A METHODOLOGY FOR ANALYZING AVAILABILITY IMPROVEMENTS FOR ARMY ROTORCRAFT

A Dissertation

Presented to

The Academic Faculty

By

Richard V. Melnyk

Captain, U.S. Army

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science in Aerospace Engineering

Georgia Institute of Technology

November, 2003

A METHODOLOGY FOR ANALYZING AVAILABILITY IMPROVEMENTS FOR ARMY ROTORCRAFT

Approved By:

Dr. Daniel P. Schrage, Advisor

Dr. Dimitri N. Mavris

Dr. Daniel DeLaurentis

Date Approved 15 October 2003

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Active Components
AH	Attack Helicopter
AIT	Advanced Individual Training
AMCOS	Army Military-Civilian Cost System
ANOVA	Analysis of Variance
AVIM	Aviation Intermediate Maintenance
AVUM	Aviation Unit Maintenance
AWCF	Army Working Capital Fund
C/X	Controlled Exchange
CCAD	Corpus Christ Army Depot
CMF	Career Management Field
CONUS	Continental United States
DA	Department of the Army
EA	Economic Analysis
EPC	Error Producing Condition
EUSA	Eighth United States Army
FMC	Fully-Mission Capable
HEART	Human Error Assessment and Reduction Technique
IPPD	Integrated Product and Process Development
IPPEA	Integrated Product and Process Economic Analysis
LIDB	Logistics Integrated Database
MARC	Manpower Requirements Criteria

MC	Mission Capable
MDO	Multi-Disciplinary Design Optimization
NMC	Non-Mission Capable
NMCM	Non-Mission Capable Maintenance
NMCS	Non-Mission Capable Supply
OEC	Overall Evaluation Criterion
ORF	Operational Readiness Float
OSMIS	Operations and Support Management Information System
PEO	Program Executive Office
PLL	Prescribed Load List
PMC	Partially-Mission Capable
QFD	Quality Function Deployment
RAMS	Reliability, Availability, Maintainability and Safety-Integrity
RC	Reserve Component
RCM	Reliability Centered Maintenance
RECAP	Recapitalization
SNL	Sandia National Laboratories
SPC	Statistical Process Control
TALDT	Total Administrative and Logistics Down Time
TCM	Total Corrective Maintenance
TOC	Total Ownership Costs
TOE	Table of Organization and Equipment
TPM	Total Preventive Maintenance
USAFMSA	United States Army Force Management Support Activity
USAREUR	United States Army Europe

SUMMARY

The purpose of this thesis was to determine the feasibility of implementing a methodology to analyze the United States Army's initiative to raise the Mission Capable rate of all aircraft 90%. Recent changes in the composition of helicopter battalions necessitated an increase in aircraft availability. The Army has analyzed and proposed several means to increase overall system availability. This thesis attempts to evaluate and compare those means within the context of a framework referred to as Dependability. Dependability, as defined within this report, consists of a hierarchical relationship between the areas of Reliability, Availability, Maintainability and Safety.

Several different approaches were explored for this application including Reliability Centered Maintenance (RCM), Six Sigma, the generic Georgia Tech Integrated Product and Process Development (IPPD) methodology and the Army's Economic Analysis (EA) model. Ultimately; a modified IPPD methodology, combined with elements of the EA model, was used to analyze the problem. The Army's AH-64 Advanced Attack Helicopter was chosen as a test case because the AH-64 required significant availability improvements to meet the 90% goal. In addition, the author has experience in the logistics, maintenance and operational aspects of AH-64 attack battalions.

The modified methodology incorporated analytical tools from the existing IPPD methodology while replacing the top-down decision support structure with the U.S. Army's Economic Analysis procedures. Overall, the methodology was effective in defining, analyzing and evaluating the problem of increasing AH-64 availability. The application of the methodology helped define the problem and identify the customer requirements using a set of qualitative and quantitative tools. Using a Quality Function

Deployment (QFD) tool, customer requirements were related to specific analytical factors used to evaluate the various alternatives proposed to increase availability. Several probabilistic tools were used to assess the benefit to cost ratio of each alternative and compare the alternatives. This methodology could prove useful in future, similar applications when modifications or improvements are proposed for existing systems.

INTRODUCTION

Thesis Statement

The Army's recent initiative to raise rotorcraft availability rates to 90% created the need for an appropriate methodology to analyze and compare availability improvement alternatives.

Motivation

Recent changes in the organization and composition of United States Army attack helicopter battalions have led senior leaders to re-evaluate the maintenance practices of these units. Reductions in the number of AH-64 helicopters in each battalion, necessitated a higher readiness rate for the remaining aircraft to maintain the same level of overall availability. As a result, the Chief of Staff of the Army mandated that all Army attack helicopter battalions maintain a 90% Mission Capable Rate by Fiscal Year 2004.[1] Current rates are much lower than that. Therefore, steps must be taken to drastically improve the Mission Capability of the attack helicopter fleet. The question that remains is how to accomplish this task. This proposal outlines a plan to study this problem and offer an analysis of the costs and benefits of various alternatives aimed at increasing AH-64 readiness in the Active Component of the U.S. Army.

---

[1] "Toward 90% Aviation Readiness", Presentation Prepared by the Army Materiel Command, 14 June 2002, 2.

Research Objectives

The goal of this effort was not to analyze the U.S. Army's AH-64 maintenance program itself. An undertaking of that magnitude would require a tremendous amount of time and money. Instead, the purpose of this research was to determine if a methodology is appropriate for the understanding and analysis of this complex problem. Specifically, this project had four questions to answer:

1. Is the methodology appropriate for understanding how the system is unavailable?
2. Is the methodology appropriate for understanding why the system is unavailable?
3. Can the methodology generate alternatives to improve the system availability?
4. Can the methodology choose the optimal alternative to improve the system availability?

Collaboration

This research was not officially sanctioned by the United States Army or the Department of Defense. Therefore, any views or beliefs presented in this project are solely the author's. However, the author did have the cooperation, advice and support of several members of the Army's attack helicopter community. These individuals, while too numerous to mention, spanned the gamut of specialties from maintenance engineers, cost specialists, safety analysts, maintainers and units in the field. A significant amount of information and collaboration was obtained from various members of the Apache Program Executive Office (PEO) in Huntsville, Alabama. These experienced individuals are responsible for the logistics and maintainability of the entire AH-64 system. A large amount of information and analysis was obtained from several presentation prepared by the PEO and Army Materiel Command (AMCOM) as a whole.

BACKGROUND

The United States Army operates the equivalent of 15 Apache Battalions in the Active Component (AC). These units operate in the Continental United States (CONUS), Europe and Korea. In addition, they are capable of deploying to conduct training or combat anywhere in the world. The Apache is the Army's heavy attack asset and was designed primarily for the destruction of enemy armored and mechanized formations but has been adapted for a spectrum of missions including close combat attack and peace-keeping operations.

There are two separate Apache models in existence today. The original A model was developed in the late 1970's and began fielding in the early 1980's. The Army purchased approximately 820 of these aircraft. The more advanced D model began operational testing in 1995 and is being gradually fielded to units to the present day. The D Model employs more advanced avionics and armament systems while retaining a majority of the drive train and airframe structure. The Army plans to convert up to 501 of the older A models to D models through the next decade.[2]

AH-64 aircraft are fielded primarily to two types of units. Six battalions belong to Corps-level Attack Regiments which report directly to a three-star level General. Eight battalions belong to Division-level Aviation Brigades that report to a two-star General. In addition, there are two company-level attack units that belong to a multi-aircraft aviation squadron which works directly for an Armored Cavalry Regiment commanded by a Colonel. This latter unit is too small to have much statistical impact and is generally

---

[2] AH-64 Apache Joint Aviation Technical Data Integration Homepage, www.apache.jatdi.mil.

considered with the divisional assets.

There are three levels of maintenance currently in use for AH-64 helicopters. The first level, Aviation Unit Maintenance (AVUM), is also referred to as organizational maintenance. This term refers to the maintenance performed by soldiers within the actual attack battalion that owns the aircraft. The next level, Aviation Intermediate Maintenance (AVIM), consists of a separate maintenance battalion normally assigned to a Division or Corps support unit. The last level, Depot, is reserved for major repairs or overhauls and is performed at the Corpus Christi Army Depot (CCAD) in Corpus Christi, Texas. The primary focus of this research is on the AVUM level of maintenance since it accounts for the overwhelming majority of unavailability associated with the AH-64 aircraft.

The attack battalions themselves are commanded by a Lieutenant Colonel and further split into five company-level units commanded by Captains. Three companies; referred to as line-units, contain all of the aircraft, pilots and crew chiefs. The Headquarters and Headquarters Company (HHC) contains the staff and support elements for the unit and is not directly related to aircraft maintenance. The Aviation Unit Maintenance Company (AVUM) contains the majority of the organizational maintenance for the battalion. Overall, the battalions have approximately 300 personnel of which only about 120 are directly involved with aircraft maintenance.

The Army's term for Operational Availability (A_o) if Mission Capability (MC). If an aircraft is fully available and functional it is considered Fully Mission Capable (FMC). If the aircraft can safely fly, but lacks certain mission characteristics such as the night-vision system, it is considered Partly Mission Capable (PMC). The FMC and PMC percentages are added to determine MC times. If the aircraft cannot safely fly, it is deemed Non Mission Capable (NMC). There are several categories to describe why the aircraft can be NMC. A diagram of those reasons appears below in Figure 1. Since the goal of this initiative is to increase the MC rate of the aircraft, PMC times were not considered. PMC time does not detract from the overall MC percentages.

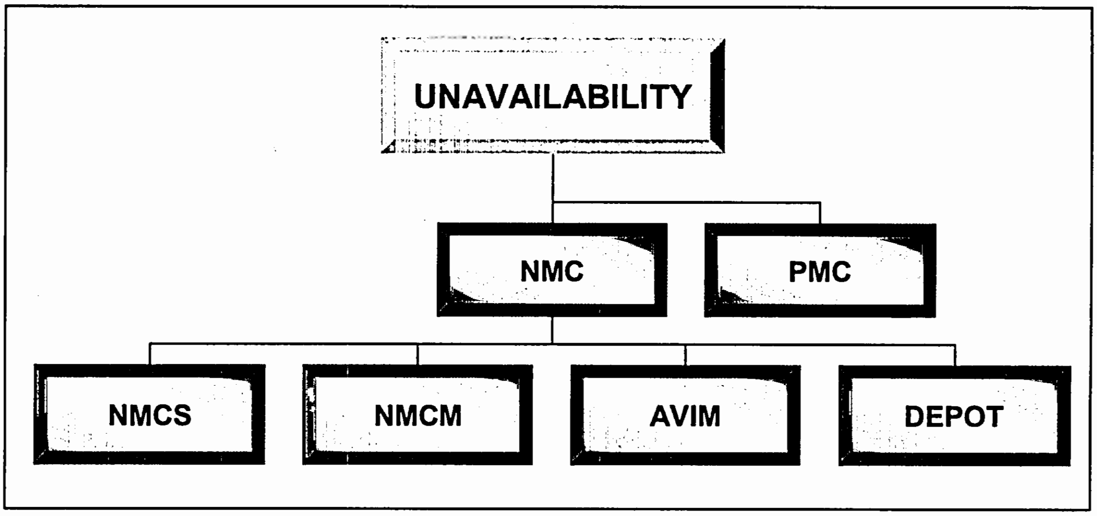

Figure 1: Army Unavailability Terms

The four different types of NMC time are depicted above. The two most significant components of NMC time are NMCS and NMCM, or Non Mission Capable Supply and Non Mission Capable Maintenance. These factors account for the amount of time an aircraft can not fly while awaiting parts or undergoing maintenance at the battalion level. The AVIM component refers to downtime spent in maintenance one level higher than the battalion level. Finally, Depot refers to maintenance time spent in major repair or overhaul at the depot level. The latter two components of downtime are extremely minor compared to the first two. All aspects of availability or unavailability are tracked in tenths of hours, or six-minute increments. Therefore, if an aircraft is awaiting a part for more than six minutes, it will begin logging NMCS time.

METHODOLOGY OVERVIEW

Any rotary wing aircraft is, by nature, a complex system. The AH-64 Apache helicopter stands out as the most technologically advanced and capable helicopter in the world. As a result, it is also one of the most complicated aircraft systems in existence today. The United States Army and all of the organizations that interact to maintain and sustain these aircraft are another complex system. When the AH-64 aircraft is coupled with the systems in place to maintain the aircraft, the result is a complex system of systems which is difficult to analyze.

Related Approaches

Before choosing the methodology to study this problem, several approaches were explored. One method currently in use for analyzing maintenance activities is Reliability Centered Maintenance. It is defined as "A process used to determine the maintenance requirements of any physical asset in its operating context."[3] RCM seeks to prevent failures of a component or system and do so in the most cost-effective manner. However, there are two shortcomings which make this approach inappropriate for the current research. First, RCM focuses mainly on the product, in this case the aircraft. It does not take into account the process used to maintain the product. Second, and more critical, RCM requires a large amount of data about specific components and their failure rates, times to repair, etc. In the case of Army aircraft, this type of data is

---

[3] John Moubray, Reliability Centered Maintenance, 2nd ed. (New York: Industrial Press, 1997), 7.

not available.

Another approach explored was Six Sigma. The Six Sigma process "Involves the use of statistical tools within a structured methodology for gaining the knowledge needed to achieve better, faster and less expensive products and services than the competition."[4] Six Sigma was developed by Motorola and used by businesses such as General Electric and Sony. It relies heavily on metrics and time-charts to analyze and improve processes within a business. The concept of Six Sigma holds some promise for analyzing Army rotorcraft availability. However, Six Sigma's strength lies in the ability to analyze and track specific metrics within a process in order to make improvements. Once again, the lack of specific data related to Army aircraft maintenance prohibits the exclusive use of Six Sigma at this time. There are limited instances where this method could be used to analyze processes within the context of a larger methodology. For example, supply chain times and component replacement intervals are potential metrics to track and compare across units.

GT Integrated Product and Process Development

Solving problems for an intricate system of systems such as this one requires a robust, integrated methodology. One such technique is the Georgia Tech Integrated Product and Process Development (IPPD) methodology. Pictured below in Figure 2, this methodology provides a framework for designing and evaluating complex systems. IPPD is a management methodology that incorporates a systematic approach to the early integration and concurrent application of all the disciplines that play a part

---

[4] Forrest W. Breyfogle III, Implementing Six Sigma, Smarter Solutions Using Statistical Methods, (New York: John Wiley & Sons, 1999), 5.

throughout a system's life cycle.[5]

The main features of this methodology are the Top-Down, Decision Support process featured in the middle of the figure, Systems Engineering Methods on the right and Quality Engineering methods on the left.

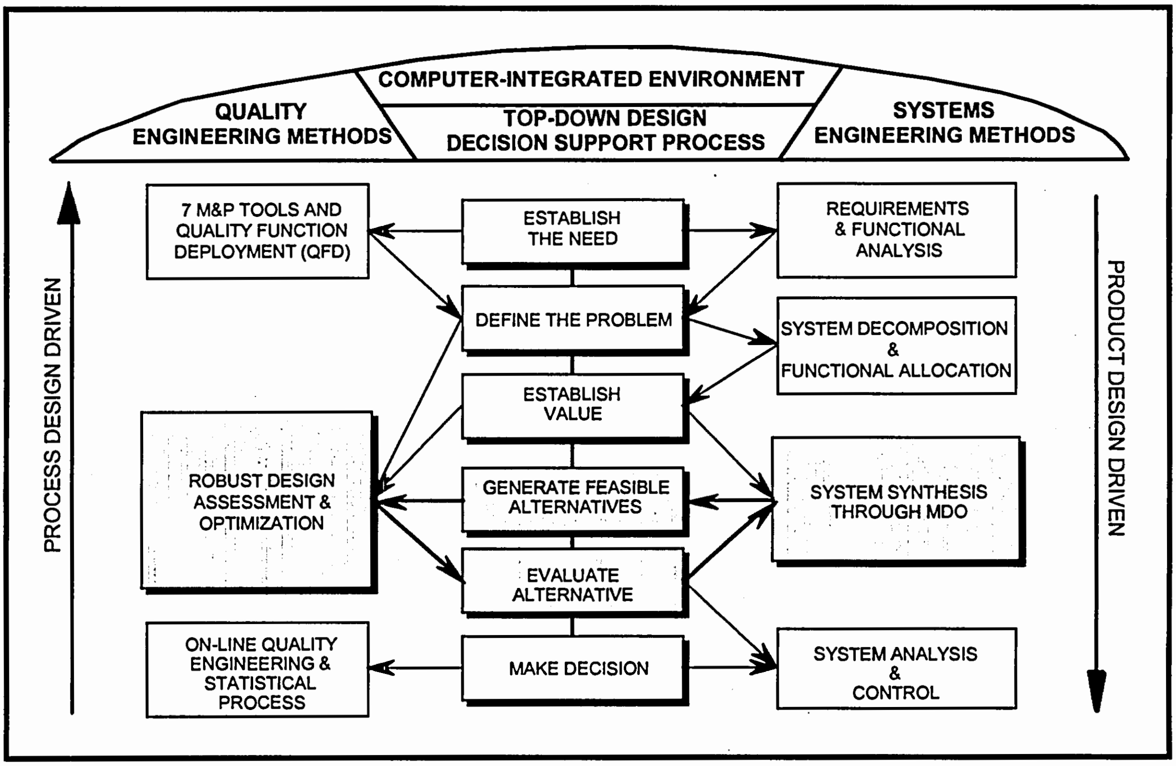

Figure 2: IPPD Methodology

This methodology has several advantages. First, it provides logical steps for

---

[5] Daniel P. Schrage, "Georgia Tech's Systems Analysis Capabilities to Measure and Track 90% Mission Capability Efforts for Army Aviation Systems" Presentation to the Army Materiel Command, (2002), 19.

making decisions throughout a product development cycle. Second, it gives the user methods to analyze both product and process factors that can affect a design. The product cannot be designed in a vacuum. Factors such as manufacturing, affordability, reliability and disposal must be considered. Finally, the methodology has an inherent focus on probabilistic methods. In any product or process development cycle there are uncertainties. In order to capture these uncertainties, probabilistic methods must be used. These methods use probability distributions, instead of deterministic values, to describe design and noise parameters. This technique allows the user to express the amount of uncertainty in a design and place confidence intervals around the results.

The main disadvantage is that IPPD was created for use early in a product life-cycle. Therefore, it assumes that the product and process are in the relatively early stages of development. In fact, IPPD is most effective if applied in the early stages of development. Unfortunately, the AH-64A and D models are both well past the design phases, and are currently in use.

Department of the Army Economic Analysis Model

A method used by the Department of the Army (DA) to analyze the economic impact of any major decisions is the Economic Analysis model. This model, which appears in Figure 3, is used whenever the monetary impact of making a choice between several alternatives will be significant.

The advantage of this model is that it is specifically tailored to the type of economic comparison required by this study. It is a logical series of steps to frame, analyze and compare the benefit to cost ratio of several alternatives. The disadvantage of this system is that it does not provide specific tools to accomplish the analysis. It tells one what steps to take, but not necessarily how to take them.

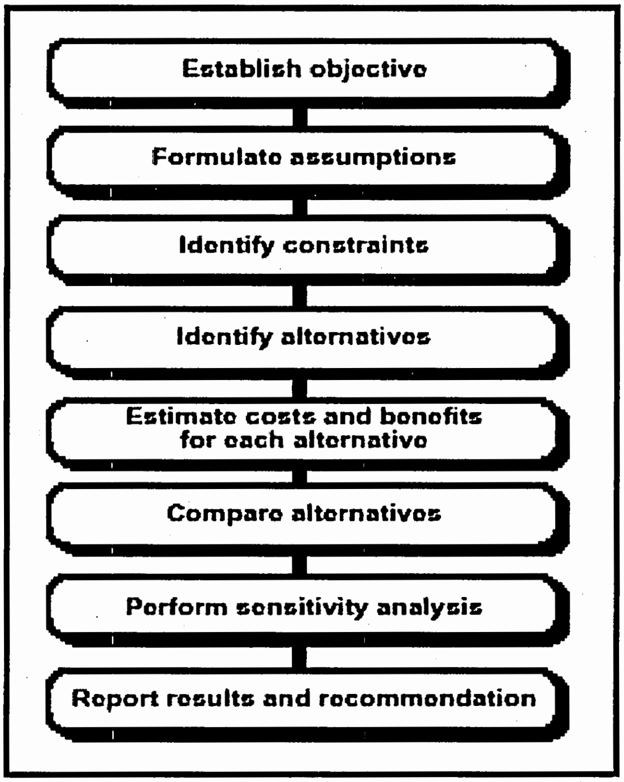

Figure 3: DA Economic Analysis Model[6]

Hybrid Model

Weighing the advantages and disadvantages of these two systems it appeared that the optimal methodology might lie somewhere in between. Therefore, for this study, the proposal is to analyze the feasibility of a hybrid methodology. This methodology will be referred to as the Integrated Product and Process Economic Analysis model (IPPEA). The proposed model appears in Figure 4.

---

[6] Department of the Army, *Economic Analysis Manual* (U.S. Army Cost and Economic Analysis Center, 2001), 7.

The model retains the Quality and Systems Engineering modules of the original IPPD methodology. However, the Decision Support Process is augmented by the steps of the Economic Analysis model to more accurately portray the analysis required for this study. The question of how to increase the Mission Capability of the AH-64 is not truly a design problem. It is a complicated analysis of a system of systems already in use. The economic aspect of this analysis is crucial to the study because of the expensive nature of this system and the resource constraints in place.

