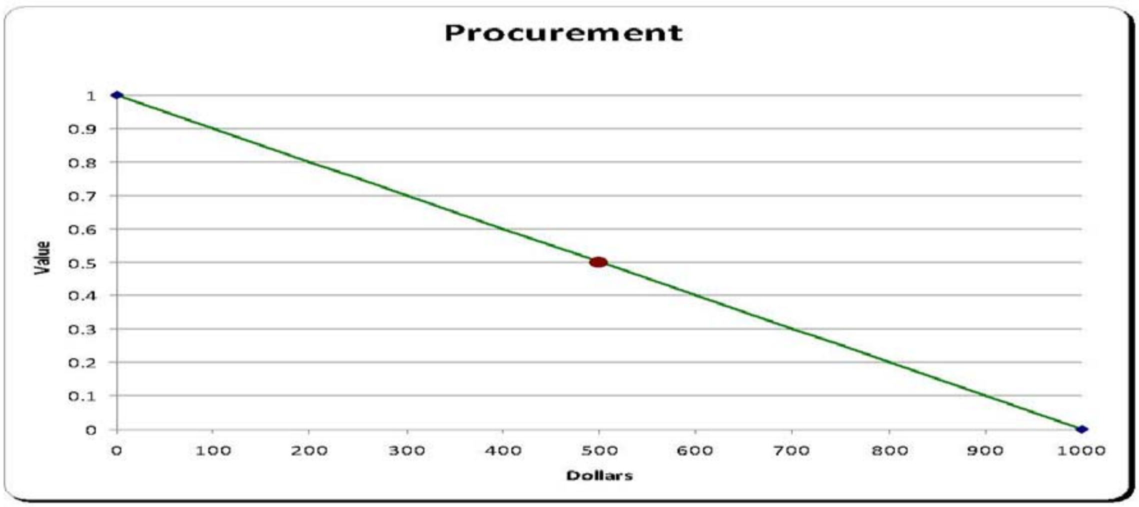


Figure 42 - A-10 Procurement SDVF

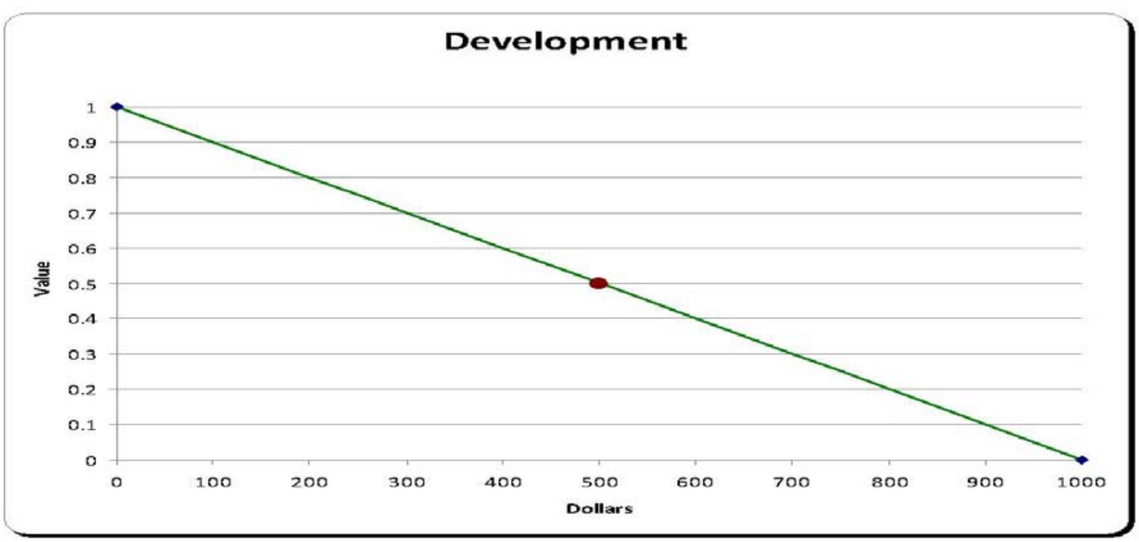


Figure 43 - A-10 Development SDVF

Figure 44 - A-10 Training SDVF

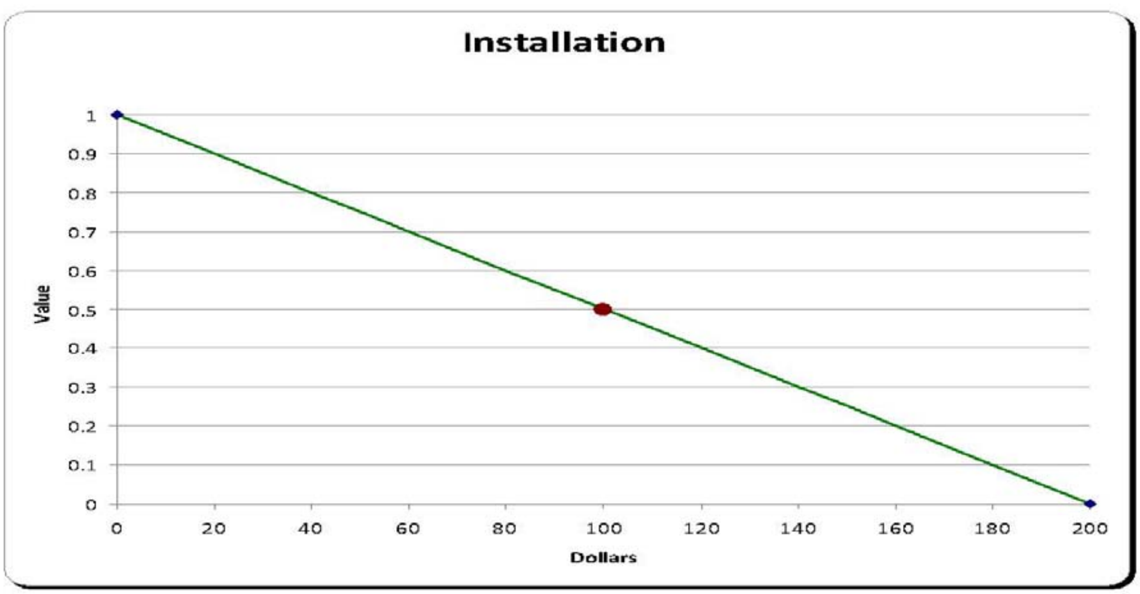


Figure 45 - A-10 Installation SDVF

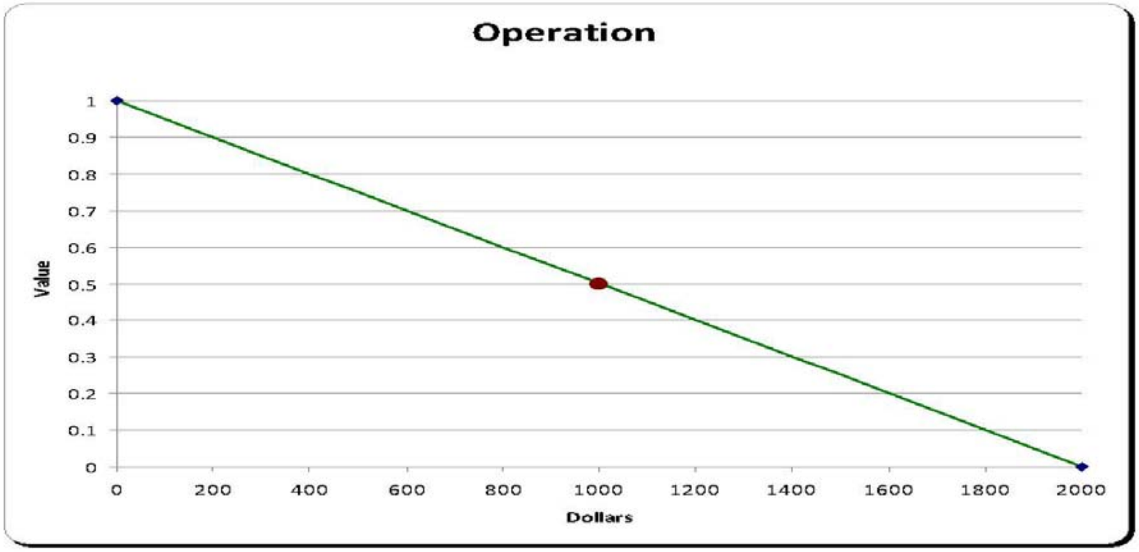


Figure 46 - A-10 Operation SDVF

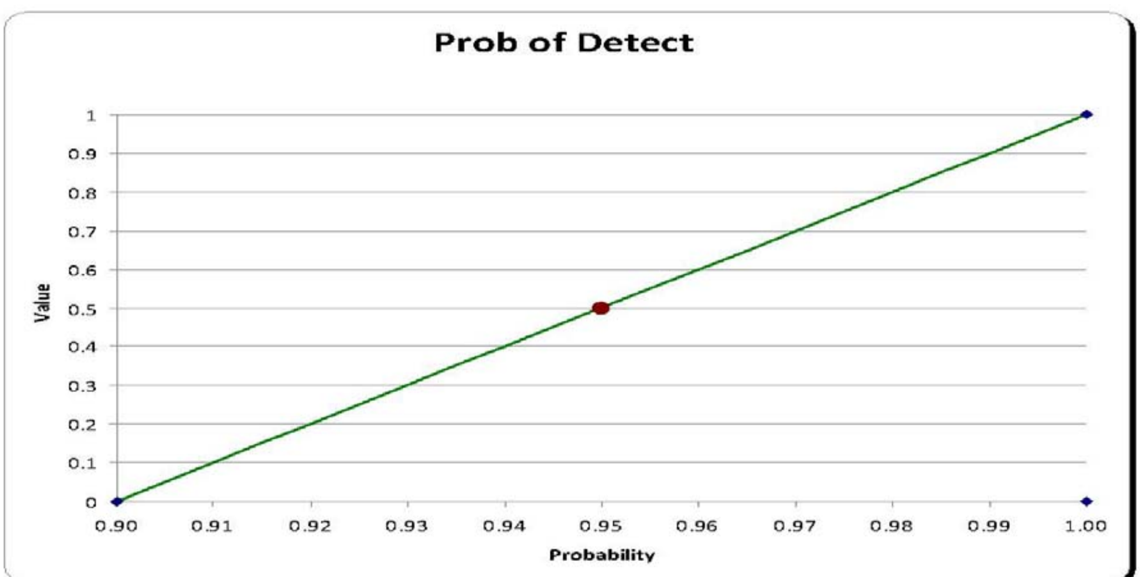


Figure 47 - A-10 Probability of Detection SDVF