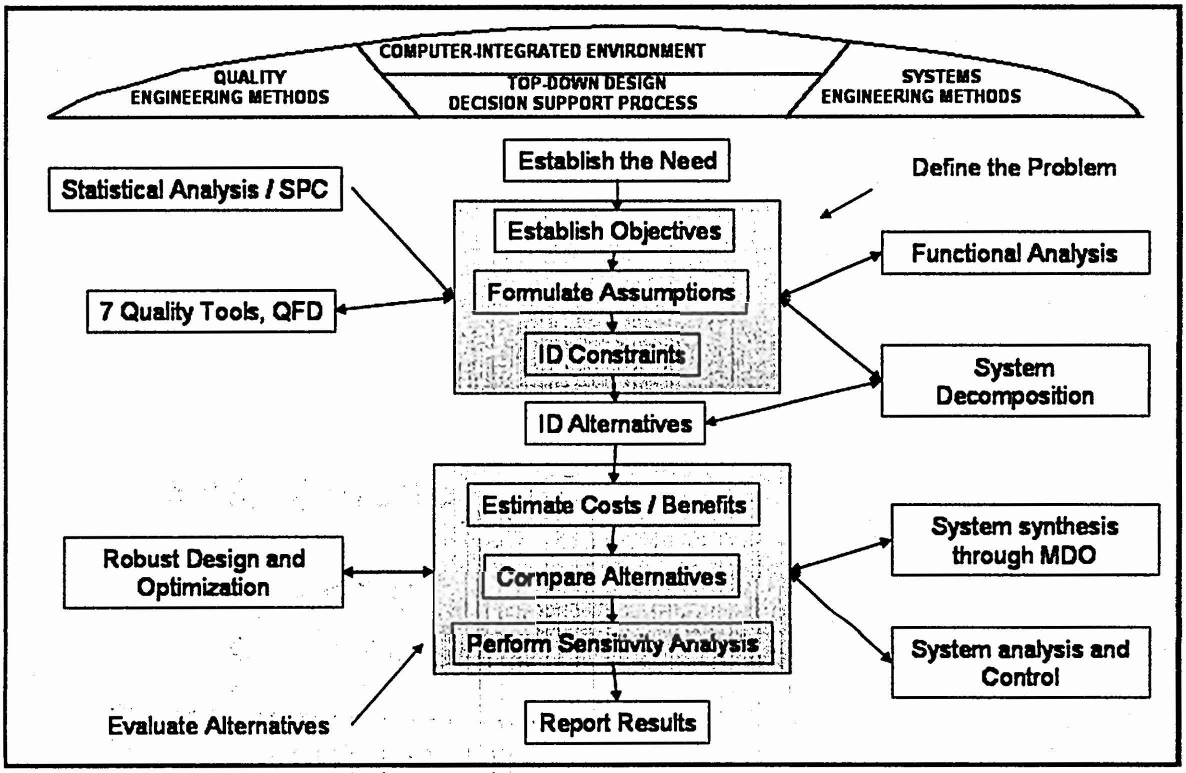

Figure 4: IPPEA Methodology

ESTABLISH THE NEED

In the late 1990's the Army was operating several different types of rotary-wing aircraft including the UH-60, CH-47, AH-64, AH-1, UH-1, OH-58A/C and OH-58D. This mixture of obsolescent and more modern aircraft required increased numbers of repair parts, maintenance specialties and logistics support.

In an effort to reduce the cost of maintaining the legacy aircraft, the Department of the Army made the decision to nearly eliminate the AH-1, UH-1 and OH-58 A/C from the Army inventory and recapitalize that money into the more modern fleet. However, this action left many Reserve and National Guard units without aircraft. Due to budget constraints, the Army could not simply purchase new AH-64s to replace the AH-1s eliminated in attack battalions. Therefore, the decision was made to reduce the number of AH-64s in the Active Component (AC) attack battalions from 24 to either 21 or 18, depending on the type of unit. The extra aircraft would be consolidated into units in the Reserve Component (RC).

From an operational standpoint, experts believed that the increased lethality and survivability of the AH-64D Longbow aircraft over the AH-64A would compensate for the reduction in numbers. However, from a training standpoint, attack battalions still needed to fly the same number of hours to maintain their current training levels. This fact was compounded by decisions made after a review of Task Force Hawk's performance in Albania in 1999. A study and subsequent policy changes eliminated a large number of non-flying staff aviator positions, increasing the need for training flight time.

In order to maintain the same flying hour programs with less aircraft, a higher level of aircraft availability was necessary. In early 2002, GEN Eric Shinseki, Chief of Staff of the Army, mandated that the Army Materiel Command study the feasibility of each of the remaining four aircraft types in the Army (CH-47, UH-60, AH-64 and OH-58D) maintaining a 90% Mission Capability rating.[7]

---

[7] "Toward 90% Aviation Readiness", Presentation Prepared by the Army Materiel Command, 14 June 2002, 2.

DEFINE THE PROBLEM

Perhaps the most important step of this process is accurately defining the problem. An improper problem definition can corrupt the remainder of the analysis. Therefore, there are many tools available to properly understand the various aspects of the overall problem. These tools are described in more detail below.

Establish Objectives

The first step in this research was to establish the operational objectives of the effort. Separate from the academic objectives, these objectives are the "Voice of the Customer". It is critical to understand what the customer wants before analyzing the rest of the problem.

As mentioned earlier, the overall goal of this initiative is to increase the Mission Capability of AH-64 units to 90%. This goal represents a significant increase in readiness over the current state of aircraft readiness. There are several key pieces of information not addressed in this initial directive that this research will attempt to analyze.

First, the 90% goal was not accompanied with a probability of success goal. Current MC rates for the Army conform fairly well to a normal distribution. Figure 5 is a histogram and box plot of the Army's MC rates from 1998-2002. The diamond in the box plot represents the mean MC rate of approximately 79% and the vertical bar in the middle of the box plot represents the median rate of 83%. In order to analyze what steps must be taken to achieve a 90% MC rate, one must understand how often units are expected to achieve that rate.

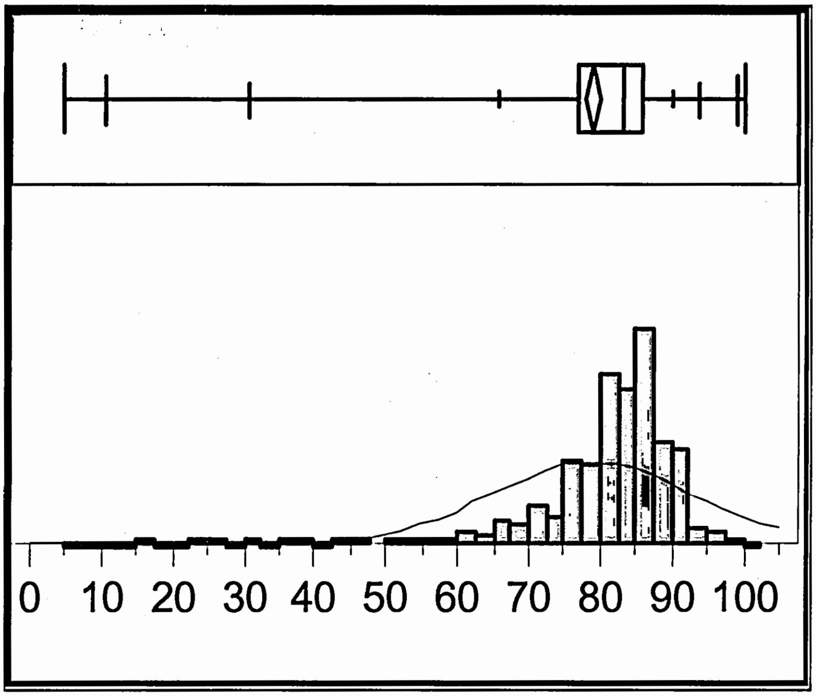

Figure 5: MC Rates for AH-64A/D from 1998-2002

For example, if units must achieve that rate 50% of the time then the median must be increased from 83% to 90% MC. However, if units must achieve the 90% MC rate 75% of their reporting periods then the curve must be shifted much further to the right, or the variance of the curve reduced. Figure 6 shows an example of how differences in the proposed probability of success change the curve for MC rate. The red band represents current rates. The green bands shows a 50% probability of success as evidenced by a simple shift of the median to 90% MC rates. The blue curve represents the drastic departure from current rates required to ensure a 95% probability of exceeding 90% MC.

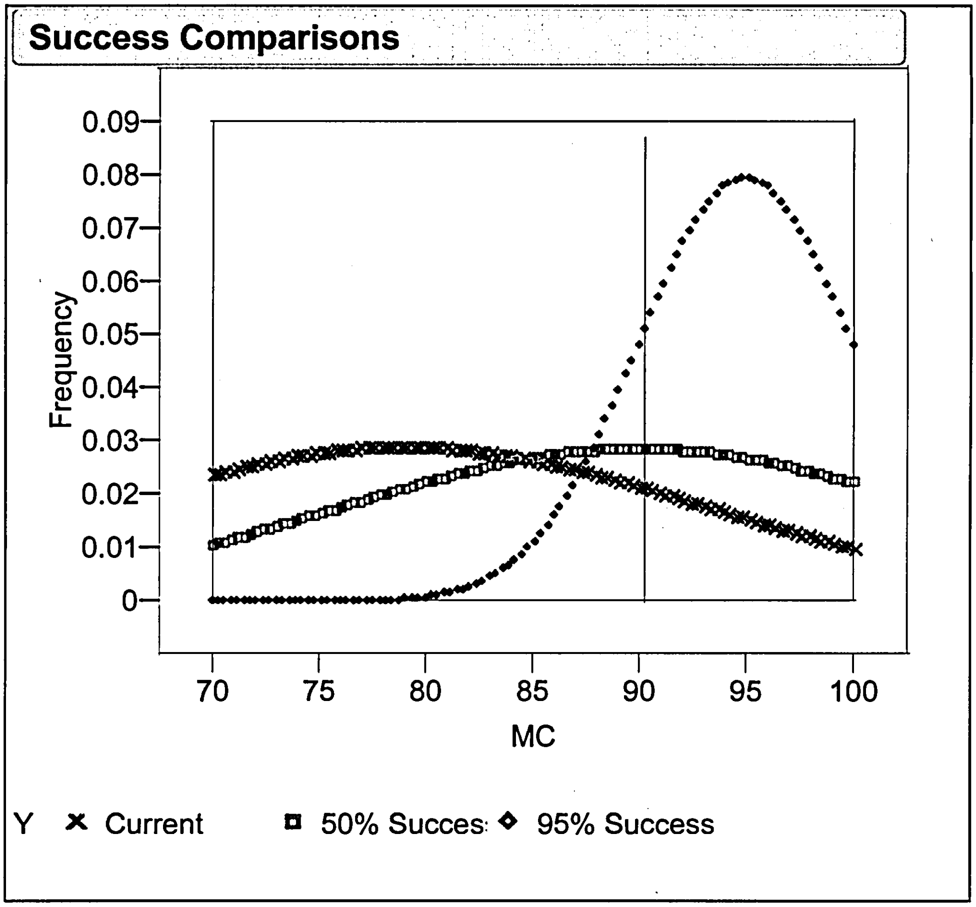

Figure 6: Comparisons of Probability of Success

The other piece of this problem missing from the 90% directive is an understanding of other related factors beside availability. Readiness does not occur in a vacuum. Aspects such as cost and safety must be considered along with the goal of increasing the MC rate. This study addresses these factors.

In order to understand the trade-offs associated with this problem, several experts in the Apache Program Executive Office (PEO) were consulted. They identified and prioritized several objectives of this initiative in addition to increasing the MC rate. The objectives, as defined by these experts are:

- Minimize Cost Impact

- Increase MC rate to 90%
- Minimize Workload Impact on Maintainers
- Minimize Safety Impact on Aircraft
- Maximize the Probability of Achieving 90% MC
- Minimize Impact on Reliability (Aircraft Abort Rate)

These factors create broader objectives for the initiative and create conditions for trade-off decisions later in the process.

Formulate Assumptions

Throughout the process of this research there will be many assumptions made to simplify the problem or because there are certain things that are simply unknown. At this point, the main assumptions made are as follows:

- The overall size of the AH-64 fleet remains the same.
- For the purpose of this study, only AC units will be analyzed.
- There will be no major change in the location of AH-64 units.
- There will be no major changes in the personnel composition of AH-64 units.
- Statistically, all analysis was conducted with a 95% confidence interval.
- There is no major difference between A and D model units. This assumption is also based on the fact that there is no significant statistical difference in MC rate between A and D model units. This point is illustrated in Figure 7. This graphical Analysis of Variance (ANOVA) displays the upper and lower 95% confidence intervals in both a diamond and circle format. The fact that the circles overlap demonstrates that the differences in the two rates are not statistically significant and can be assumed to be the same.
- There is insufficient data at this time to determine if the reduction in aircraft to maintainer ratio caused by removing aircraft from each battalion has made any

impact on the readiness of the system.

- An assumption was made about the probability of success associated with the 90% initiative. Mandating a 90% MC rate is sufficient from a regulatory requirement. However, from an analysis point of view, one must understand what the lower confidence bound on that value is. For the purpose of this study, the assumption is that 50% probability of success is the goal.

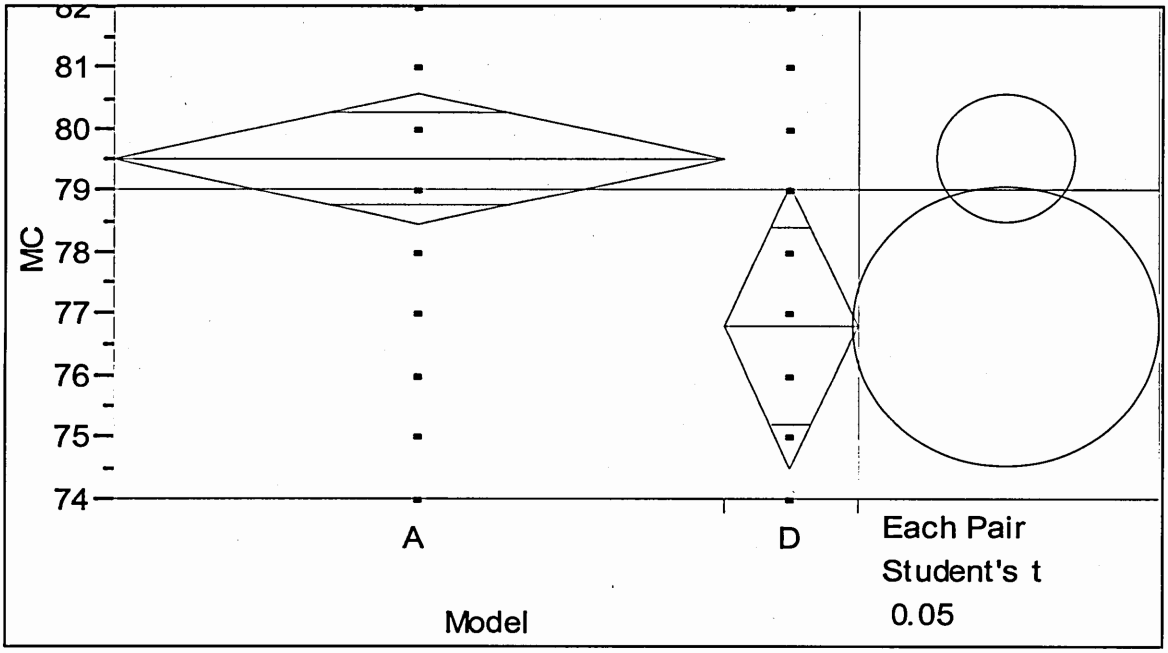

Figure 7: MC Rates for A and D Models from 1998-2002

Identify Constraints

The major constraints identified at this stage involve budgetary and personnel considerations. As outlined in the assumptions section, there will be many more constraints identified throughout the research process. At this time the following constraints have been identified:

- Personnel: No major increase in military personnel in a unit (also an assumption)
- Budgetary: No major, additional budgetary assets allocated to the units
- Physical: Attack battalions can not physically carry more spare parts due to the requirement to deploy with their Prescribed Load List (PLL) using organic transportation assets
- Aircraft: Because the aircraft is already in the support and production phases of their life cycle, it can not be completely re-designed. Any changes will consist of relatively minor modifications to the aircraft (recapitalization).

Statistical Analysis

This step was perhaps the most important aspect of understanding and defining the problem. It involved using statistical analysis methods to understand the current level of performance of the product and process. Unlike traditional design problems, the AH-64 already has some statistical data associated with it. The purpose of this step in the study was to use this data to try and understand the extent and causes of current aircraft unavailability.

During this phase of the study a fairly large database of readiness indicators was built. The data included monthly availability rates by unit to include the categories of unavailability for a five year period from 1998-2002. In addition, information such as cost per hour, unit manning percentages and maintainer utilization rates were compiled, when available. The source of this data consisted of several closed-source, unclassified databases including the Army's Logistics Integrated Database (LIDB), the AH-64 Apache Joint Aviation Technical Data Integration Homepage, the U.S. Army Operating and Support Management Information System (OSMIS) Relational Database and the U.S. Army Military-Civilian Cost System (AMCOS) Database.

Categorically, all of the AH-64 units can be classified by location and unit type.

Units can be located in the Continental United States (CONUS), Europe or Korea. Units were further classified as Corps or Division assets. Each of these categories were analyzed with respect to several outputs such as the average aircraft age, MC rates, NMCS rates, NMCM rates and cost per flying hour of operating the aircraft. The first example of this analysis appears below in Figure 8. The MC rates for units were compared by location. The ANOVA results on the right of the graph clearly indicate that there is a statistically significant difference in MC rates based on location.

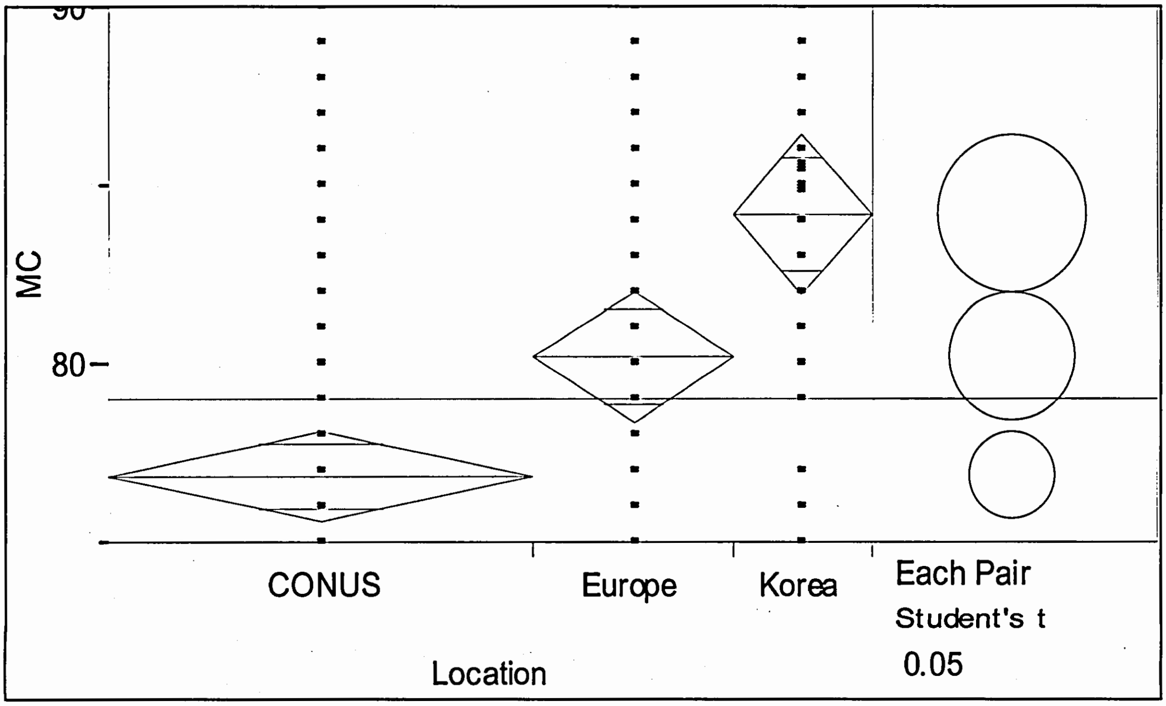

Figure 8: MC Rate Comparison by Location

Another example of the statistical analysis appears in Figure 9. In this case, the MC rates were compared against the type of parent unit for each battalion. The ANOVA circles indicate two things. First, the ACR data indicates a large variance because there is only a small amount of data associated with this unique unit. However, the median

MC rates of the ACR unit are closely centered with divisional units. Second, there is a large difference in the MC rates between corps and divisional units, as indicated by the lack of overlap between the two circles associated with unit types.

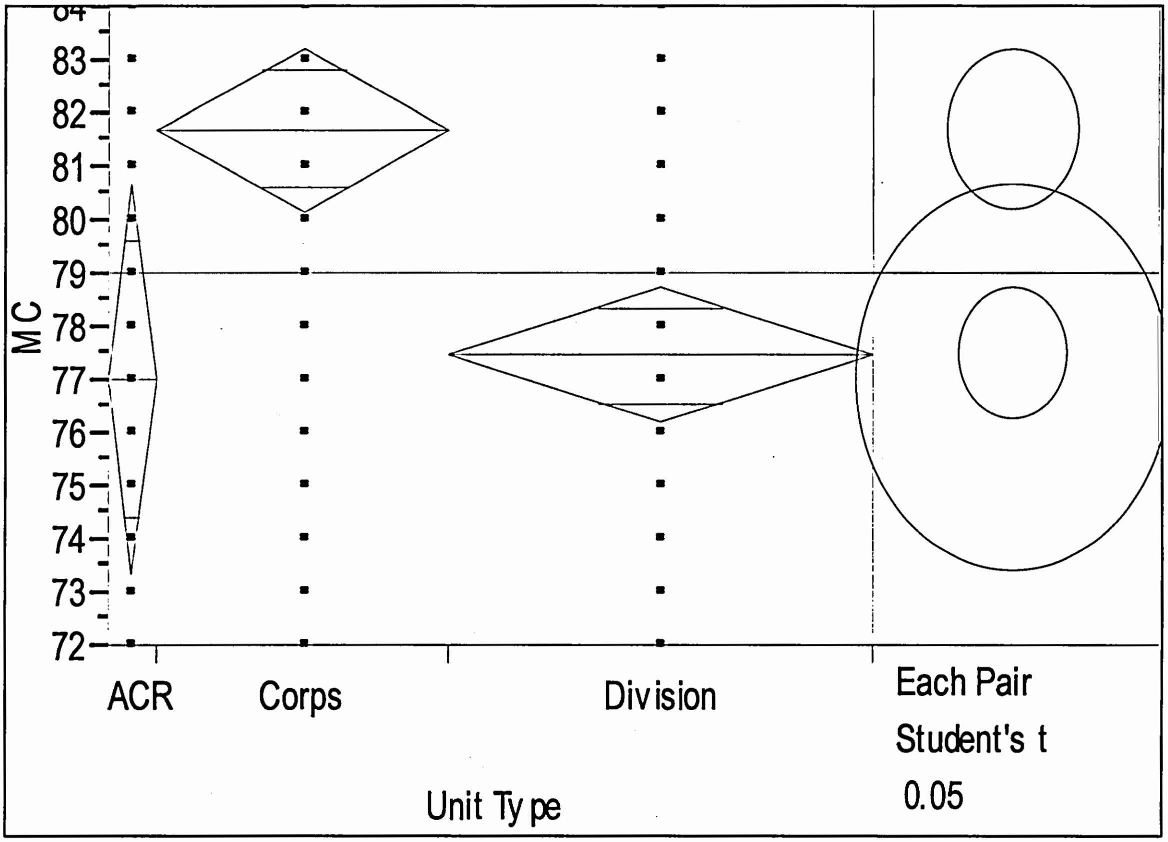

Figure 9: MC Rate Comparison by Unit Type

This process was repeated for several other categories and all of the output data described earlier. Due to the extensive nature of these results, all of the graphs are not included in this report. The results are summarized below.

MC Rate Analysis Conclusions:

- Median MC rate for 5 years is 83%
- Difference between A and D model not significant

- CONUS has lowest MC rate, Europe is in the middle and Korea is the highest
- Corps units have higher MC rate than Division units

NMCS Rate Analysis Conclusions:

- Korea has lower NMCS rates than CONUS and Europe
- Corps units have lower NMCS rates than Division and ACR

AVUM Rate Analysis Conclusions:

- AVUM rates higher in CONUS than Europe and Korea
- AVUM rates lower in Corps units than Division

Functional Analysis

Functional analysis involves understanding the system as a whole and identifying the functions can be used to guide the design synthesis in later steps.[8] Traditionally, the functions for a design consist of tasks that must be accomplished by a product. In this case the functions are the functions related to the availability, readiness and maintenance of the AH-64. The first step was to put the availability of the entire system in perspective to the other functions related to aircraft maintenance.

Typical references related to the maintenance of systems refer to terms such as reliability, availability and maintainability; often interchangeably. The term RAMS is also currently used to refer to Reliability, Availability, Maintainability and Safety-Integrity.[9]

---

[8] U.S. Department of Defense Systems Management College, *Systems Engineering Fundamentals* (Fort Belvoir, Virginia: Defense Systems Management College Press, 1999) 37.

[9] David J. Smith, Reliability Maintainability and Risk, Practical Methods for Engineers, 6th ed. (Boston: Butterworth-Heinemann, 2002) 3.

Within the scope of this study each of these terms is analyzed separately and referred to under the umbrella term of Dependability. Figure 10 is an affinity diagram that shows the relationship between the various aspects of dependability. Dependability, as shown, consists of availability and safety. Availability is further decomposed into product and process factors. The product factors consist of the traditional reliability and maintainability of the aircraft. The process factors consist of the administrative and logistics aspects of keeping the aircraft available. This diagram is a critical first step in understanding the actions that take place to keep an aircraft functional. It is this relationship that places the rest of the analysis in context.

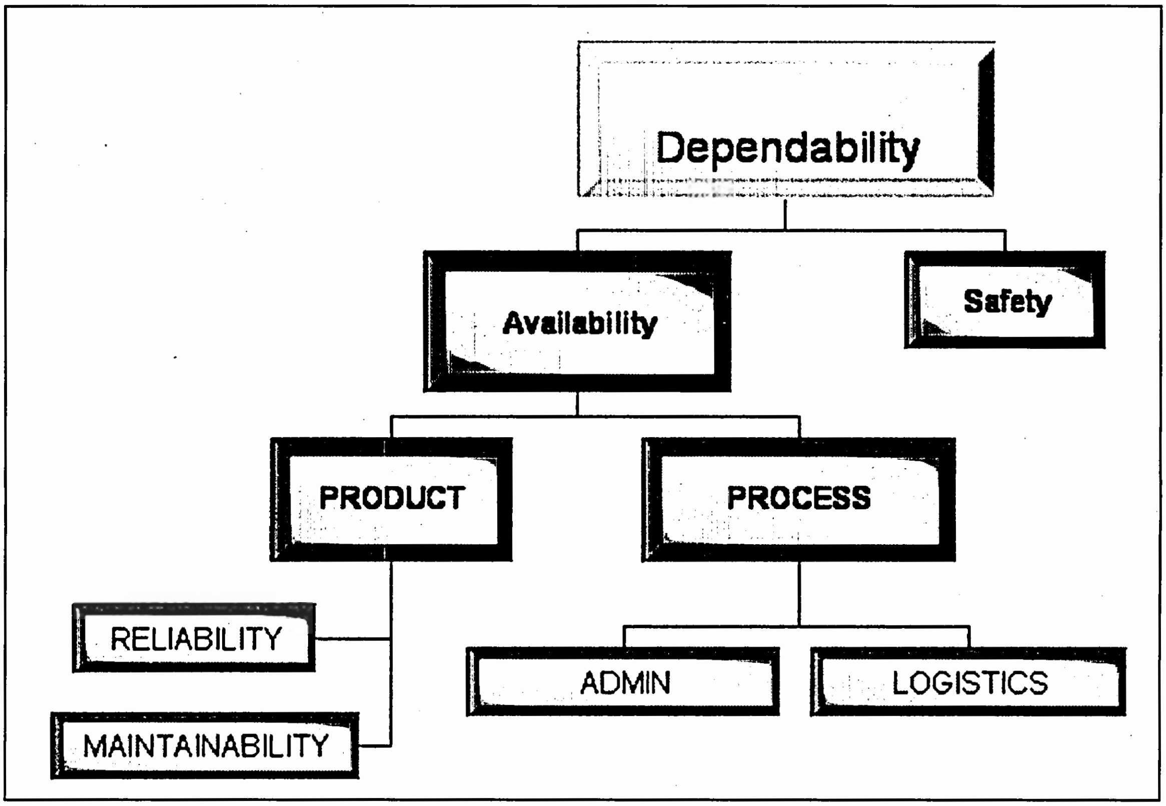

Figure 10: Dependability Affinity Diagram

Seven Tools of Quality

There are seven named tools available in the IPPEA methodology to assist in the management and understanding of the problem. They include flow charts, run charts, control charts, check sheets, Pareto diagrams, cause and effect diagrams (Ishikawa), and scatter diagrams.[10] Run charts, control charts, Pareto diagrams and scatter plots were used during the statistical analysis steps of this research and their results analyzed appropriately. One tool; critical to the research process, is the Ishikawa diagram.

A review of the objectives of this research can be summarized into four steps. How is the system broken, why is it broken, how can it be fixed and what is the best way to fix it. To this point, all of the efforts have focused on how the system is broken. The Ishikawa diagram is an important tool because it bridges the gap between *how* and *why* something occurs.

The first areas analyzed were those causes that contribute to unavailability. While there are countless individual contributions, the major causes can be analyzed and summarized in Figure 11. The major causes analyzed were Reliability, Maintainability, Administrative and Logistics. Then, each branch was further broken down into sub-causes. All of the branches effectively 'feed' into the effect, which is downtime or unavailability.

---

[10] Victor E. Sower, Michael J. Savoie, and Stephen Renick, An Introduction to Quality Management and Engineering, (Saddle River: Prentice Hall, 1999) 33.

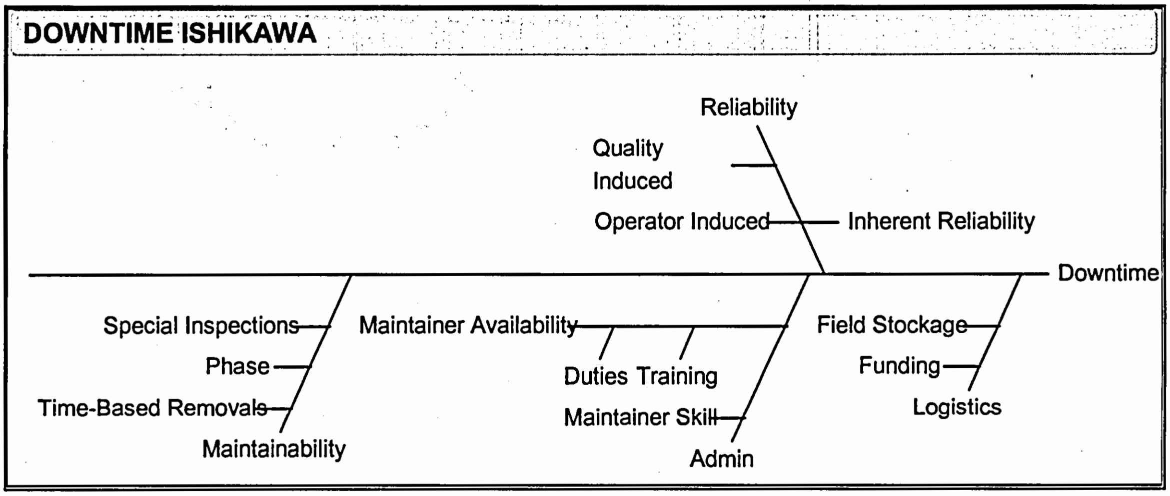

Figure 11: Unavailability Ishikawa

Ishikawa diagrams were also used to analyze the cause of two facts discovered during the Statistical Analysis step. During that step it was determined that both the location and type of unit had a significant effect on availability. It is important to understand why. Figure 12 and Figure 13 display some of the causes that can affect the differences in availability based on location and unit type. One cause that appears in both diagrams is the availability of manpower based on location and unit type. Units overseas tend to have more manpower available due to fewer distractions caused by family commitments and the ability to work longer hours. Divisional units tend to add more distractions due to their additional administrative and training requirements.

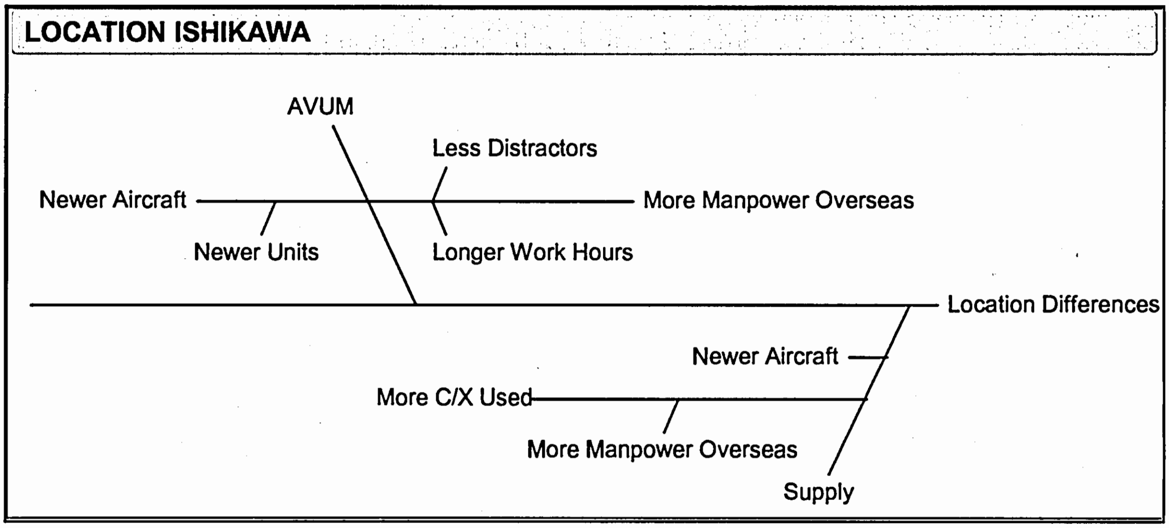

Figure 12: Location Ishikawa

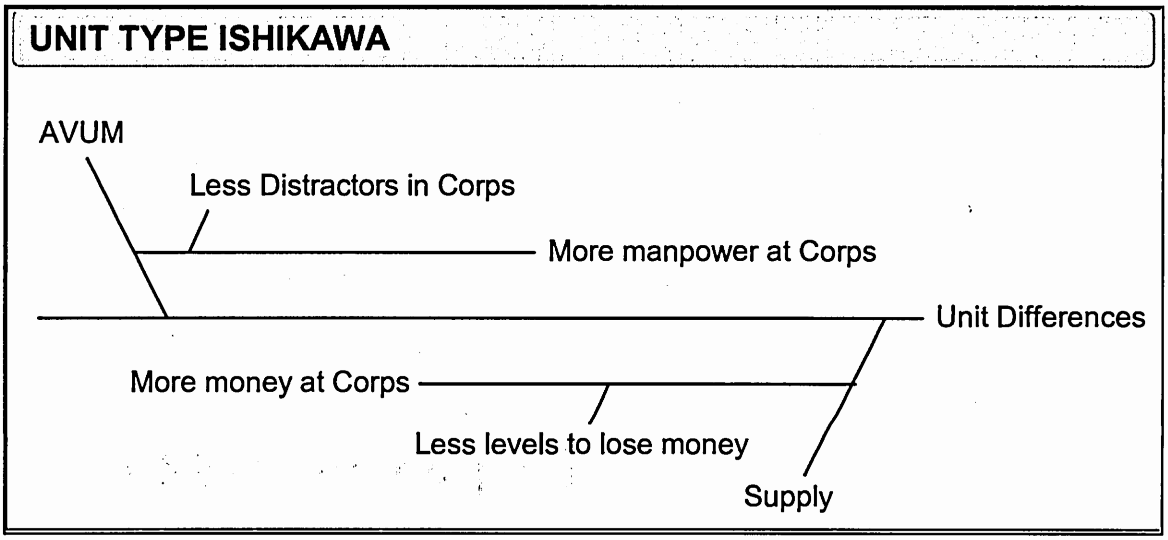

Figure 13: Unit Type Ishikawa

System Decomposition

The System Decomposition phase entailed breaking the system, in this case the entire maintenance structure, into sub-components for analysis. This step was done to gain a better understanding of the pieces that comprise the system and gain insight in later steps into how they may interact. Both the product and processes of the system were decomposed for a more in-depth analysis.

Experts in the Apache PEO analyzed the characteristics of unavailability and identified the composition on unavailability based on causes.[11] The three main categories analyzed were Total Corrective Maintenance (TCM), Total Preventive Maintenance (TPM) and Total Admin and Logistics Downtime (TALDT). The next three charts display the percentage contribution to unavailability caused by each of these causes and their sub-causes.

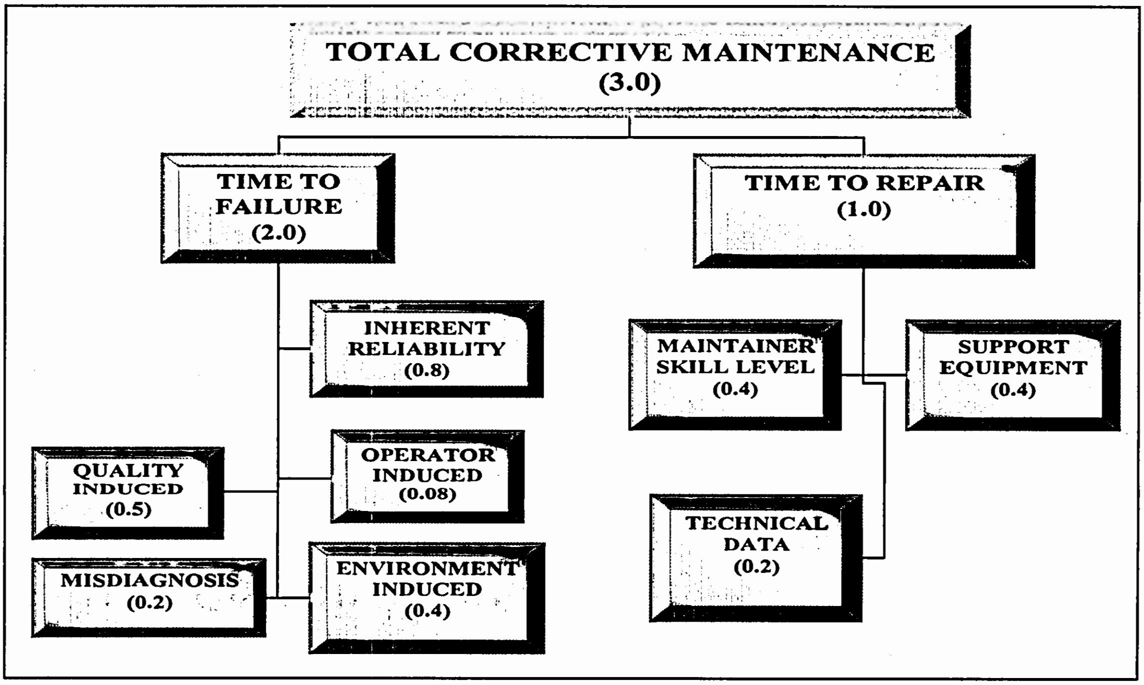

Figure 14: TCM Decomposition

---

[11] "Toward 90% Readiness: Feasibility Analysis to Raise Readiness and Support Soldiers," Presentation by AMCOM Aviation Task Force, November, 2001.