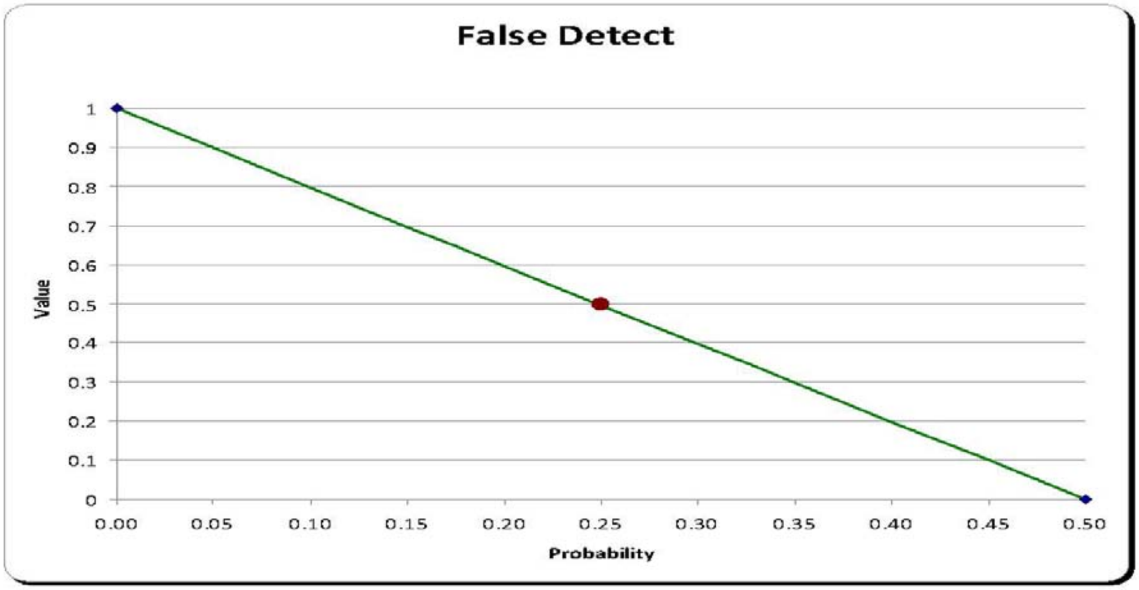


Figure 48 - A-10 Probability of False Detection SDVF

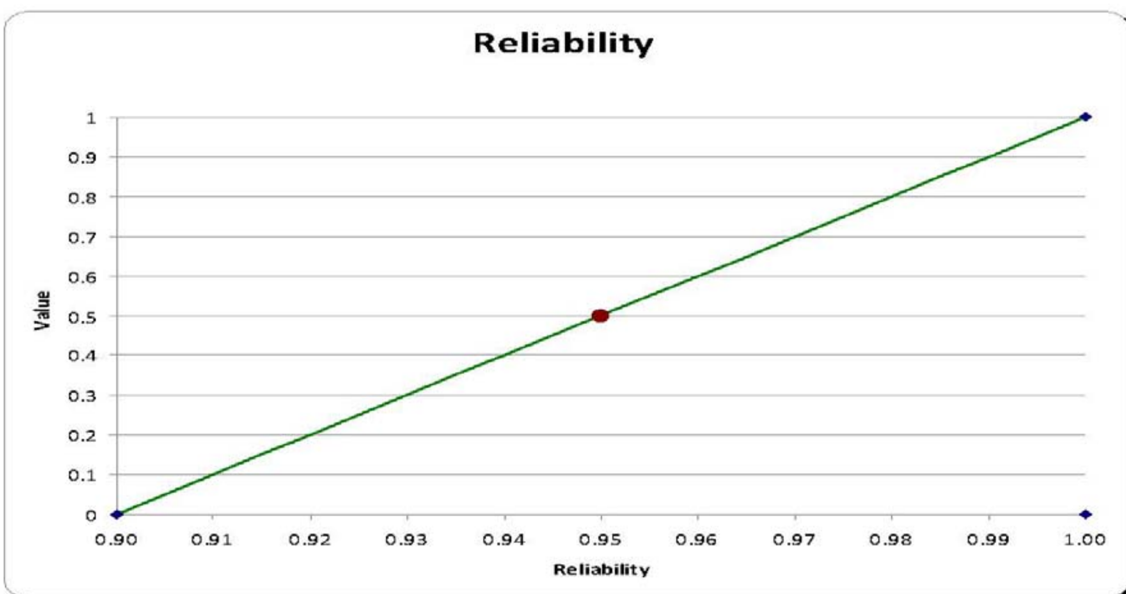


Figure 49 - A-10 Reliability SDVF

Figure 50 - A-10 Aircraft Downtime SDVF

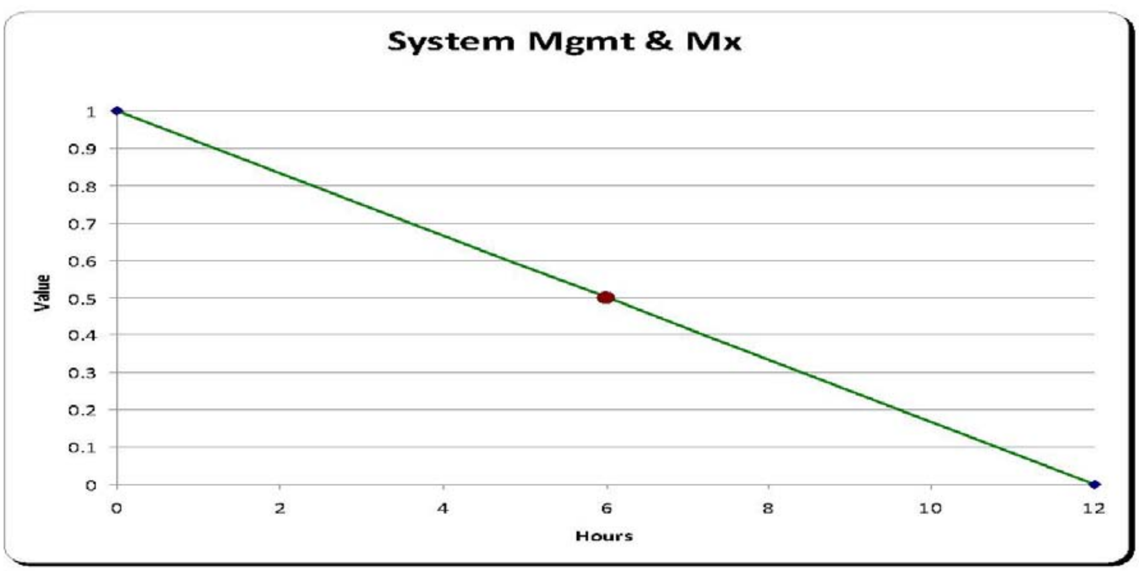


Figure 51 - A-10 System Management & Maintenance SDVF

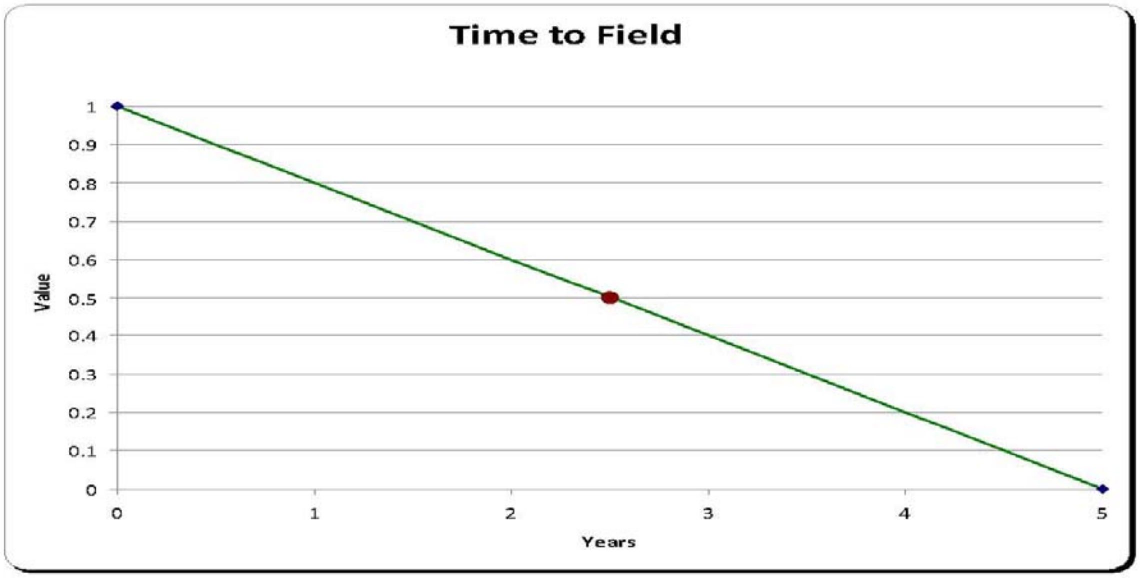


Figure 52 - A-10 Time to Field SDVF

Appendix E - A-10 Sensitivity Analysis

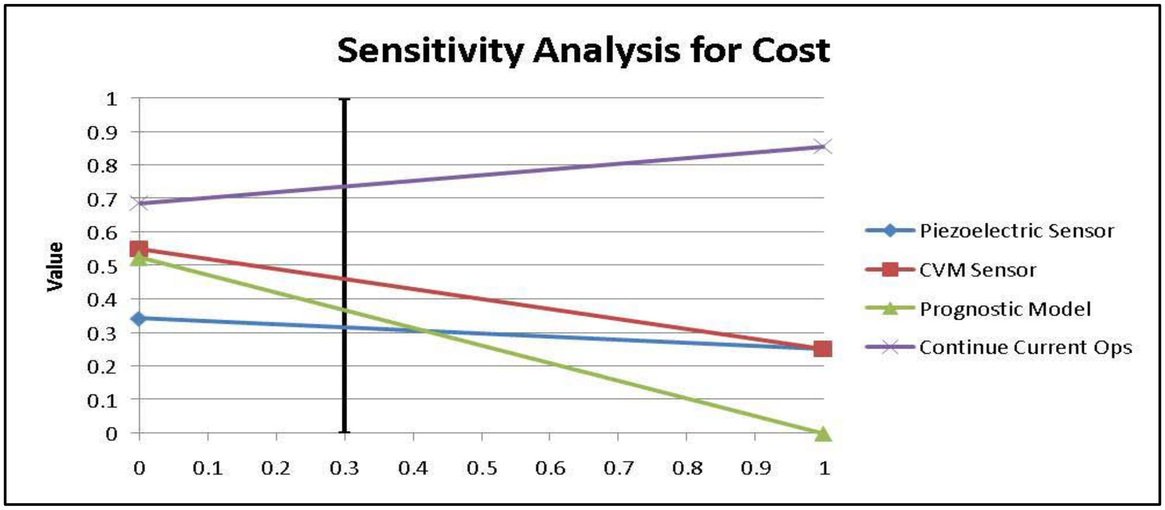