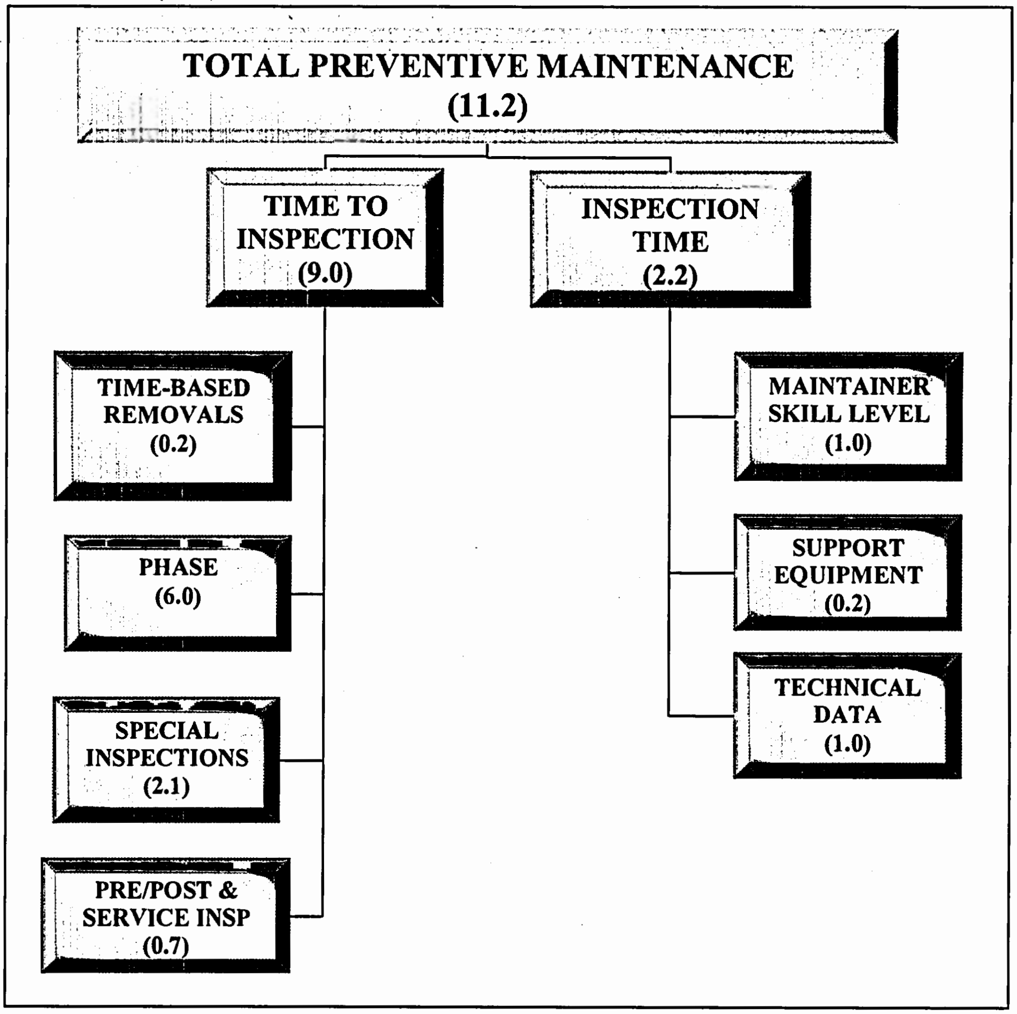

Figure 15: TPM Decomposition

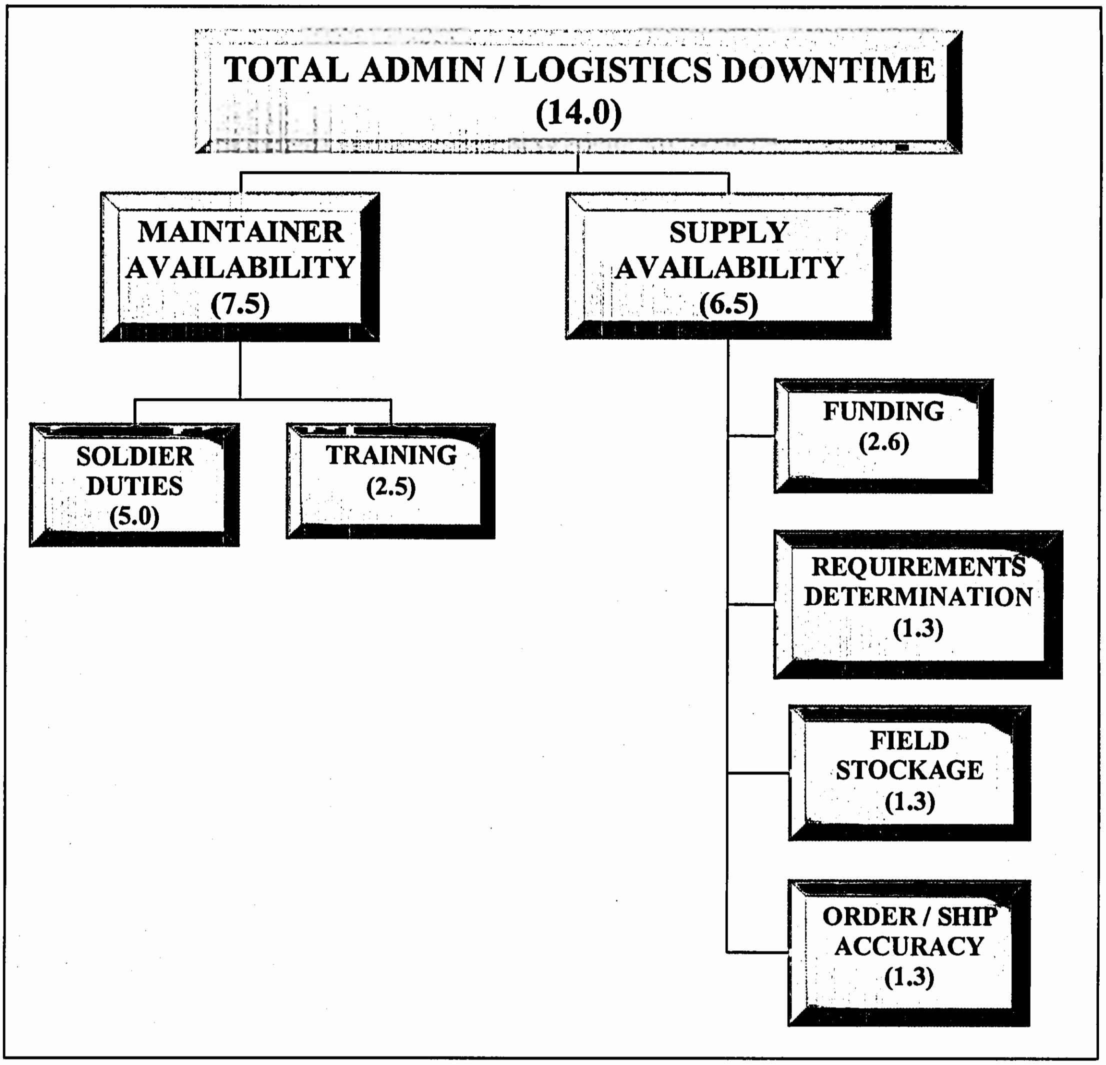

Figure 16: TALDT Decomposition

After further analysis, each cause of unavailability can be characterized in one of four sub-categories of unavailability. Those categories, featured in Figure 10, are Reliability, Maintainability, Administrative and Logistics. They are the four main aspects of the larger category of Dependability. A look at the contributions of each of the four sub-categories appears below. What is immediately clear is that the largest contributor to unavailability is related to administrative causes. The second largest contributor is the maintainability of the system. The actual reliability of the aircraft is by far the smallest contributor to overall unavailability.

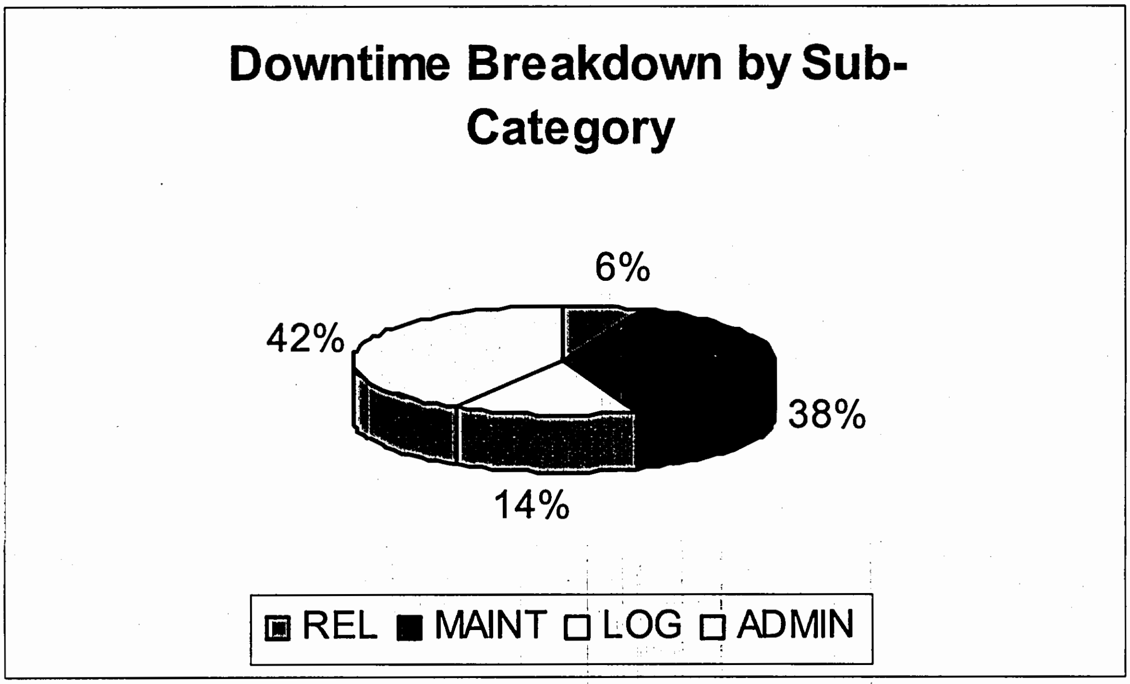

Figure 17: Sub-Category Unavailability Decomposition

In addition, each cause can be grouped into one of the two major categories of Dependability: Product and Process. Again, product causes are those directly related to the aircraft itself while process causes are associated with the means in which the aircraft is sustained. Figure 18 shows the decomposition of unavailability based on the two major categories. What is readily apparent is that the process of sustaining the AH-64 contributes more to the unavailability of the system than the aircraft itself. This observation is critical because it shapes the way the system availability needs to be improved.

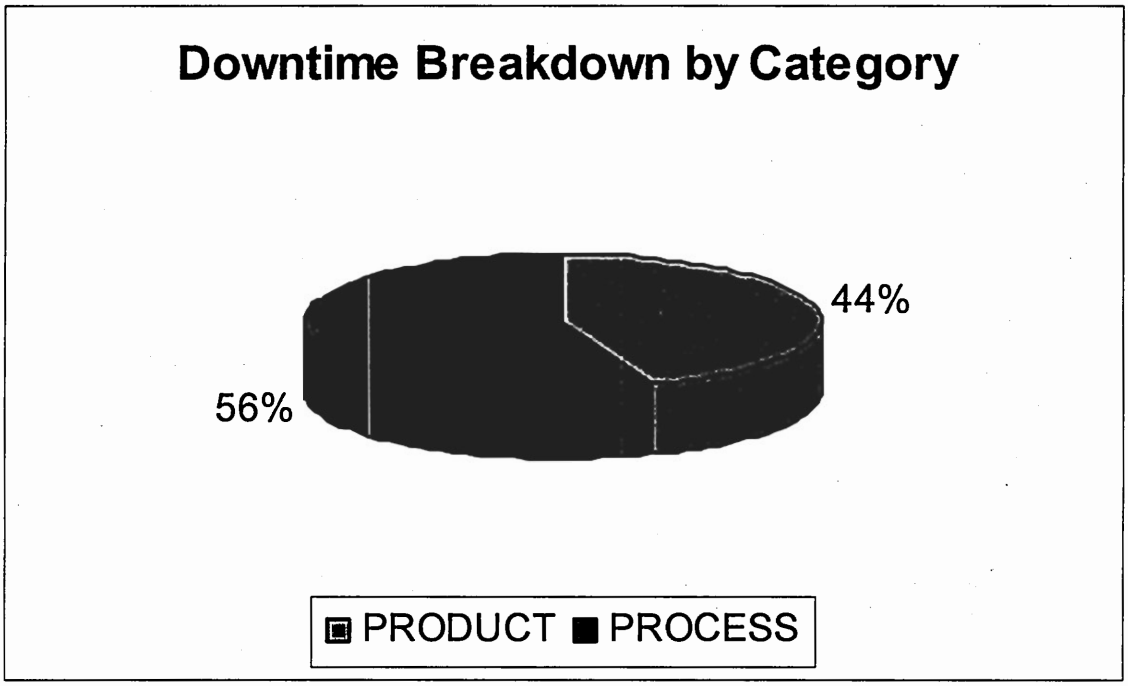

Figure 18: Category Unavailability Decomposition

In addition to the process-focused decomposition conducted mainly by the Apache PEO, Sandia National Laboratories decomposed the unavailability based on specific aircraft systems and sub-systems.[12] They focused on the top unavailability

---

[12] "Sandia Support for Toward 90% Readiness," Presentation by Sandia National Laboratories to The Apache Program Executive Office, 15 October, 2001.

drivers for the aircraft which appear below in Figure 19. Their study shows that the Drive System, Rotor System and Phase inspections are the three largest direct contributors to unavailability. This information can be used to later study the effects of improving the dependability of those systems.

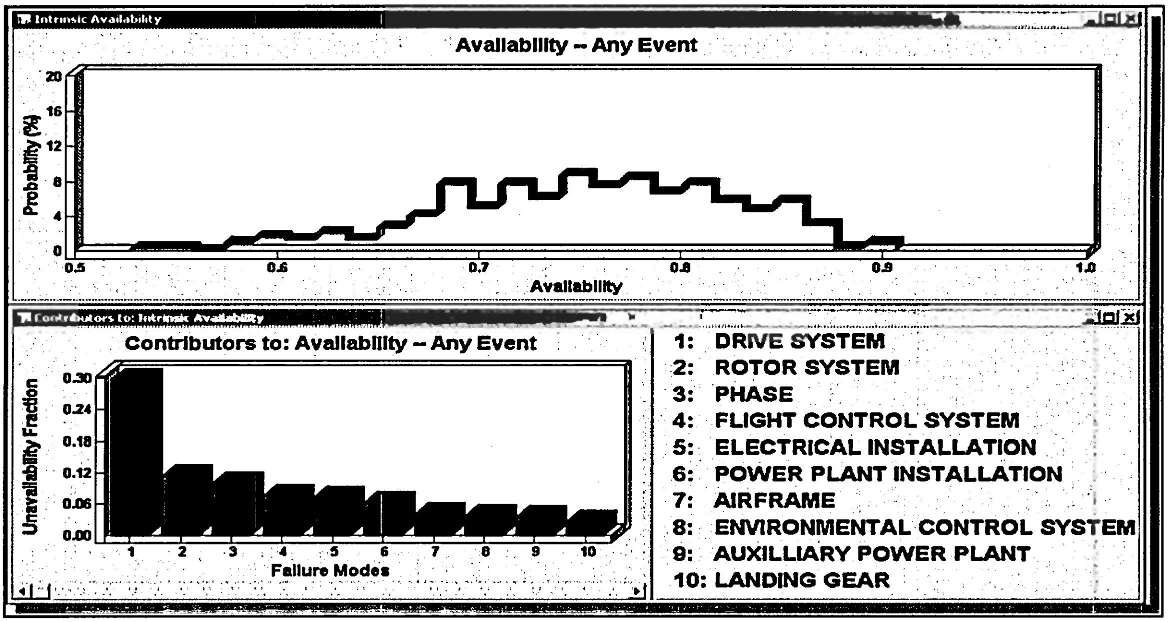

Figure 19: Aircraft Unavailability Decomposition

Quality Function Deployment

The last step in defining the problem was the Quality Function Deployment (QFD). The purpose of the QFD is to ensure that the customer's definition of quality is considered during the development or economic analysis process.[13] In this case, the

---

[13] Victor E. Sower, Michael J. Savoie, and Stephen Renick, An Introduction to

customer is defined as members of the PEO trying to accomplish the task of improving availability. The traditional role of the 'Voice of the Engineer' is replaced in this application by the 'Voice of the Analyst' in the IPPEA methodology.

Initially, a survey was conducted with key members of the PEO staff actively involved in the initiative to increase AH-64 availability. A list of customer requirements was given to each person and ordered in level of importance. The results of that survey appear in the table below. The table indicates that, depending on an individual's area of expertise, the emphasis they placed on the factors differed. In one case, the senior engineer also differentiated between peace and wartime weights. Instead of characterizing the weights of the customer requirements deterministically, the values were parameterized for use in a probabilistic QFD.

Table 1: Voice of Customer Survey Results

Position	Cost	Availability	Maint Impact	Safety	Prob of Success	Reliability
System Safety Mgr	6	7	5	1	9	8
System Engineer	7	9	3	1	8	4
	1	9	3	7	8	4
TOC Analyst	4	9	7	2	8	6
General Engineer	7	6	3	1	8	5
Min:	**1**	**6**	**3**	**1**	**8**	**4**
Mean:	**5**	**8**	**4.2**	**2.4**	**8.2**	**5.4**
Max:	**7**	**9**	**7**	**7**	**9**	**8**

Subsequent work on the QFD consisted of brainstorming the specific means to accomplish the customer requirements. These means, referred to in this research as the 'Voice of the Analyst, were based on the results of the statistical analysis and Ishikawa diagrams. The 'Voice of the Analyst' in hierarchical form appears in the diagram below.

Quality Management and Engineering, (Saddle River: Prentice Hall, 1999) 45.

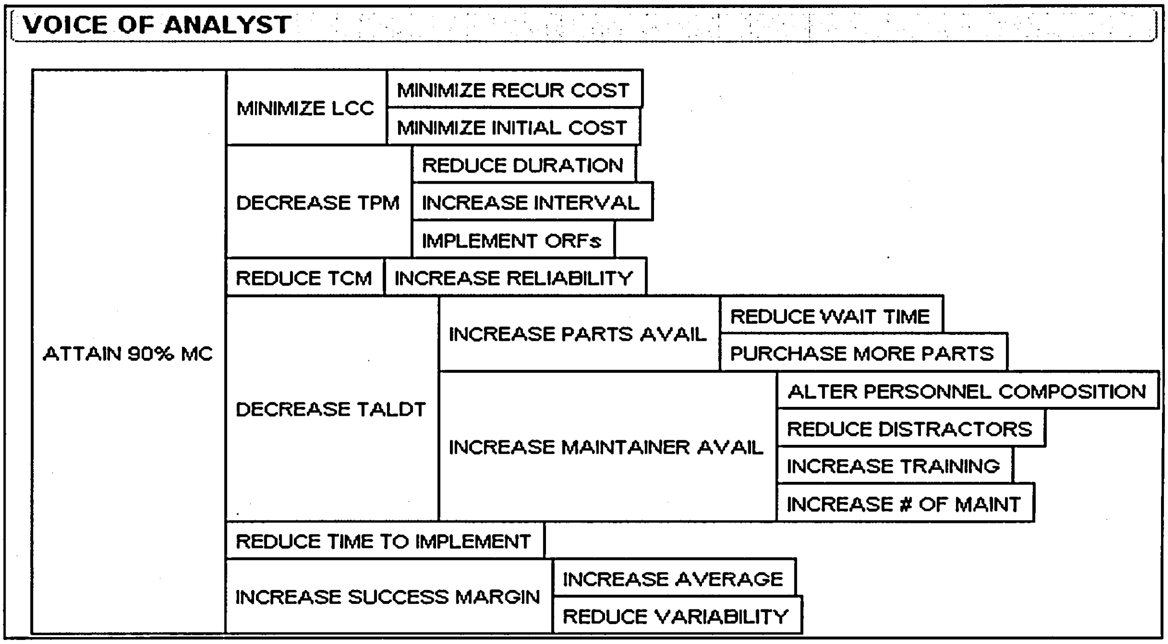

Figure 20: Voice of the Analyst

The 'Voice of the Analyst' consists of specific means to increase availability of the AH-64 system and address other aspects of Dependability identified during the Define the Problem phase of this research. When possible, these actions are quantifiable in nature.

Finally, the QFD, or House of Quality, was constructed. Using a probabilistic approach to the QFD, the customer requirements were considered as distributions based on the survey results. Each factor from the analyst was compared against the customer requirements to determine how each requirement and factor interacted. The probabilistic QFD appears in Table 2. The House of Quality displays the customer requirements, analyst factors and their relationship in a table format. The weights of the customer requirements in green are actually distributions, based on the survey results. An example of one of these distributions appears below in Figure 21.

Assumption: Reliability **Cell: B8**

Triangular distribution with parameters:

Minimum	4.00
Likeliest	5.40
Maximum	8.00

Selected range is from 4.00 to 8.00

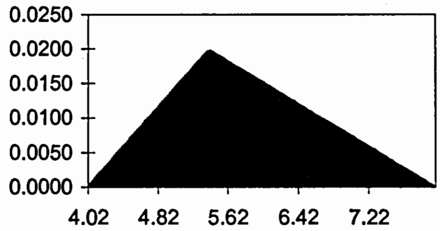

Figure 21: Example Triangle Distribution for Customer Requirements

The values in the middle table represent the relationship between the customer requirements and the analyst factors ranging from very weak (1) to very strong (9). Lastly, the values in blue represent the relative weights of each analyst factor in distribution form after conducting a Monte Carlo simulation. These distributions were used to compare alternatives and conduct sensitivity analyses between the different customer requirements.

Table 2: Probabilistic House of Quality

		Voice of Analyst						
Voice of Customer	**Weight**	**Initial Cost**	**Recurring Cost**	**Decrease TPM**	**Decrease TCM**	**Decrease TALDT**	**Time to Implement**	**Success Margin**
Minimize Cost	4.54	9	7	5	7	9	5	1
Maximize Availability	7.95	5	3	7	9	9	3	9
Minimize Maint Impact	4.11	7	3	5	7	5	3	1
Increase Safety	5.15	1	3	5	9	5	1	3
Increase Probability of Success	8.63	7	3	7	7	7	9	9
Increase Reliability	4.91	3	5	7	9	5	3	7
		189.71	133.88	219.49	283.14	243.72	156.47	207.75
		13.23	9.34	15.30	19.74	16.99	10.91	14.49

IDENTIFY ALTERNATIVES

The next major step in this methodology involves identifying ways to solve the problem. The QFD process was already used to determine factors that will affect the solution and their relative weights. The current step focused on specific methods that can increase the availability of the AH-64 and address the other requirements identified by the customer.

Undoubtedly, there are hundreds of ways to simply increase the MC rate of the AH-64 fleet. These methods range from simply changing the way units report their readiness to major changes in the aircraft or personnel structure. However, given the complexity of the U.S. Army and the limited funds available to accomplish this initiative, alternatives are limited to those that are realistic in nature. The following table is a morphological matrix which analyzes particular focus areas. Various methods to improve these focus areas were brainstormed and added to the table. These methods are the equivalent of alternatives in a more traditional product development cycle.

Table 3: Morphological Matrix

FOCUS AREAS:	A	B	C	D
Administrative	Maintainer Training	Enlisted Manpower		
Maintainability	ORFs	Enlisted Phase Teams	Contractor Phase Teams	Phase Interval
Logistics	Stock Availability	Reduce Wait Time		
Reliability	Recapitalization			

EVALUATE ALTERNATIVES

Evaluating each alternative consisted of several steps. First, each alternative was assessed independently to determine the relative strength of the alternative, based on an Overall Evaluation Criterion (OEC). This was accomplished by calculating or estimating the value of each analytical factor for the particular alternatives. Using a probabilistic decision matrix, each alternative received a number indicating the relative strength. Next, the alternatives were synthesized to determine an optimal solution accounting for the constraints present in this problem. Finally, a sensitivity analysis was performed to understand what factors present in the problem have the most effect on the outcome.

ESTIMATE COSTS / BENEFITS OF EACH ALTERNATIVE

Introduction

The first step in estimating the costs and benefits of each alternative was to establish a standard way to compare each alternative. For the purpose of this study, the life cycle of the initiative was considered to be five years. This number was chosen because many of the assumptions made earlier in the study may become invalid beyond a five-year period. There is no way of extrapolating the costs, effects of aging aircraft, unit locations and unit composition past that point. The AC force was calculated at a level of 306 aircraft. For most alternatives, the effective benefit and cost can only be calculated as a maximum MC rate increase or dollar value, respectively. To model the relative costs and benefits of each alternative a simple linear relationship between the costs and benefits was assumed. Finally, all figures values were based on 2003 values, or current values of money.

In keeping within the overall framework of the problem, all of the alternatives can be categorized as either administrative, maintainability, reliability or logistics improvements. A review of these sub-categories of unavailability in Figure 17, reveals that they are in order of relative percentage of downtime. Therefore, the sub-categories will be discussed in order of importance.

A large portion of the data used to analyze the alternatives was obtained from the Army Material Command's Deputy Commander for System Support (DCSS) Office and the Apache PEO. Both of these agencies have studied this problem based on the Army Chief of Staff's directives. Their findings and data are based on the input of experts with many years of maintenance and logistics experience. The goal of this part of the methodology is two-fold. First, analyzing the alternatives within the context of Dependability and using an OEC provides a basis of comparison between alternatives. Additionally, the probabilistic tools used as part of the methodology provide a means to model and analyze costs and benefits when there are unknown aspects of the problem.

Administrative

Administrative causes account for the largest percentage of unavailability, or 42%. Because the Army aircraft maintenance system is so complex, there is much room for administrative improvements. The following two alternatives involve increasing training provided to initial-entry enlisted maintenance soldiers and increasing the effective utilization rates of maintainers by increasing manpower. Increased training attempts to reduce the downtime caused by lack of maintainer skill. Increased manpower attacks unavailability caused by NMCM time, other than phase maintenance.

Increased Maintainer Training

One cause of unavailability, according to the system decomposition, is the training level of the enlisted maintainers who work on the AH-64. These soldiers, primarily in the 15 / 67 series Career Management Field (CMF), are typically junior enlisted soldiers with fewer then four years of experience. In addition, the actual training they receive before reaching their units of operation is minimal. In an Apache battalion, roughly 59% of the maintainer workforce is in the grade of E4 or below.[14] As a result, the enlisted force charged with maintaining a complex system such as the Apache is a relatively inexperienced group. This fact is compounded by the fact that all of the senior enlisted positions (E7), are platoon sergeant roles that often require administrative work

[14] U.S. Army Force Management Support Activity Database.

away from the flight line. A proposed alternative to increase MC rate is improving the amount of training maintenance soldiers receive in their Advanced Individual Training (AIT).

Judging the benefits and costs of increasing the training level of new recruits is a two-fold problem. First, one must quantify the negative effects of a lack of training and determine the potential improvement due to increased training. In addition, it is important to determine how much additional training is necessary to calculate the costs associated with increasing the training time.

To accomplish the first task a technique known as HEART, or Human Error Assessment and Reduction Technique was used. This technique, developed in the 1980s, uses three criteria to quantify human errors. First, it quantifies the type of tasks performed, based on their complexity and familiarity. Next, the conditions under which the tasks are performed are classified based on factors such as stress, supervision, rest and morale. Finally, a constant of proportionality is used in order to calibrate the effects of errors.[15]

For this application, the types of tasks normally performed by Apache maintainers were modeled as a discrete distribution accounting for the percentage of times those tasks were performed. Table 4 shows the types of tasks and their corresponding values, based on the HEART methodology. The figure below also displays the proportion each task accounts for in the total workload of a maintainer. These proportions were based on estimates of the actual workload of an AH-64 battalion.

---

[15] David J. Smith, Reliability Maintainability and Risk, Practical Methods for Engineers, 6th ed. (Boston: Butterworth-Heinemann, 2002), 119.

Table 4: HEART Task Values

Tasks:	Value:
Totally Unfamiliar	0.55
No Supervision	0.26
Complex Task	0.16
Fairly Simple Task	0.09
Procedure Checks	0.003

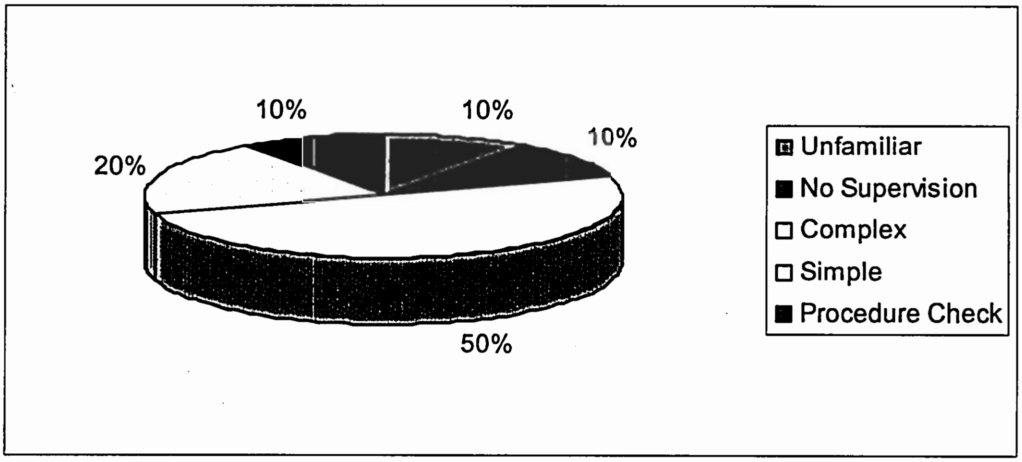

Figure 22: HEART Task Proportions

Next, typical Error-Producing Conditions (EPCs) present during AH-64 maintenance, were included in the model. The values associated with these EPCs were obtained from the HEART methodology. Finally, proportionality constants were used to calibrate the model to the percentage of downtime errors caused by the 'operators' in the System Decomposition step. The entire model was built using the commercially available software Crystal Ball™. A Monte Carlo simulation was performed using 100,000 iterations to simulate the multitude of tasks and conditions that can occur. According to expert analysis, approximately 5.68% of all downtime can be attributed to the skill or training level of maintainers. The baseline HEART model closely approximated this value during several Monte Carlo simulations.

Table 5 shows the probabilistic model used for this simulation. The green box for Task Value is the discrete distribution that models the types of tasks performed. The EPCs along the left are the values associated with the conditions that can commonly occur during AH-64 maintenance. The modifiable column indicates which conditions can be modified with additional training. The proportion column is a series of constants used to calibrate the model to the existing error percentages. The green values in the Training Factor column are distributions that account for the percent reduction in the error producing conditions caused by additional training. In order to model improvements in the error percentage, those factors that could be affected by training were reduced by a factor which was modeled as a uniform distribution ranging from 0.50 to 0.75. These values were chosen because there is no way to eliminate all of the error associated with a lack of training, and there is no deterministic way of quantifying what percentage of errors can be eliminated with additional training unless an extensive study is conducted. However, this approach offers a way to model the uncertainty associated with maintainer training.

Table 5: HEART Probabilistic Model

EPC:	Value:	Modifiable:	Proportion:	Training Factor:	New Proportion:	Contribution:
Unfamiliar w/ Situation	17	Y	0.3	0.5	0.15	3.4
Shortage of Time	11	N	0.27	1	0.27	3.7
Newly Qualified	3	Y	0.2	0.5	0.1	1.2
Stress	1.3	Y	0.1	0.5	0.05	1.015
Low Morale	1.2	Y	0.05	0.5	0.025	1.005
Disruption of Sleep Cycle	1.1	N	0.08	1	0.08	1.008
TOTAL:	**34.6**		**1**			**11.328**

After conducting the Monte Carlo simulation, the following results were obtained. The blue line in Figure 23 is the cumulative distribution of error percentage in the baseline model. The red line represents the cumulative distribution of the improved error percentage. Overall, the model predicts that approximately 2.23% of all downtime can be eliminated with an increase in the amount of training new soldiers receive. Since the average MC rate for the AH-64 is 79%, the increase in MC rate due to training benefits amounts to roughly 0.47%.

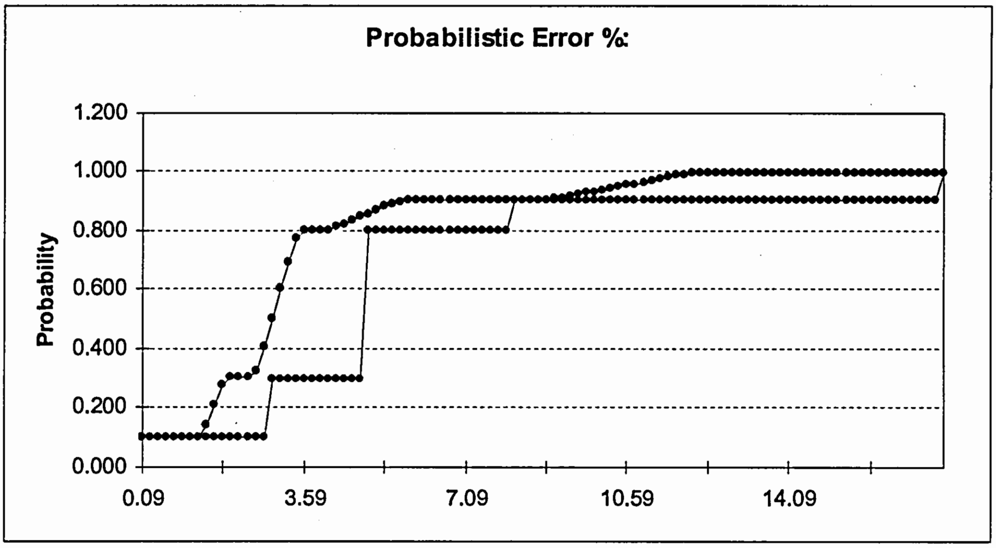

Figure 23: HEART Model Overlay

The next step in evaluating the merits of increasing the training level of maintainers is approximating the costs associated with this alternative. AIT for Apache maintainers is conduced at The Army's Logistics School at Fort Eustis, Virginia. The cost associated with training each new soldier was obtained from the Army's FORCES database. With the addition of this data, the following data for this alternative was calculated. Table 6 shows the results of the cost-benefit analysis for increasing maintainer training. The number of units and maintainers per unit were used to estimate the annual number of trainees necessary. The additional cost of training soldiers had to be estimated, since it is not known how much additional training is necessary. The current cost of training is already known. The additional costs were modeled as a uniform distribution ranging from zero to double the current cost. The green cell below the Additional Cost heading represents this uniform distribution. The MC increase is modeled as a normal distribution based on the Monte Carlo simulation conducted within the HEART model.

Table 6: Maintainer Training Cost-Benefit Data

Parameters:	Units:	Values:
# Battalions:	#	15.00
Maintainers / Battalion:	#	135.00
Trainees / Year:	#	405.00
Add'l Cost / Trainee:	$	[redacted]
Five Year Cost:	$ Millions	[redacted]
MC Increase:	%	[redacted]

<u>Increase Enlisted Manpower</u>

The decomposition in Figure 16 indicates a significant portion of TALDT caused by a lack of maintainer availability. Training, other duties and personal responsibilities all contribute to reducing the amount of time maintainers spend working on maintenance-related tasks. A study conducted in the United States shows that maintainers only spend 31% of their time actually working on maintenance-related tasks.[16] A sample of a unit outside the CONUS, conducted as part of this research, indicates that this number is closer to 55% there. This higher value is probably due to the fact that there are less family distractions overseas and commanders are more

[16] "Toward 90% Aviation Readiness", Presentation Prepared by the Army Materiel Command, 14 June 2002.

willing to enforce long workdays. One alternative to reduce this problem is to eliminate personal distractions, other training opportunities and duty responsibilities. However, this method may not be feasible for several reasons.

First, soldiers will always have personal responsibilities to attend to. Commanders will never be able to eliminate these problems without completely changing the operating habits of outside institutions such as health clinics, banks, legal offices, etc. Second, unlike civilian aircraft maintainers, Army personnel must conduct numerous training tasks including weapons qualifications, Nuclear, Chemical and Biological Training, and other training related to operating in a combat environment. Finally, the assumptions associated with maintainer availability may be flawed to begin with.

The Army's Manpower Resources Criteria (MARC) indicates that an Apache maintainer should be available between 2701 and 2957 hours per year, for Corps and Divisional units, respectively.[17] Assuming 10 hour workdays, that translates to between 270.1 and 295.7 days a year. Disregarding all days off except weekends, there are only 261 workdays available to work with. Typical units have at least 10 holidays during a given calendar year, reducing the number of available days to 251. In addition, soldiers are authorized 30 days of leave per year. Assuming up to 5 of those days may be weekends also, that brings the number of workdays available to 226. In order to be available for 2957 hours in 226 days, a soldier would have to work 13 hour days when he or she was available. Clearly, the expectation of available manpower at the most basic level is unrealistic.

Without further study, analyzing increased maintainer availability is unrealistic. Another alternative is to increase the actual number of maintainers employed to

[17] U.S. Army Force Management Support Activity Database.

compensate for the lack of availability. This alternative, Increasing Enlisted Manpower, involves increasing effective availability through the use of additional manpower.

These results were calculated by conducting a regression analysis using the unit readiness data obtained as part of this research. This analysis demonstrated that the difference in NMCM or AVUM time between CONUS and OCONUS units was statistically significant and was approximately 2%. Table 7 is a table generated in the software tool JMP™ that shows that the V Corps and EUSA, located in Germany and Korea respectively have a lower AVUM rate than III Corps and XVIII Airborne Corps units. The latter units are CONUS-based. Furthermore, it is known that the maintainer utilization rate in CONUS is 31%. Based on the survey conducted as part of this thesis, the rate in Korea is closer to 55%. Assuming that the utilization rate in Germany is similar to Korea, this means that an 11% increase in maintainer availability should equate to a 1% increase in MC rate.

Table 7: AVUM Regression Analysis

AVUM Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	14.788136	0.407242	36.31	<.0001
Unit Type{Corps-Division&ACR}	0.3062294	0.512182	0.60	0.5501
Unit Type{Division-ACR}	1.2794258	0.748175	1.71	0.0876
Parent{V&EUSA-XVIII&III}	-2.185277	0.374252	-5.84	<.0001
Parent{XVIII-III}	-1.48497	0.530664	-2.80	0.0053

The only task remaining for this alternative is to estimate the costs associated the increased manpower necessary to account for this utilization deficit. In order to calculate the costs, three categories were considered: Training, Support and Salary. The training costs are an initial cost based on data obtained from OSMIS on the cost of the Fort Eustis based initial training. Support costs were also obtained from OSMIS based on the per capita costs associated with funding at Fort Hood, Texas. Finally, the salary costs are easily obtained and represent a numerical average of the pay grades associated with an AH-64 battalion. The results of the cost-benefit analysis appear below in Table 8.

Table 8: Increased Manpower Cost-Benefit Data

Parameter:	Units:	Values:
Util Increase:	%	57.8
Manpower Increase:	# People	1170.5
Training Costs:	$ Millions	27.7
Support Costs:	$ Millions	52.2
Salary Costs:	$ Millions	269.2
Five Year Costs:	$ Millions	349.1
MC Increase:	%	5.3

Maintainability

The maintainability analysis in this report focuses on the preventive inspections required to maintain the AH-64. Inspections on the aircraft fall into one of three major categories: Scheduled, Special and Phase. There are several different scheduled inspections ranging from a 10 Hour-14 Day inspection to a 125 Hour inspection conducted on the aircraft. Most of these inspections do not pose a significant impediment to availability. Special inspections, on the other hand, are the result of unforeseen safety hazards, typically discovered after a major problem. These inspections are added to existing scheduled maintenance or conducted separately, based on the circumstances. Both of these categories of inspections have the potential to benefit from a Reliability Centered Maintenance approach. In this approach, a comprehensive look at every component would be conducted. This strategy is aimed at determining the most cost-effective way to inspect, replace or repair each component. Unfortunately, the type of detailed component failure data necessary for RCM, was not available for this research. Therefore, the maintainability improvements focused on phase maintenance.

Phase inspections are large-scale inspections conducted at 250 hour intervals that involve disassembling large portions of the aircraft. The inspection is time-consuming and can cause high amounts of downtime if conducted slowly or if delayed due to the lack of repair parts.

Without severely altering the phase inspection tasks, there are three ways to reduce the amount of downtime associated with phase inspections. One is to reduce the amount of time an aircraft spends in phase maintenance. This is done by reducing the phase duration through additional manpower and better supply availability. Another method is to increase the interval between phases, thus reducing the number of phases required in a given period. The last method is to have spare aircraft available to use when an aircraft is in phase. These spare aircraft, referred to as Operational Readiness Floats (ORFs), are usually kept and maintained by the intermediate level maintenance organization and were more widely used in the past. However, aircraft losses have depleted the number of ORFs, reducing their widespread use.

One challenge in analyzing alternatives in the maintainability category was developing a model to capture the dynamic nature of aircraft maintenance. Typical reliability tools such as fault trees and reliability block diagrams are static in nature. Another tool, known as Markov chains, provides a means to model stochastic events. The disadvantage of Markov chains is that they become progressively larger when the model entails more than four or five components. Therefore, a tool known as a Stochastic Petri Nets (SPNs) was explored.

Petri Nets were presented in the 1960's in a PhD thesis by Carl Petri in Germany.[18] Designed to model dynamic systems, Petri Nets have evolved from deterministic to probabilistic applications with the ability to model probability distributions.

Petri nets consist of four basic components: places, transitions, tokens and arcs. Places represent a state in the process. For example, in the phase inspection model, a place can represent an aircraft in an available status or an aircraft in phase. Transitions represent the stochastic, or time based nature of changes in the model. Transitions can be immediate, deterministically time-delayed, or time-delayed based on a probability distribution defined by the user. A transition could represent the interval between phase inspections or the amount of time an aircraft spends in phase. Tokens represent the object in the model. For instance, an aircraft or aircraft component could be modeled as a token. When a transition allows the movement of a token it is like a door that opens in the model. The transition is said to have 'fired' when this happens. Lastly, arcs determine the path tokens take throughout the model. Arcs can either enable or inhibit movement in the model, depending on their use. A graphical representation of these Petri net components appears in Figure 24.

---

[18] Petri Nets World Online Homepage, www.daimi.au.dk/PetriNets.

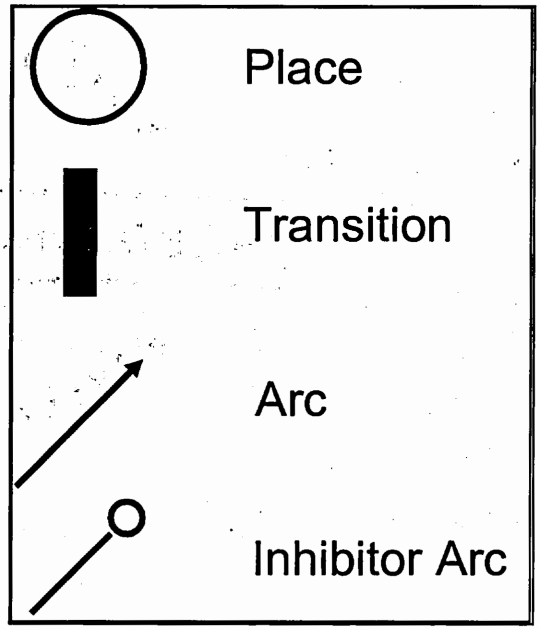

Figure 24: Petri Net Components

In order to analyze maintainability improvements to AH-64 maintenance, two basic Petri net models were built. The first, which appears in Figure 25, works as follows. Tokens representing the aircraft in a battalion begin in the upper left-hand corner in the place called 'Operate'. In this place the aircraft are not in phase and are considered available. On a pre-determined schedule, one aircraft moves through the transition called 'Interval' and is placed in 'Prephase'. The interval represents the number of days between aircraft phases, based on a 4800 hour annual flying-hour program. Once in 'Prephase', the aircraft moves through one of the two immediate transitions to the right and into the 'Tm1' or 'Tm2' place. These two places represent two phase teams at the battalion level. Inhibitor arcs prevent more than one aircraft from moving to a team at one time. The 'Duration' transitions represent the duration of a phase inspection. They can be modified to be longer or shorter and can be modeled as a constant, or a probability distribution. The 'Spares' place represents a holding spot for

ORF aircraft, if used in the model. ORF aircraft move through the 'Admin Delay' transition representing one day for paperwork and other administrative procedure. Another inhibitor arc prohibits more than 21 or 18 tokens from entering the 'Operate' place, depending on whether the unit is a Corps or Divisional battalion.