Figure 53 - A-10 Sensitivity Analysis for Cost

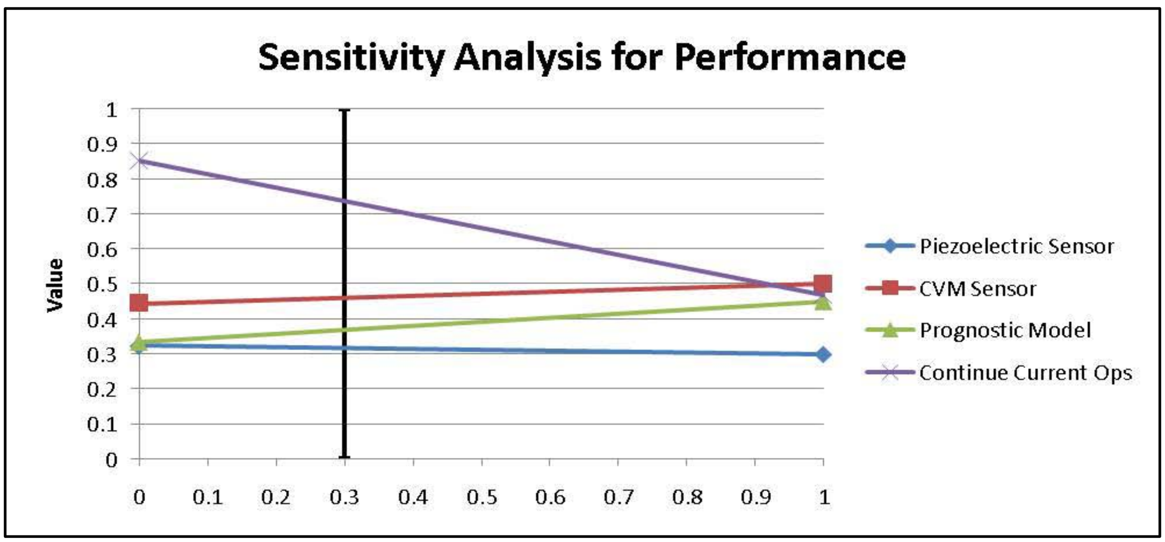


Figure 54 - A-10 Sensitivity Analysis for Performance

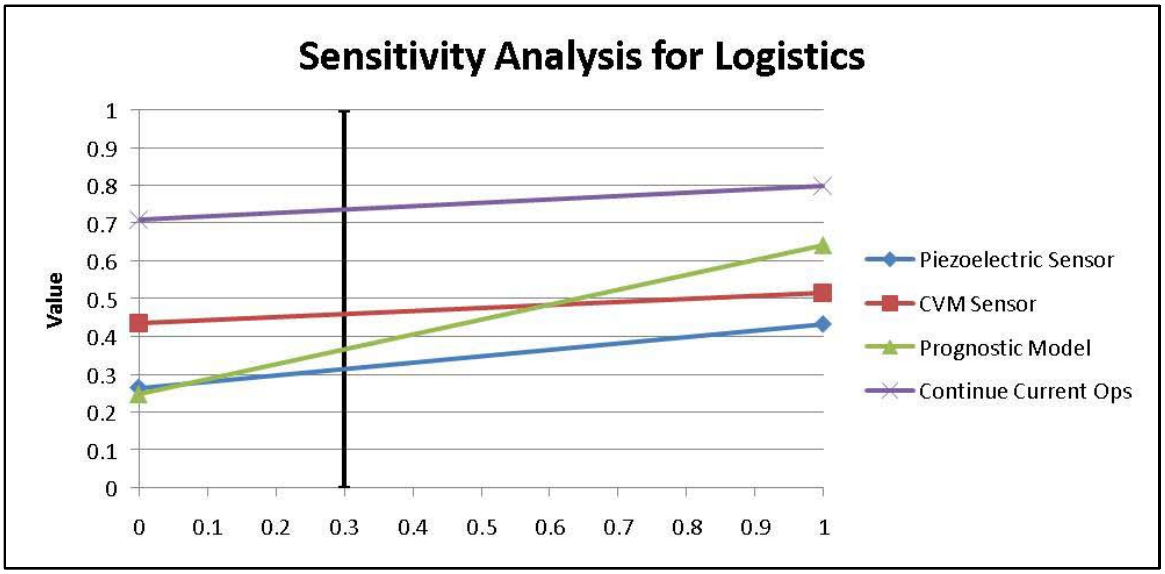


Figure 55 - A-10 Sensitivity Analysis for Logistics

Appendix F - F-15 SDVF's

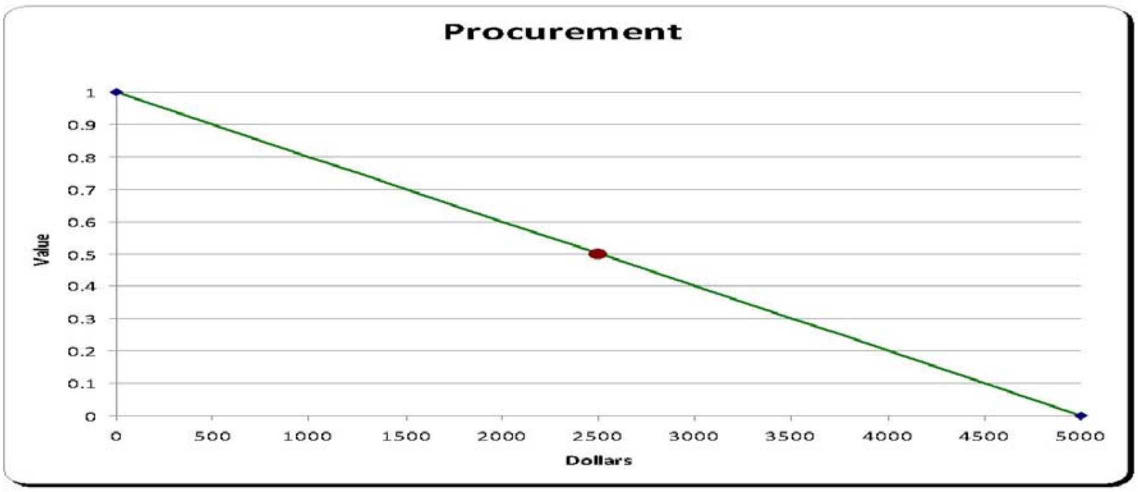


Figure 56 - F-15 Procurement SDVF

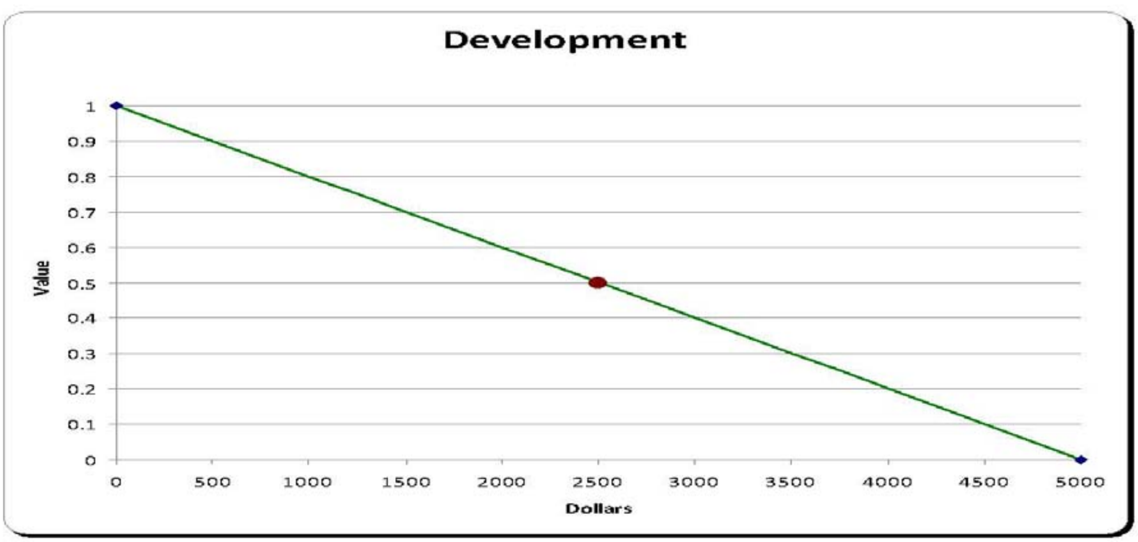


Figure 57 - F-15 Development SDVF

Figure 58 - F-15 Training SDVF