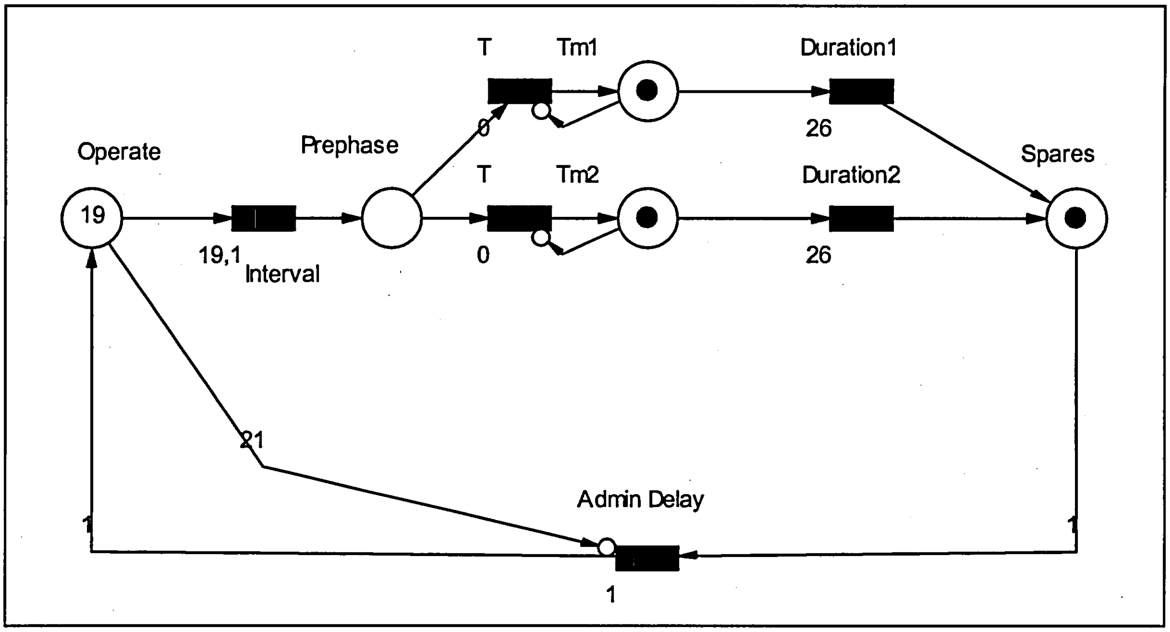

Figure 25: Phase Inspection Petri Net Model (1 Battalion)

This deceptively simple model is a very powerful tool. Built in less than ten minutes, it can be quickly modified to analyze the impact of additional phase teams, shorter phase durations or additional ORF aircraft. An output window displays the number of tokens in any place over a specified time period. Figure 26 is an example of an output graph of a simulation conducted with a model portraying a battalion with 21 aircraft and no spares. The horizontal axis represents days and the vertical axis represents the number of tokens, or aircraft, in the 'Operate' place. Prior to the 400 day mark, the duration of the inspection was 26 days. After 400 days, the model was changed to a 16 day phase duration simply to demonstrate the changes in availability.

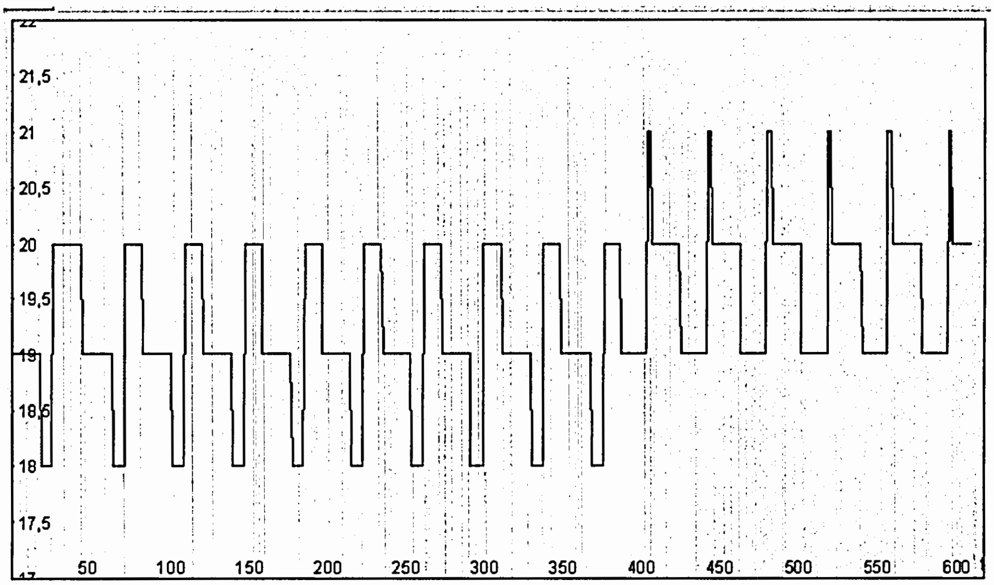

Figure 26: Petri Net Results (21 Aircraft, No ORFs)

Implement Spare Aircraft (ORFs)

This alternative and following two methods focus on potential availability improvements involving phase inspections and maintenance. All three methods relied on the use of the Petri Net models previously described.

The use of spare aircraft to compensate for aircraft in phase is not a new idea. ORFs were used in the past to replace an aircraft that was destroyed or required a large amount of time in repair. However, as previously mentioned, aircraft attrition has caused a reduction in the number of ORFs throughout the fleet. In order to model the benefits of ORF aircraft, several simulations were conducted using Petri nets under various conditions. First, a simulation consisting of 24 aircraft and no ORFs was conducted to ensure the accuracy of the baseline model. Historical data attributes approximately 8%

unavailability due to phase inspections. The Petri Net model resulted in 7.9% downtime in simulations.

Simulations with up to two spare aircraft per battalion were conducted for both Corps and Divisional units, consisting of 21 and 18 aircraft, respectively. In addition, a more complex model was used to simulate two units sharing one ORF. In most cases, there is more than one attack battalion at a given location. This expanded model appears in Figure 27. Both battalions featured in the model are identical to the previous model for one battalion. However, the 'Spare' place is shared by both battalions. Therefore the spare aircraft can move to whichever battalion needs it.

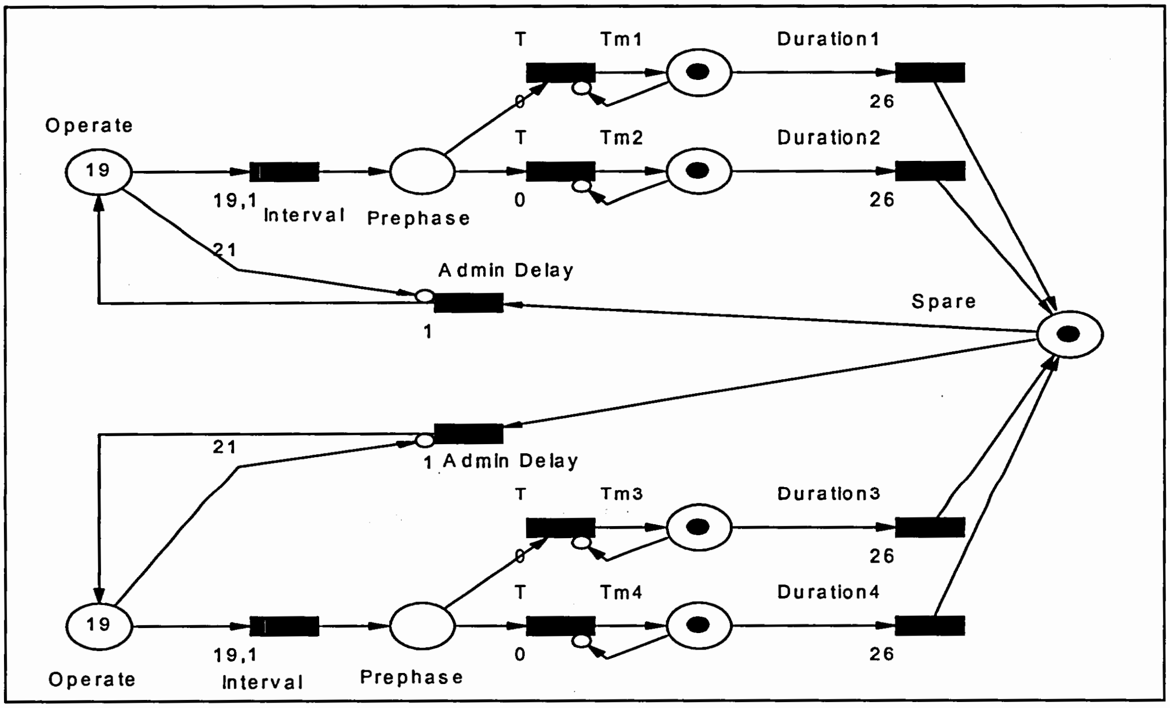

Figure 27: Phase Inspection Petri Net Model (2 Battalions)

After conducting the appropriate simulations, the corresponding MC benefit was calculated for each condition. The cost associated with purchasing additional aircraft was obtained from the OSMIS database. For comparison, only the purchase cost for new aircraft was considered. There should only be a negligible cost associated with housing the aircraft since hangar space already exists in unit areas. In addition, the operating costs of the aircraft should also be relatively transparent since all units receive an operating budget for a specific flying hour program and cannot exceed those hours, regardless of the number of aircraft. The ORF operating costs will simply be a part of the overall operating budget which would not change under the new program. The cost-benefit data for this alternative appears below in Table 9.

There are two important things to note in this chart. First, the MC increase when 2 spares per battalion are implemented appears to exceed the 8% unavailability mentioned for the baseline. This anomaly occurs because the baseline unit consisted of 24 aircraft. Obviously, smaller units incur a sharper availability penalty if the same number of phases must be conducted in a given period. Second, the ORF alternative presents the greatest potential MC increase and the corresponding highest cost. The use of 2 ORF aircraft nearly eliminates any downtime associated with phase inspections.

Table 9: Implement ORF Cost-Benefit Data

		Spares / Battalion:		
Parameter:	**Units:**	**0.5**	**1**	**2**
Cost:	**$ Millions**	207.1	414.2	828.4
Division MC Increase:	**%**	6.1	6.3	10.6
Corps MC Increase:	**%**	4.4	4.6	8.9
Fleet MC Increase:	**%**	5.4	5.6	9.9

<u>Increase Enlisted Phase Teams</u>

The next two alternatives are essentially two different ways to accomplish the same result. The Ishikawa diagrams showed that the availability of maintenance personnel was an impediment to expedient phase maintenance. Reducing the duration of phase inspections is one way to reduce the NMCM time associated with them. The Apache PEO estimates that phase inspections have the potential to be reduced from 26 days to 16 with additional manpower and improved spare parts availability. It is critical to note at this time that a prerequisite for this alternative and the subsequent one is to also implement the Supply Availability alternative as well, which will be discussed later.

For the phase duration analysis, the Petri Net models were used. The results were compiled in a similar manner as the ORF alternative. It is reasonable to assume that in order to accomplish the reduction in phase duration, a corresponding increase in phase team manpower was required. For the purpose of this study, that manpower was assumed to double from 16 members to 32. All of the costs associated with this alternative were calculated using OSMIS data based on 16 additional enlisted soldiers per battalion. The results of the analysis appear below.

Table 10: Increase Enlisted Phase Teams Cost-Benefit Data

Parameter:	Units:	Values:
# Battalions:	#	15.0
Maint Increase / Battalion:	#	16.0
New Maintainers:	#	240.0
Training Costs:	$ Millions	5.7
Support Costs:	$ Millions	10.7
Salary Costs:	$ Millions	55.2
Five Year Cost:	$ Millions	71.6
MC Increase:	%	3.1

Increase Contractor Phase Teams

Currently, aviation units employ contractor maintenance to augment the organic assets available. Contract maintenance carries several inherent advantages and disadvantages. Contractors do not conduct military training or duties that detract from their utilization on the flight line. However, civilians are more difficult to utilize on weekends and holidays, after-hours, and in certain field and combat environments. Finally, contractors typically have higher salaries than enlisted soldiers and therefore cost more per capita to employ. The following table provides the cost-benefit data for contract phase teams. Cost data was obtained from presentations regarding the 90% MC initiative. The contractor option is more expensive for the same benefit than the enlisted phase team alternative.

Table 11: Increase Contractor Phase Teams Cost-Benefit Data

Parameter:	**Units:**	**Values:**
# Battalions:	**#**	15
Cost / Battalion:	**$ Millions**	11
Five Year Cost:	**$ Millions**	165
MC Increase:	**%**	3.1

Increase Phase Interval

The last way to reduce unavailability associated with phase inspections consists of increasing the interval between phase inspections. Initially, this alternative appears promising because it offers the hope of reducing downtime with no additional costs and it reduces manpower requirements. However, there is a risk associated with this alternative. An aircraft undergoes a major disassembly during a phase. An outside viewing an Apache in phase would probably refer to the aircraft as 'gutted' or 'stripped'. As a result, the inspection is used to examine the condition of many safety-critical components that do not get inspected otherwise. Increasing the time between phase inspections without careful analysis could be dangerous and actually increase downtime and costs due to component failures. It is easier to inspect and replace a part in phase inspection than it is to repair it once it fails in operation.

Studying and recommending an optimal phase interval requires a tremendous amount of data. Component failure rates (MTBF), replacement costs, replacement times (MTTR) are all required for a proper analysis. More importantly, an analyst must understand the interval in which a failure can be detected prior to complete failure, similar to a damage-tolerance approach to maintenance.

An example of the type of analysis needed appears in Figure 28. For each component inspected solely during phase inspections, the failure probability distribution can be modeled with a tool such as Crystal Ball™. If the detection interval is known it can be modeled as the green band around the phase in which the fault will be found and is 'safe'. The red bands indicate regions where the component failure will cause unscheduled or corrective maintenance to occur. In this case, a RCM approach could be utilized to understand the costs and risks associated with inspecting, repairing and replacing components.

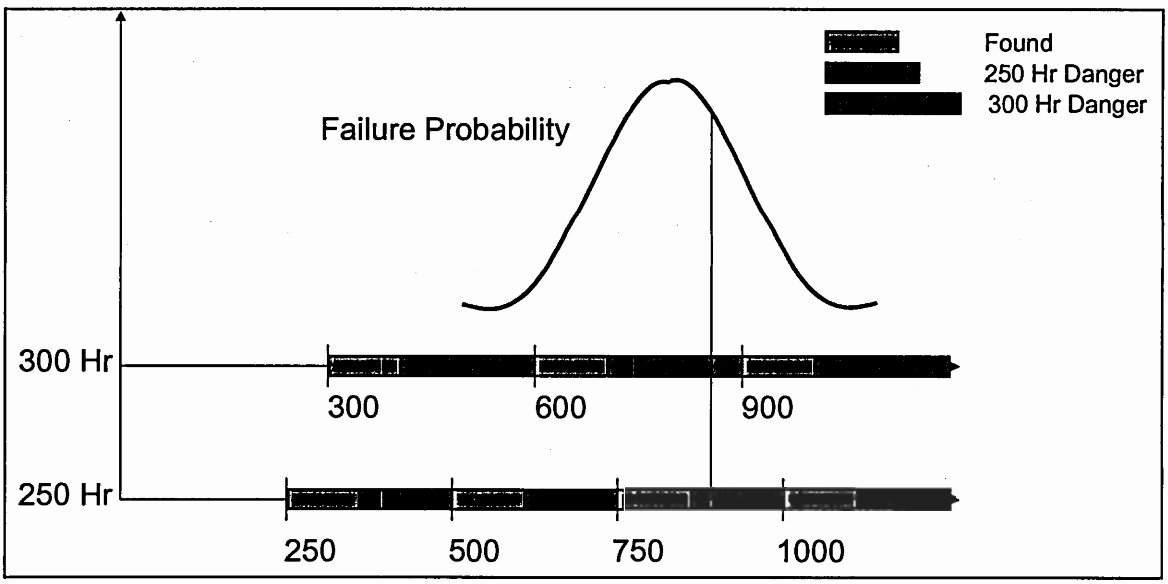

Figure 28: Phase Interval Analysis Model (Proposed)

Unfortunately, this data is currently unavailable in significant quantities for the AH-64 system. The Army does not have the capability in place to collect and analyze this type and volume of data. As a result, increasing the phase interval cannot be fully analyzed or considered as a viable alternative for this research.

Increase Stock Availability

A current goal of the Army Materiel Command is achieving a stock availability of 85%. This means that 85% of the parts required will be available in the supply system. In recent years, a combination of increased operational tempo, shortages of funds and aging aircraft have reduced the stock availability below 85% and as low as 70%. Experts believe that attaining 85% stock availability is achievable and will have a positive effect on aircraft readiness.[19] Table 12 below provides an estimate of the costs and benefits associated with increasing stock availability.

The effects of a lack of stock availability are often masked by two factors. First, the practice of controlled exchange hides the lack of spare parts in the system. Controlled exchange is the practice of removing parts from an aircraft already unavailable, often an aircraft in phase, and placed them on an aircraft that needs the parts.

Second, in the past, if an aircraft was unavailable for supply and maintenance at the same time, the downtime due to maintenance took precedence and was the only condition reported. Inevitably, NMCS was not fully reported in the past. Recent policy changes to Army Regulation 700-138 should address and remedy this problem.

---

[19] "Toward 90% Readiness: Feasibility Analysis to Raise Readiness and Support Soldiers," Presentation by AMCOM Aviation Task Force, November, 2001.

Figure 29 reinforces all these assertions by showing the profiles of NMCS and AVUM downtime due to various factors such as average supply wait time, the number of controlled exchanges (C/X) reported per month, and the $/hour spent on aircraft operations. It is interesting to note that longer supply times actually appear to reduce NMCS downtime, while increasing AVUM time. This phenomenon is probably due to the fact that units that must consistently wait longer for parts probably give up and resort to more controlled exchange. This process, however, increases maintenance time.

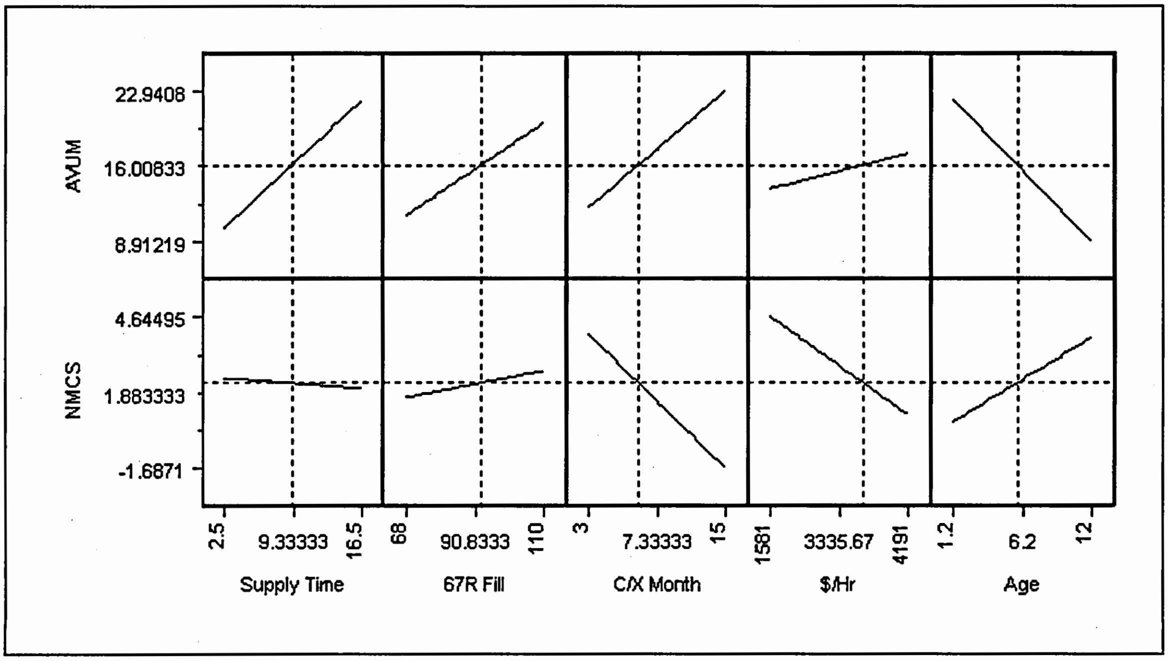

Figure 29: NMCS and AVUM Profiles

The table below summarizes the costs and benefits associated with increased stock availability. This data was taken from the AMCOM presentation on 90% MC. Another critical note about this alternative is the fact that it is required for the alternatives involving reduced phase inspection durations. Additional manpower will not reduce phase times if repair parts are not readily available.

Table 12: Stock Availability Cost-Benefit Data

Parameter:	Units:	Values:
Initial Cost	$ millions	120.5
Annual Cost	$ millions	4.5
5 Year Cost	$ millions	143.1
MC Increase	%	3.6

Recapitalization

Recapitalization involves investing capital to improve the inherent reliability of components that already exist on the aircraft. Although the AH-64D model employs advanced avionics and weapons systems, the airframe, drive train and the majority of other components remain identical between the A and D model aircraft. As a result, despite the appearance of a newer AH-64 fleet, the cost and time to maintain the fleet increases slightly as the airframes age.

Surprisingly, statistical analysis does not indicate that age has an adverse effect on MC rate for aircraft. Figure 30 below shows a line fit of MC rate vs. Age for the AC fleet. The green line represents the line fit about the mean, which is the red line. Although the green line displays a slight downward trend, regression analysis can not prove that the downward trend is statistically significant.

Figure 30: MC Rate vs. Age for AC Fleet

Although, aircraft age does not seem to affect the MC rate of units, it does have an impact on the money spent on aircraft maintenance. The next two charts show the average age comparison between CONUS, Europe (USAREUR) and Korea (EUSA). Europe clearly has the oldest aircraft while Korea has the newest aircraft overall. The cost per hour of maintaining these aircraft follows the age trend also with Europe spending more to operate their aircraft, and Korea spending the least. Therefore, one can conclude that age affects the cost of maintaining aircraft by increasing the rate at which parts must be replaced. Replacing parts takes time and manpower. If the replacement rate can be reduced through recapitalization then manpower requirements should be reduced and operating cost savings realized.

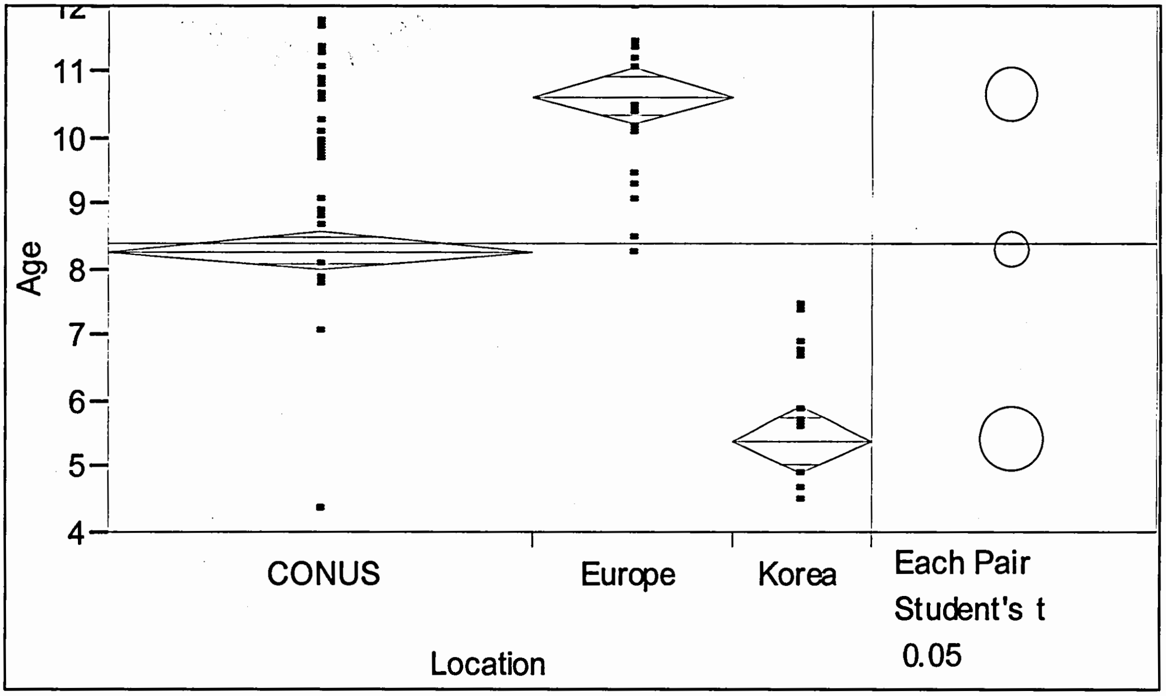

Figure 31: Average Aircraft Age by Location

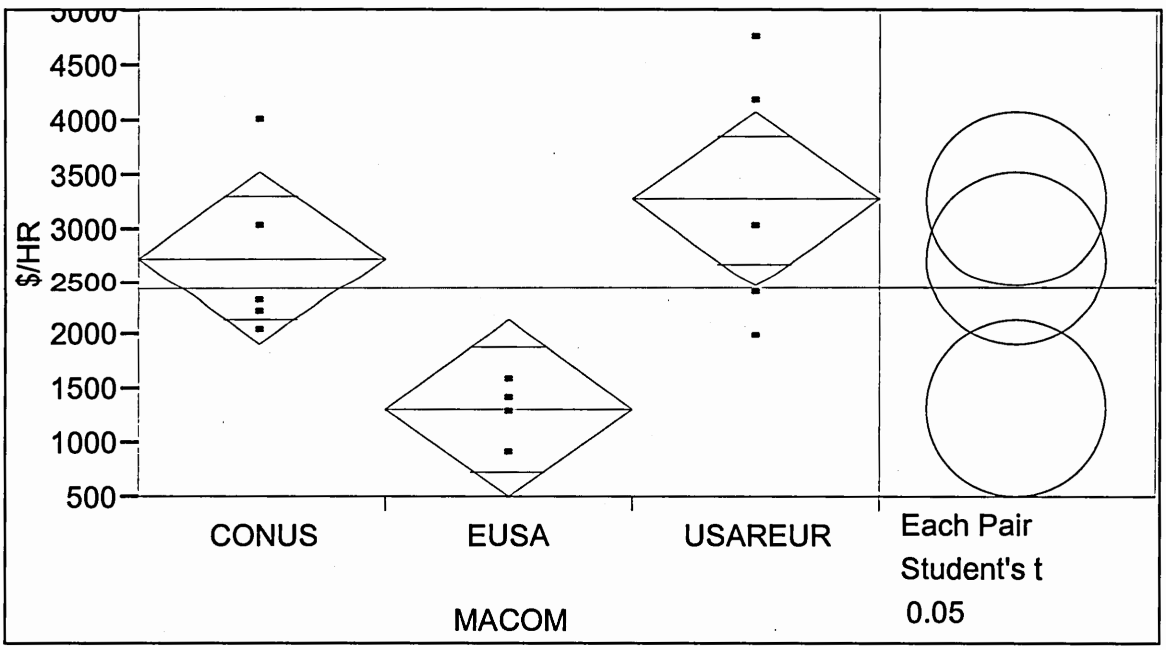

Figure 32: Operating Cost / Hour by Location

For approximately three years, Sandia National Laboratories (SNL) conducted a study for the Apache PEO on the benefits of recapitalizing specific components on the AH-64. The study, which culminated in a report published in September, 2002, was conducted primarily at Fort Campbell and Fort Hood. Over 2000 failures were analyzed and the top 39 cost and maintenance drivers were analyzed.[20]

Due to the scope of the SNL study, their results form the basis of the cost and benefit analysis of this thesis. This alternative is unique because, although recapitalization requires an initial investment; over a five year period, the alternative actually saves money. All of the other alternatives cost money over a five year period. The table below is a summary of the initial costs, availability benefits and five year savings associated with the recapitalization alternative.

Table 13: Recapitalization Cost-Benefit Data

Parameter:	**Units:**	**Plan 1:**	**Plan 2:**	**Plan 3:**
Initial Cost:	**$ millions**	20.5	41.0	61.5
Annual Cost Decrease:	**$ 1000 / acft**	100.0	165.0	195.0
5 Year Cost:	**$ millions**	-132.5	-211.5	-236.9
MC Increase:	**%**	2.0	2.4	2.5

Summary

A final look at the costs and benefits associated with each of the alternatives appears in the table below. This data represents the maximum MC benefit for each

---

[20] "Apache Recapitalization Optimization Final Results," Report Submitted by Sandia National Laboratory to The Apache Program Executive Office, September 2002, 5.

alternative. A cursory examination reveals the worst and best alternative in cost, MC benefit and cost-benefit ration with red and green highlights, respectively. Using ORFs to reduce phase downtime offers the greatest potential MC increase, but is very costly. Recapitalization does not have a large potential MC rate benefit, but the fact that is reduces life-cycle costs gives it a unique cost-benefit ratio. Maintenance training is a relatively cheap option, but it does not promise substantial benefits, giving it the worst cost-benefit ratio.

Table 14: Cost-Benefit Summary Data

Alternative:	Cost: $ Millions	MC Increase: %	Cost / Benefit: $ Millions / %
Maint Training	47.8	[redacted]	[redacted]
Enlisted Manpower	349.1	5.3	65.9
ORFs	[redacted]	[redacted]	83.7
Enlisted-Phase	71.6	3.1	23.1
Contractor-Phase	165	3.1	53.2
Supply Availability	143.1	3.6	39.8
Recap	[redacted]	2.5	[redacted]

COMPARE ALTERNATIVES

To this point in the methodology, the effort has been to understand what the problem is, why the problem exists and how to fix it. The final, and most important stage, is to determine the best way to fix the problem. Previous work did not offer a means to compare alternatives and ultimately recommend an optimal solution. This methodology offers that recommendation by correlating the customer requirements to evaluation criteria via the QFD results obtained earlier.

Decision Matrix

Critical to this methodology is the means of comparing the relative merits of the various alternatives presented. For example, if two alternatives both promise to increase the MC rate of a unit by 3%, which alternative is better? If they also both cost the same, which alternative is better? If an analyst recommended completely eliminating phase inspections, on first look that would offer a tremendous boost to MC rates. However, it is potentially dangerous. Yet without an advanced evaluation criteria, the alternative seems promising.

The use of an Overall Evaluation Criteria (OEC) is a numerical method to evaluate and compare the relative merits of two or more alternatives. In this application, the OEC was developed in conjunction with the QFD process. A survey posed to experts in the maintenance and logistics arena prioritized a set of customer requirements. Then, a series of corresponding means of accomplishing those requirements were formulated. The QFD relates the weights of the customer requirements to the importance of the analyst's requirements. These requirements are then used as evaluation criteria for each of the alternatives.

In this application, the QFD was developed using probability distributions for the weights of the customer requirements in order to capture the range of input from experts. As a result, the weights of the analyst's requirements are distributions as well. A graph of the evaluation criteria outcomes appears below. An explanation of each criterion, in order of relative importance follows.

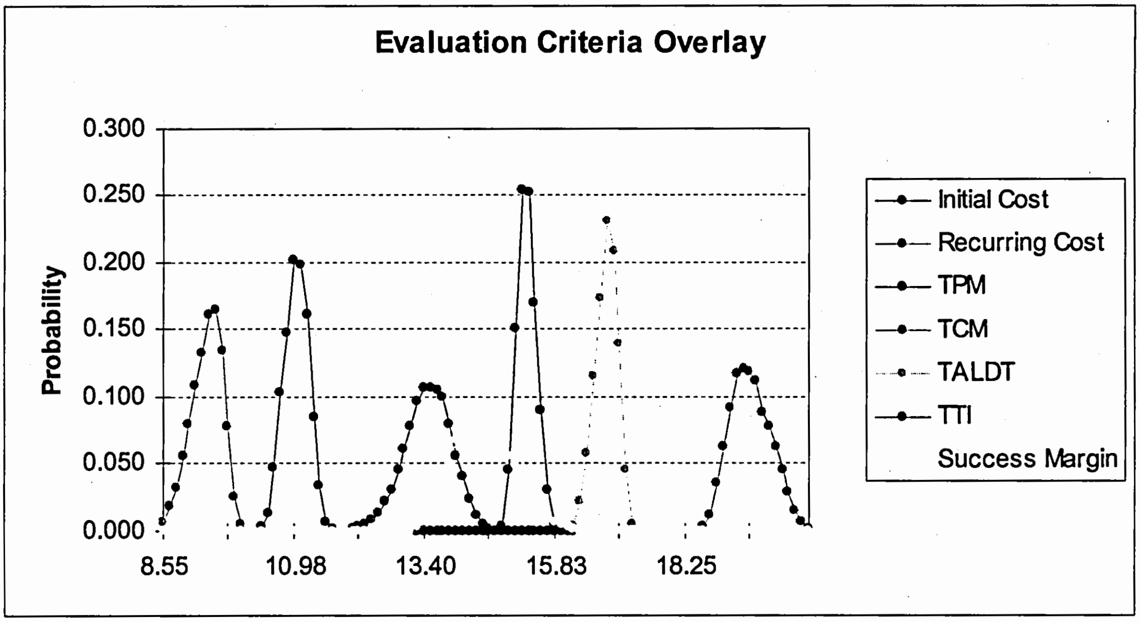

Figure 33: Evaluation Criteria Distributions

The most critical evaluation criterion is the level of decrease in Total Corrective Maintenance or TCM. This criterion is measured as the increase in MC rate caused by a corresponding reduction in TCM. It is a quantitative criterion. The Total Admin and Logistics Down-Time (TALDT) is the next criterion. This value is quantitative and similar to the TCM value discussed earlier. The next three criteria all have similar levels of importance. Total Preventive Maintenance (TPM) is the increase in MC rate as a result of a corresponding decrease in TPM. Success margin is a measure of the percentage of time the fleet would meet or exceed the 90% MC goal with the addition of the appropriate alternative. It is quantitative and measured through the use of a probabilistic model explained later. Initial cost is a measure of the initial outlay of funds associated with a particular alternative. This value is quantitative and measured in millions of dollars. The next critical value is the Time to Implementation or TTI. This criterion is qualitative and is a best judgment of the amount of time it would take to implement and see any benefits from an alternative. It is assumed that it would take a minimum of one year to experience benefits from any alternative. TTI is a measure of how long it would take beyond that initial period. Finally, the Recurring Cost is a measure of the costs that would occur after the initial expenditure of funds. These costs include annual salaries or supply costs that contribute to the five year total cost. This value is quantitative and also measured in millions of dollars.

The distributions for each of these criteria are calculated from a Monte Carlo simulation conducted with the QFD table. A simulation was conducted varying the customer requirements, according to their distributions from the customer survey. Then the distributions for the evaluation criteria become the coefficients for the OEC.

The OEC, which appears below, is a numerical way of computing a value for each alternative based on the various factors present in this problem. It is a technique used when more than one factor impacts a problem. If MC rate was the only factor impacting this problem, an OEC would not be necessary. However, this situation is complex and requires a more advanced technique.

$$OEC = \frac{\alpha\left(\frac{TPM}{TPM_{BL}}\right)+\beta\left(\frac{TCM}{TCM_{BL}}\right)+\gamma\left(\frac{TALDT}{TALD_{BL}}\right)+\delta\left(\frac{Success}{Success_{BL}}\right)+\varepsilon\left(\frac{TTI}{TTI_{BL}}\right)}{\zeta\left(\frac{INIT\_Cost}{INIT\_Cost_{BL}}\right)+\eta\left(\frac{RECUR\_Cost}{RECUR\_Cost_{BL}}\right)}$$

Figure 34: Overall Evaluation Criteria

The actual implementation of the OEC occurred in a decision matrix. The matrix calculates the value for each alternative based on the formula for the OEC. Once again in this application, the decision matrix was implemented using a Monte Carlo simulation. The simulation varied the values for the weights of each evaluation criteria and the actual benefits of each alternative. The values for the MC rate benefits were modeled as distributions, according to their expected benefits. The decision matrix appears below in Table 15.

Table 15: Alternative Decision Matrix

Evaluation Criteria	**Weight:**	**Increase Maint Training**	**Increase Enlisted-Other**	**ORFs**	**Increase Enlisted-Phase**	**Increase Contractor-Phase**	**Stock Availability**	**Recapitalization**
Initial Cost	[redacted]	47.8	27.7	828.4	5.7	0	120.5	61.5
Recurring Cost	[redacted]	0	321.4	0	65.9	165	22.6	298.4
Decrease TPM	[redacted]	0	0	[redacted]	[redacted]	[redacted]	0	0
Decrease TCM	[redacted]	0	0	0	0	0	0	[redacted]
Decrease TALDT	[redacted]	[redacted]	[redacted]	0	0	0	[redacted]	0
Time to Implement	[redacted]	3	5	1	7	9	5	3
Success Margin	[redacted]	5.44	13.09	21.62	8.52	8.52	9.2	7.66
	OEC	5.9074	2.8676	1.4459	8.798	4.0638	7.3338	17.065
	Relative OEC	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

The column on the left represents the evaluation criteria. The light blue column under the heading 'Weights' are the results from the QFD simulation. Values under the individual alternatives represent the corresponding values for each criterion. Green boxes represent distributions, and change during the Monte Carlo simulation. Finally, the red value for recurring cost under the Recapitalization alternative is a negative value due to the savings inherent in this option. The results of the decision matrix appear below in Figure 35. They represent the range of values for each alternative based on the OEC formula. A discussion of the results follows.

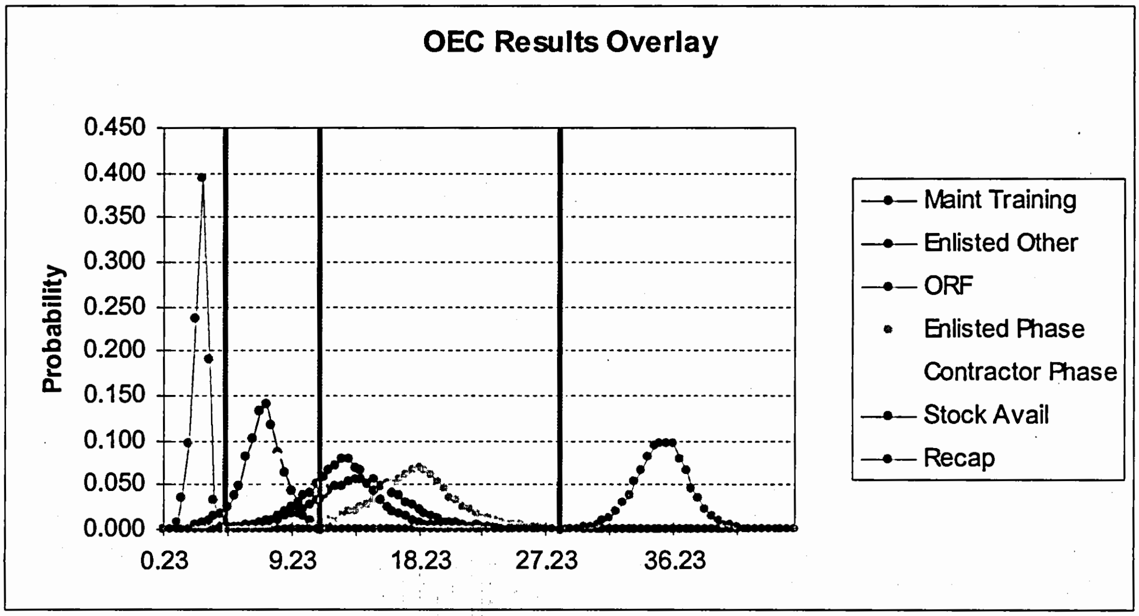

Figure 35: Alternative OEC Results

The results of the decision matrix simulation fall into four groups. Clearly the best alternative, according to the OEC, is Recapitalization. There is no overlap between the OEC curve for this alternative and the others. Although this alternative offers modest increases in MC rate, it does so at an overall cost savings and improves the system reliability.

The next group consists of three alternatives that can not be considered better or worse than each other. Enlisted phase teams, additional Maintainer Training and Increased Stock Availability are all relatively close, yet clearly lower than Recapitalization. In the next group are Increased Enlisted Manpower and Contractor Phase teams. These two alternatives are costly with a moderate MC increase. Finally, although ORFs promise the highest MC rate increase, this alternative is also extremely costly. In addition, it is estimated that this alternative would take the longest to implement due to the lengthy acquisition and fielding process associated with new aircraft.

Perform Sensitivity Analysis

A critical feature resulting from the use of distributions to quantify uncertainty is the probabilistic results of any calculations performed. For example, typical decision matrices yield a deterministic number that is ranked relative to the results of the other alternatives. However, using the techniques explained in this report, the calculation results have variation and represent a range of possible values.

Because of this use of probability distributions it is easier to determine the impact that input variables have on the outcomes of calculations. For example, the distribution for the weight of each customer requirement affects the values for the weight of each evaluation criteria. The variation in evaluation criteria affects the values for the OEC calculations for each alternative. A sensitivity analysis quantifies and analyzes these effects.

Figure 36 is an example of a sensitivity analysis on the effects that the customer requirement weights had on the values for the evaluation criteria weights. In this example, the green bars show the contribution each of the customer requirements had on the variability in the value for the TCM coefficient. Clearly, Cost had the biggest effect on the TCM coefficient's variability. Similar analysis for each of the evaluation criteria shows that the customer requirements Cost and Safety were the largest contributors to variation in the evaluation criteria. A review of Table 1: Voice of Customer Survey Results reveals that those two requirements have the widest range of values for their relative weight. This range reflects the diversity in the field of emphasis of the experts surveyed. To reduce the variability in the QFD results, additional analysis is required to refine the importance of the customer requirements. Such analysis; however, is beyond the scope of this research.