Figure 59 - F-15 Installation SDVF

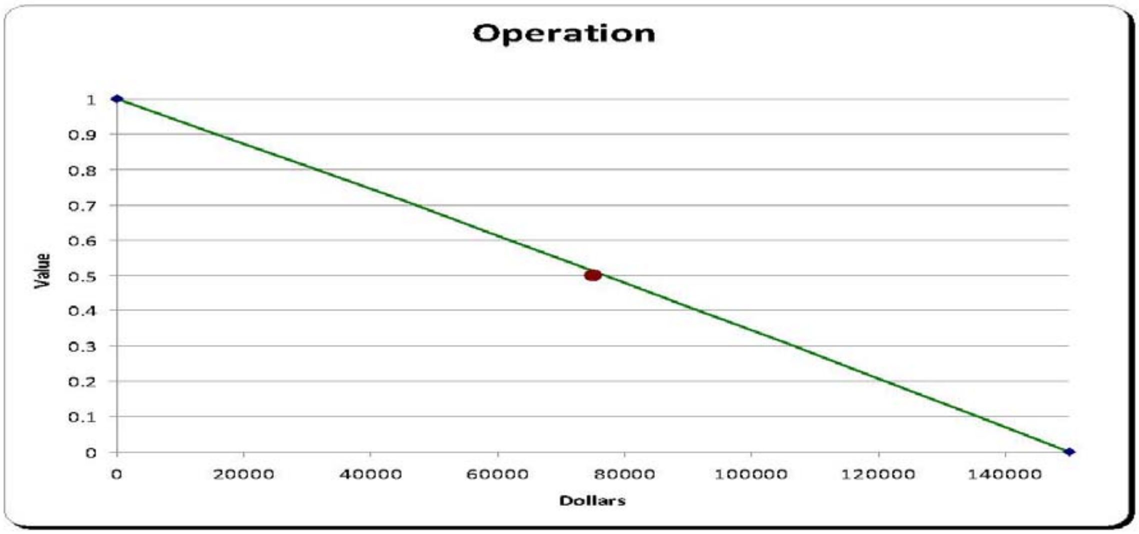


Figure 60 - F-15 Operation SDVF

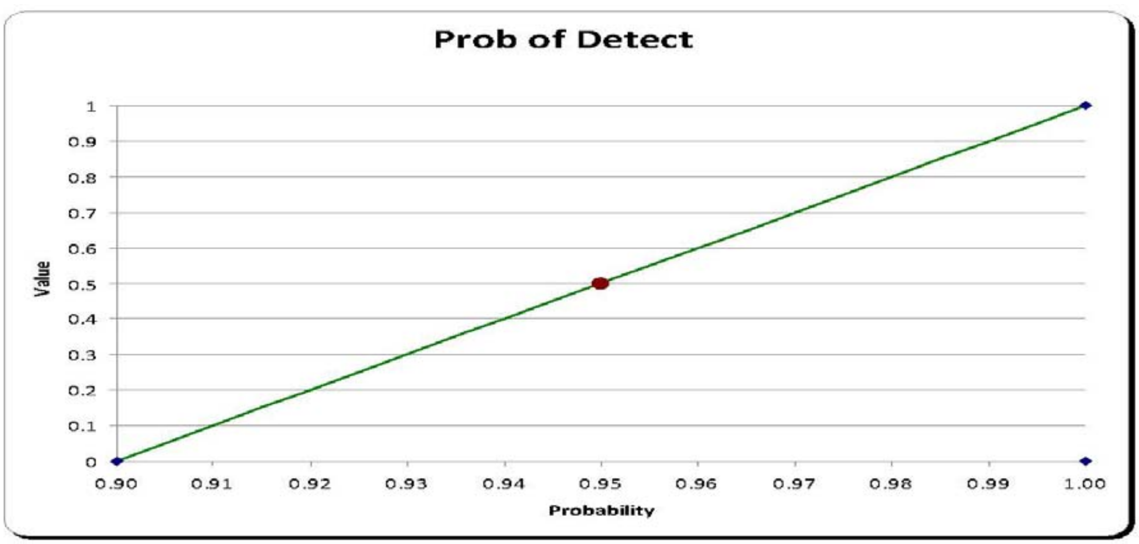


Figure 61 - F-15 Probability of Detection SDVF

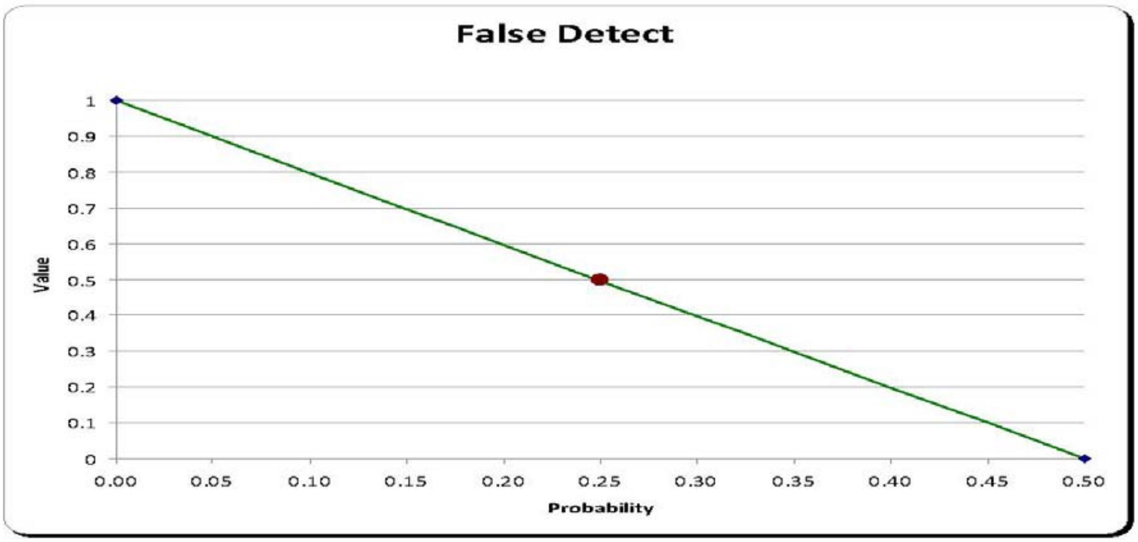


Figure 62 - F-15 Probability of False Detection SDVF

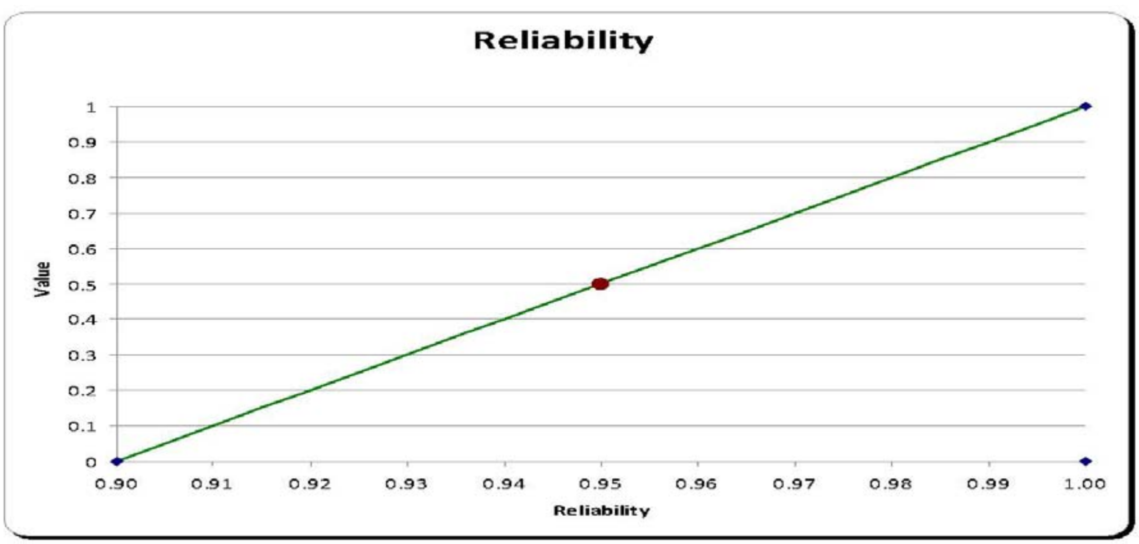


Figure 63 - F-15 Reliability SDVF

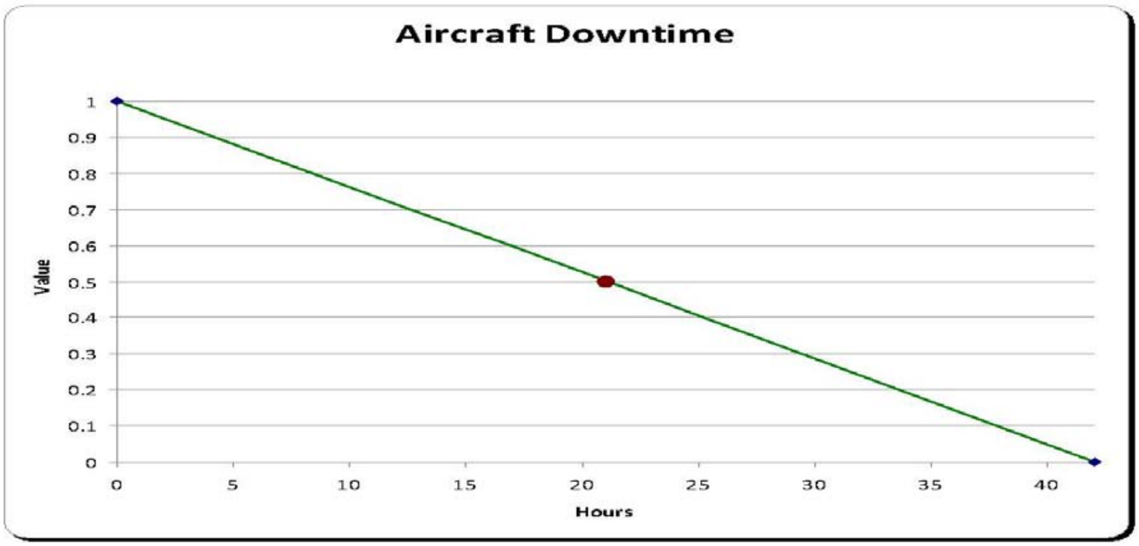


Figure 64 - F-15 Aircraft Downtime

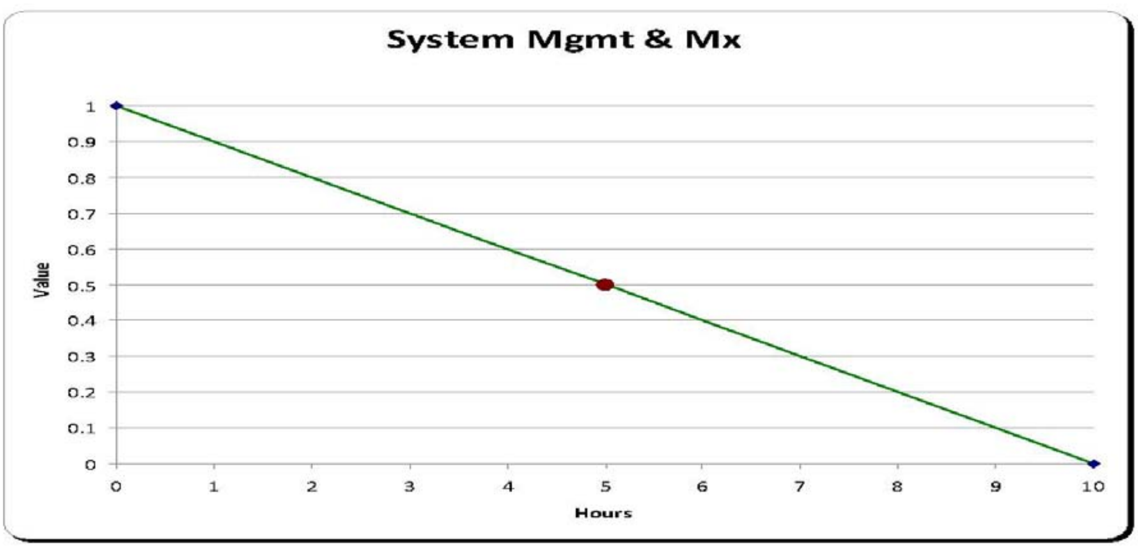


Figure 65 - F-15 Management & Maintenance SDVF

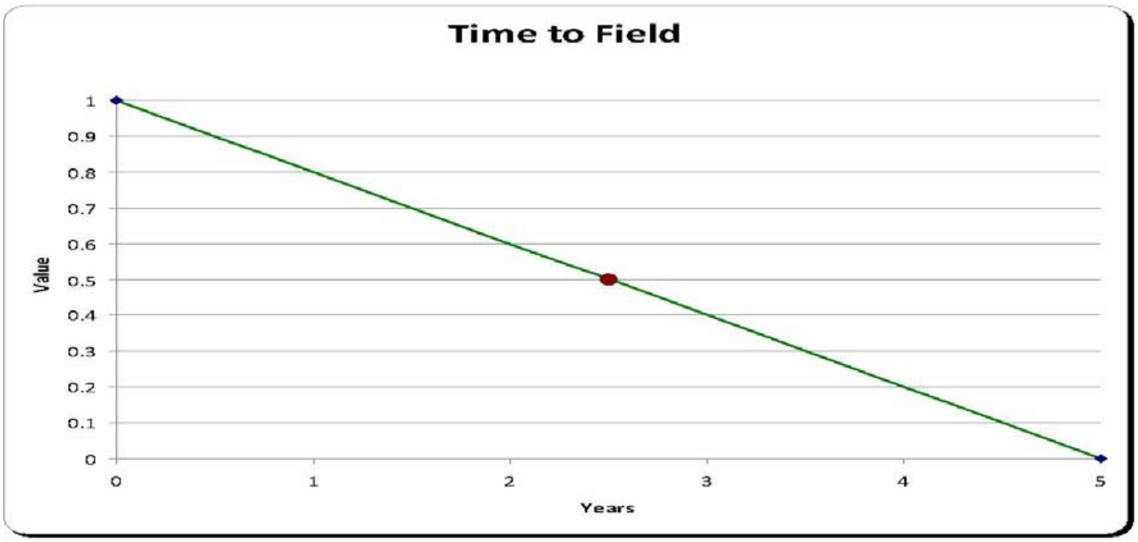


Figure 66 - F-15 Time to Field SDVF

Appendix G - F-15 Sensitivity Analysis

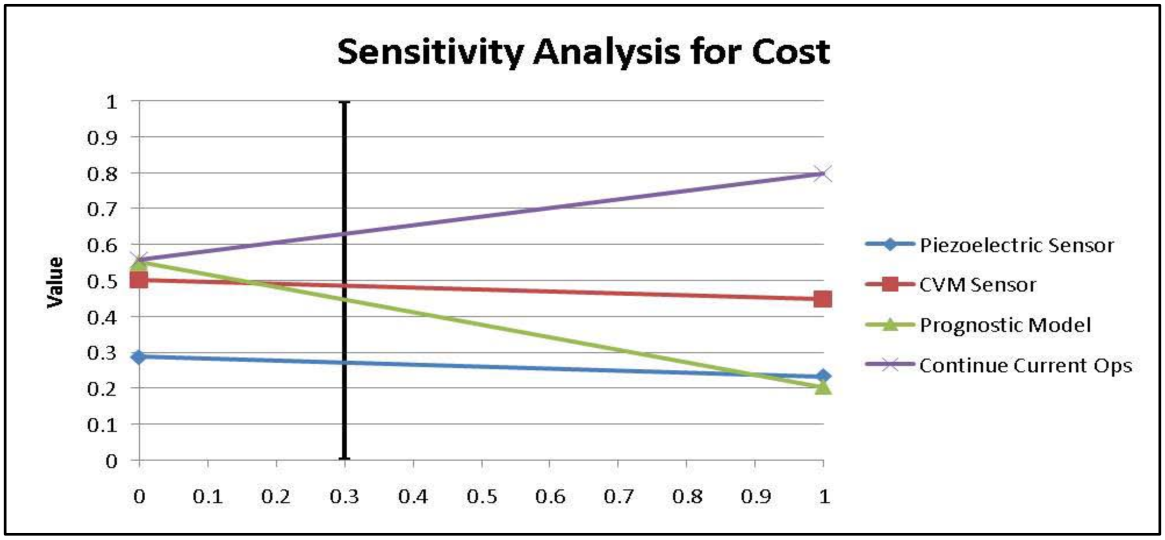


Figure 67 - F-15 Sensitivity Analysis for Cost

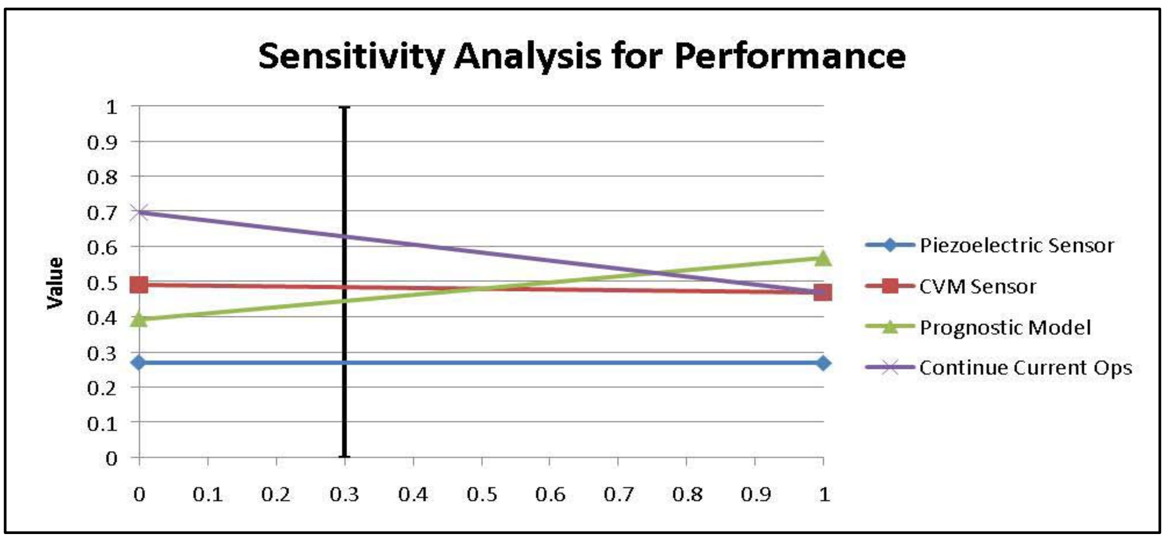


Figure 68 - F-15 Sensitivity Analysis for Performance

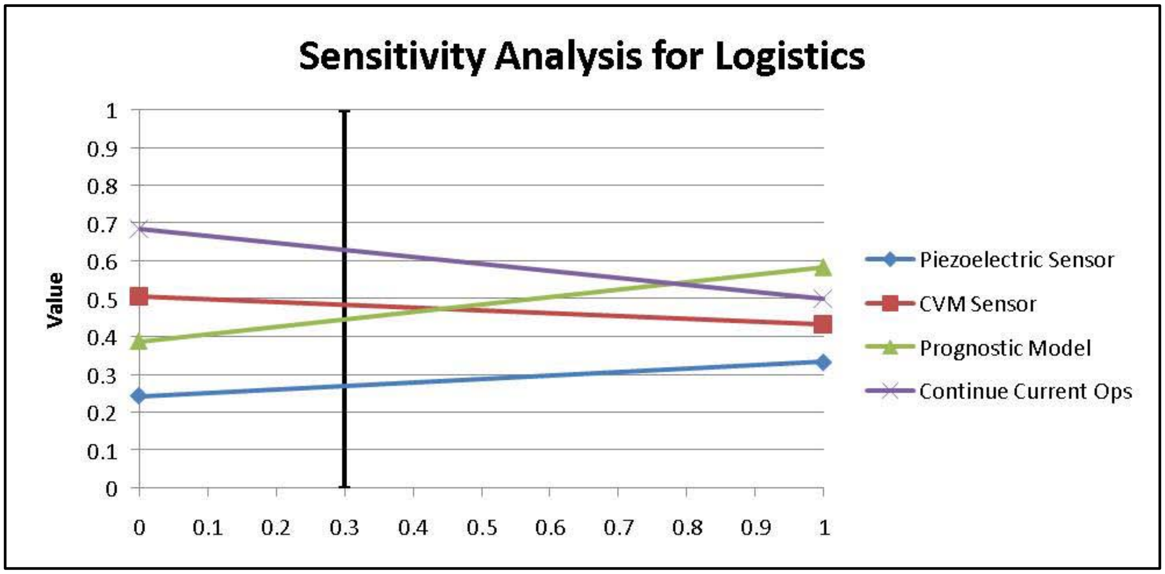


Figure 69 - F-15 Sensitivity Analysis for Logistics

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Current Air Force operations are undergoing significant changes necessitated by increasing fiscal constraints, increasing aircraft usage, and recent drawdown in personnel to perform maintenance, repair, and other necessary functions. In order to deal with these challenges, the Air Force must effectively improve current operations. This paper will explore potential structural health monitoring (SHM) solutions to some of the challenges facing aircraft maintenance and repair operations. As with any problem, a variety of solutions exist and this paper will explore the potential solutions and limitations of various options. Aircraft SHM is an intriguing concept with potential capability to revolutionize current Air Force maintenance operations. However, this capability needs to be balanced with the total life cycle cost associated with developing, training personnel, integrating, maintaining, and disposing of the SHM system. This thesis attempts to analyze several potential solutions to SHM problems by developing and implementing a value-focused thinking model as a decision-making tool.

15. SUBJECT TERMS
Structural Health Monitoring, Value Model, Value-Focused Thinking, Sensors

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