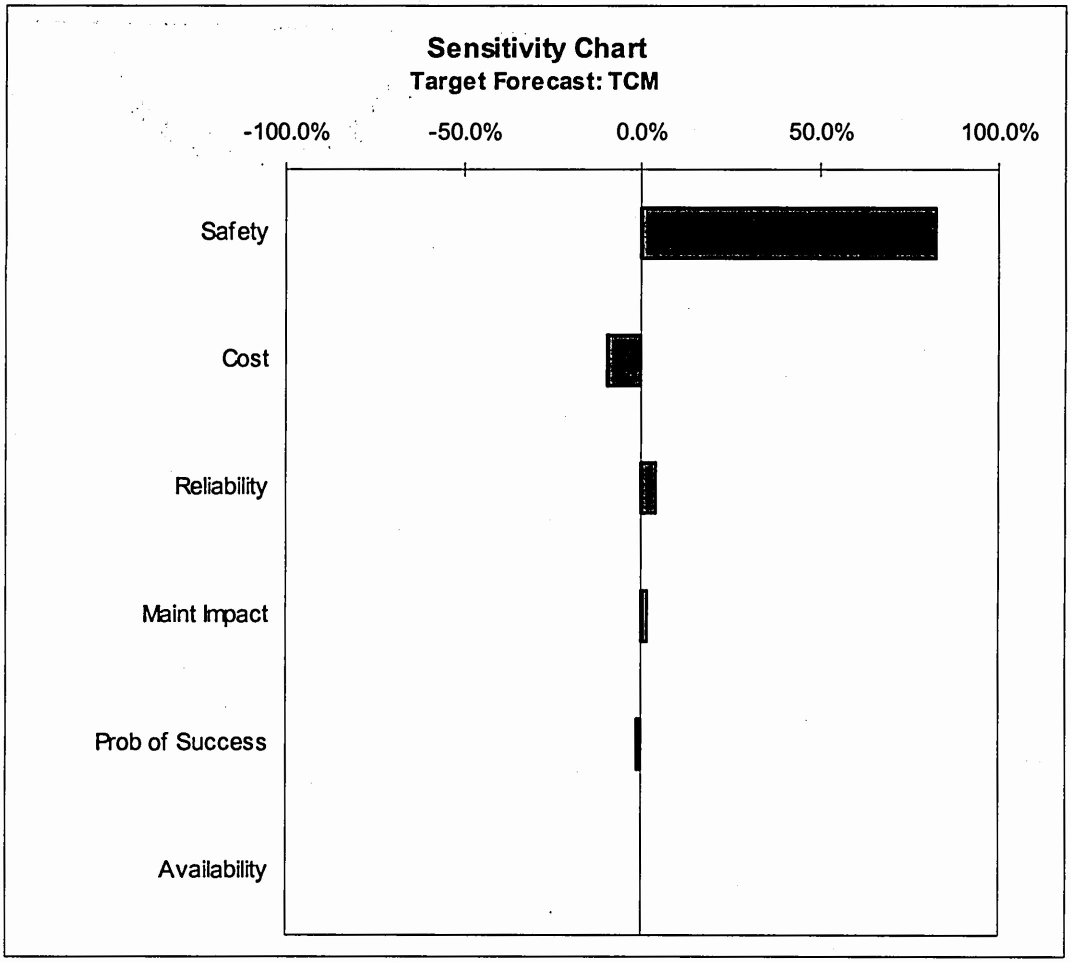

Figure 36: Sensitivity Analysis for TCM Weighting

An additional set of sensitivity studies was performed on the OEC results to determine the factors contributing to the variability in the alternative outcomes. Figure 37 is an example of that analysis using the results of the decision matrix for Recapitalization. Clearly, the majority of variability in the OEC results is caused by the distributions for the various MC rate improvements. These rates are forecasts and can not be known with greater uncertainty unless actual studies are performed. It is important to note that the customer requirement Safety has enough variability to also affect the outcomes of the OEC results.

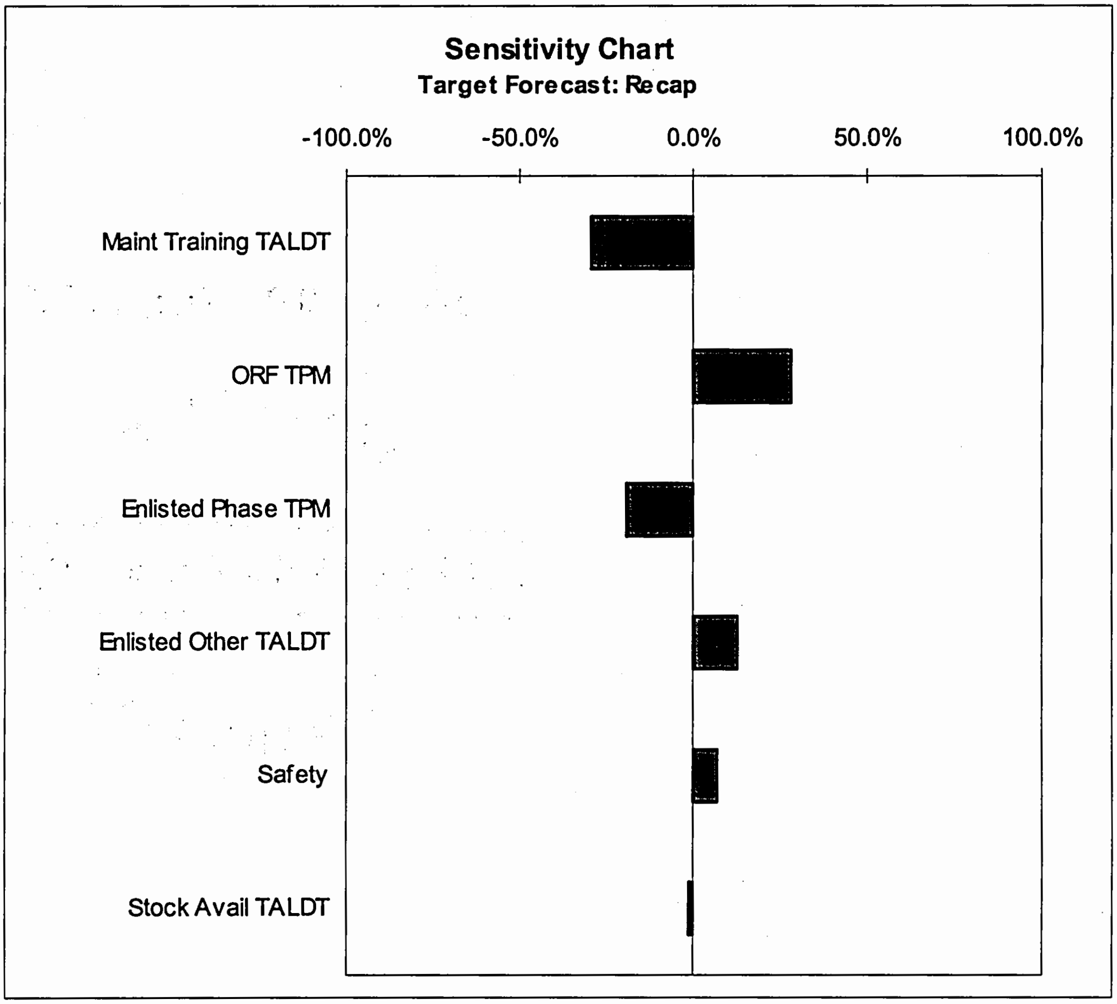

Figure 37: Sensitivity Analysis for Recapitalization OEC Result

Design Synthesis Through MDO

To this point, each of the alternatives has been analyzed, compared and presented individually. However, it is not realistic to assume that decision-makers would choose one alternative to implement and disregard the rest. More appropriately, the alternatives would be grouped into options, based on their compatibility and feasibility. The final stage of this research is aimed at devising and comparing options based on synthesizing the alternatives into viable options.

In order to do this, first one must look at the options and understand their relationships. A tool used in Quality Management known as an Interrelationship (IR) Digraph can be modified to accomplish this goal. An IR Digraph normally depicts causal relationships between categories from an affinity diagram.[21] In this application, it can be used to compare which alternatives are incompatible and which are required to work in combination.

Table 16: Interrelationship Digraph for Alternatives

Interrelationships	**Increase Maint Training**	**Increase Enlisted-Other**	**ORFs**	**Increase Enlisted-Phase**	**Increase Contractor-Phase**	**Stock Availability**	**Recapitalization**
Increase Maint Training	■						
Increase Enlisted-Other		■					
ORFs			■				
Increase Enlisted-Phase				■	■	▩	
Increase Contractor-Phase				■	■	▩	
Stock Availability						■	
Recapitalization						▩	■

Legend:	
Prerequisite:	▩
Exclusive:	■

[21] Victor E. Sower, Michael J. Savoie, and Stephen Renick, An Introduction to Quality Management and Engineering, (Saddle River: Prentice Hall, 1999), 42.

Table 16 is a modified IR Digraph featuring all of the viable alternatives compared against each other. Read from the left side, this table graphically displays which alternatives can not be combined and which ones depend on another alternative for implementation. For example, if one reads down on the left side to Increase Enlisted-Phase and then across, there is a red box corresponding to Increase Contractor Phase. This is because these alternatives are mutually exclusive. On the other hand, moving one block to the right in this same row reveals a green box corresponding to Stock Availability. This box indicates that the Enlisted Phase alternative can not be implemented without also implementing the Stock Availability alternative. Stock Availability is a requirement for several alternatives because increasing manpower to expedite maintenance is not feasible without also ensuring spare parts are readily available to conduct that maintenance.

Options

The purpose of an analyst is to provide options for decision-makers. The final stage of this research is to group the alternatives into credible options, compare those options and finally recommend a decision.

The Morphological Matrix utilized earlier in this methodology was a brainstorming method to develop alternatives to solve the problem. The Morphological Matrix can be used again to organize the alternatives into options. Table 17 shows the implementation of the second matrix to create four overall options for achieving 90% MC.

Table 17: Option Morphological Matrix

PLANS:	Administrative	Maintainability	Logistics	Reliability
Minimize Costs:	Enlisted Other	Enlisted Phase Teams	Stock Availability	Recapitalization
Maximize MC:	Maintainer Training Enlisted Other	ORFs Enlisted Phase	Stock Availability	Recapitalization
No ORFs:	Maintainer Training Enlisted Other	Enlisted Phase Teams	Stock Availability	Recapitalization
No Enlisted Increase:	Maintainer Training	ORFs Contractor Phase	Stock Availability	Recapitalization

The four options presented are:

1. Minimize Costs
2. Maximize MC Rate
3. No use of ORFs
4. No Additional Enlisted Maintainers

These options represent likely scenarios that could develop due to external influences. The first option accounts for a limited budget due to current military commitments. While the 90% MC initiative is important, there are not unlimited funds to implement it. The second option instead reflects an urge to maximize the MC rate at all costs. It serves as a counter-point to the first option. The No ORFs option assumes that, based on complications with acquisitions and contracts, the Army will not choose to acquire additional aircraft to use as ORFs. Purchasing aircraft is a long and difficult process and this option takes that difficulty into account. The final option acknowledges the current limits on personnel strength in the Army. Therefore, this option assumes that there will be no additional enlisted maintainers available to provide manpower.

Comparing Options

In order to analyze the costs and benefits of each option, a method was developed to model the combinations of alternatives. This method, utilized in the software package JMP™, created a range for each of the independent variables. In this case, the independent variables were the amount of spending on each of the seven alternatives. The response variable was the MC rate. The response was calculating by generating a formula for the MC rate, assuming a linear relationship between spending and MC rate for all of the alternatives.

Once the variables and response was created, a contour profile was used in the software package to analyze the impact of changing various spending amounts. Figure 38 is an example of the tool used to analyze various spending levels and their impacts on the MC rate of any option. Each of the seven alternatives is featured on the top of the profiler. The bar to the right of the alternative title is a sliding bar that allows the user to change the spending level, which appears numerically to the right of the bar. The response value is below the sliding bars. In this instance, the MC rate is 91.42%. The gray blocks indicate the upper and lower limits analyzed of 90 and 100%, respectively. The contour to the lower right is a graphical representation of the MC rate associated with input from two of the seven independent variables. Currently, the Enlisted Other and ORF alternatives are selected.

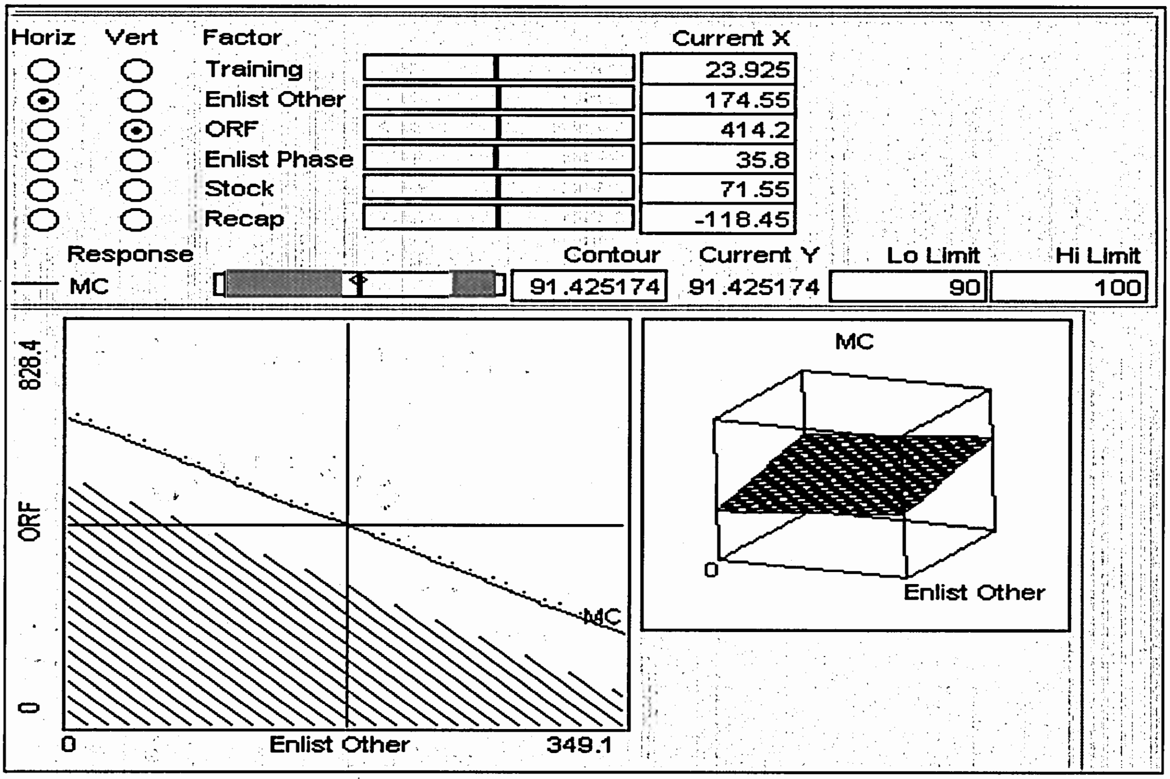

Figure 38: Interactive Contour Profiler

This profiler was used to set the alternative spending levels associated with the four options to understand what dollar values would create a particular MC rate. After the spending levels associated with the four plans were established, the success margin for each option was calculated again using a Monte Carlo simulation. The model for MC rates built in Crystal Ball™ using the unit MC rate parameters was used. MC rate improvements were again modeled as distributions and the combination of improvements for each option was simulated.

The end result, after using the interactive contour profiler and the probabilistic model, was another decision matrix. The OEC used was identical to the one used for the individual alternatives. The decision matrix appears below in Table 18. A final Monte Carlo simulation was performed to determine the best overall option to recommend. The results also appear below.

Table 18: Options Decision Matrix

Evaluation Criteria	Weight:	Minimize Cost	Maximize MC	No ORFs	No Enlisted Increase
Initial Cost	13.23	215.4	1091.6	263.2	1058.2
Recurring Cost	9.34	111.5	111.5	111.5	173.6
Decrease TPM	15.30	2.809	12.709	2.809	12.412
Decrease TCM	19.74	2.5	2.5	2.5	2.5
Decrease TALDT	16.99	4.9683	5.4025	5.4025	3.3041
Time to Implement	10.91	7	3	5	9
Success Margin	14.49	38.2	53	39.1	47
	OEC	5.45	2.89	4.93	2.58
	Relative OEC	34.38	18.22	31.09	16.30

The results of the simulation appear in two formats. The first graph shows the distributions for the OEC of the four options. The second graph shows the cumulative distributions for each OEC result. The second graph is useful for comparing the options and using a confidence interval to determine if an option is truly 'better' than another.

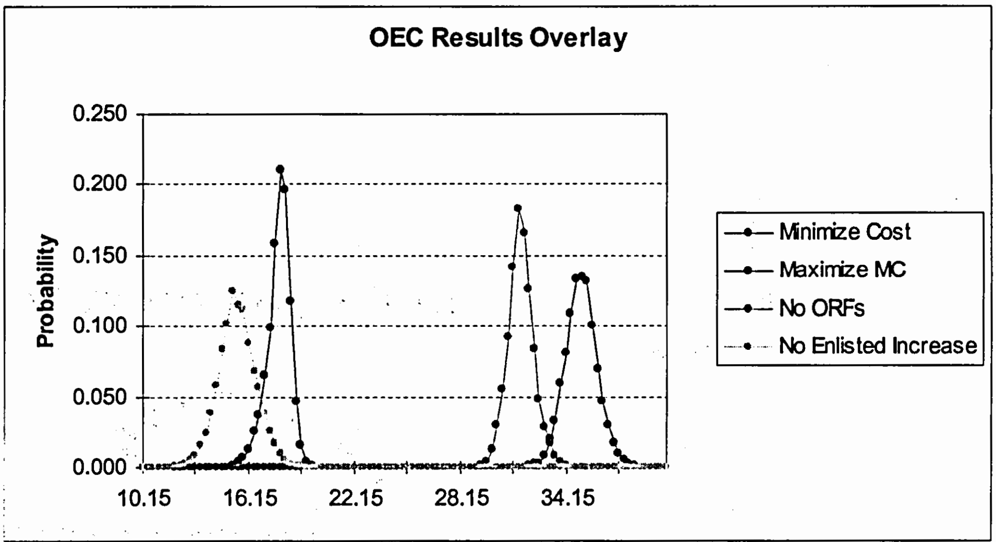

Figure 39: Alternatives OEC Results

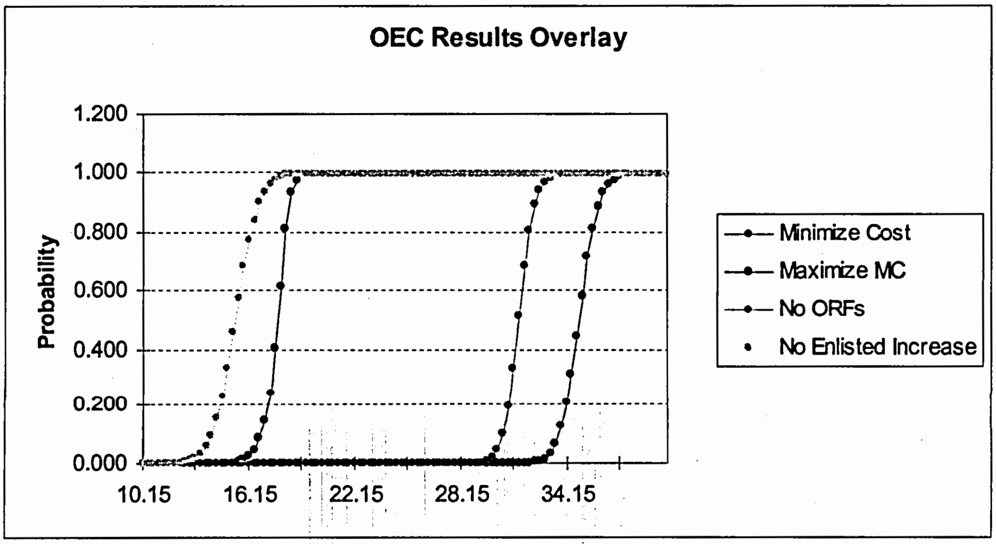

Figure 40: Alternatives OEC Cumulative Results

Figure 40 shows the results of the OEC simulation. It is evident from the cumulative distributions that the Minimize Cost option is the best overall option. The 95th percentile of the No ORFs option is still lower than the 5th percentile of the Minimize Cost option. Therefore, one can be 90% confident that the two options are far enough apart to be considered different. The Maximize MC and No Enlisted Increase are clearly 'worse' than the top two options.

Report Results

The final step of this methodology consists of reporting the results of the analysis. This document and a corresponding presentation, comply with this step of the process. An additional document, with a more narrow focus on the results, will be prepared at a later date for submission to the Apache PEO.

CONCLUSIONS

Since this is an academic effort, there are two types of conclusions to draw from this effort. The first section will deal with the operational conclusions to be drawn about the MC rate analysis. The final section will look at the research from an academic viewpoint and draw conclusions based on those goals.

Operational Conclusions

As stated throughout this paper, the problem of improving the availability of the Army's AH-64 Apache is a complex one. The combinations of factors that impact aircraft readiness are difficult to isolate, define and analyze. This research did; however, identify several key things.

First, there is a real difference in aircraft availability based on the location of particular units and the type of unit in question. Overseas units clearly enjoy higher MC rates as do units that report directly to Corps headquarters instead of Divisions. The most likely cause for this discrepancy is the availability of enlisted personnel to perform maintenance. The average age of aircraft probably plays a role, but is difficult to quantify.

Second, there are several credible alternatives to improve aircraft readiness. These alternatives, ranging from increased manpower, better spare parts availability to additional aircraft, can improve aircraft readiness. However, the exact amount they can improve MC rates is not known precisely. Based on input from several logistics experts, the most promising alternative is the Recapitalization plan.

Finally, a series of options exist to attack the MC rate problem from several angles. Taking all of the factors into account, the best overall option appears to be the one that achieves a moderate probability of success, while minimizing the cost impact to the Army.

Academic Conclusions

Despite the real-world nature of this problem, ultimately this was an academic exercise aimed at achieving specific goals. The overall purpose of this thesis was to explore the feasibility of using a methodology to analyze availability improvements to Army rotorcraft. The AH-64 Apache was chosen as a test vehicle because of the author's experience with the aircraft and the pressing need to improve readiness.

Specifically, the thesis aimed to determine if a methodology could answer the following four questions about the Apache readiness problem:

1. Is the methodology appropriate for understanding how the system is unavailable?
2. Is the methodology appropriate for understanding why the system is unavailable?
3. Can the methodology generate alternatives to improve the system availability?
4. Can the methodology choose the optimal alternative to improve the system availability?

An additional goal was to conduct the analysis using common, Microsoft Office™ based tools to ensure that the methodology could be easily transferred to personnel involved with the Apache readiness problem.

A discussion of the degree to which those goals were achieved follows. In the first case, the methodology was extremely effective in understanding how the system is unavailable. The use of statistical tools, such as ANOVA, provided a clear way to understand current MC rates and the factors that affected MC rates. In addition, the use of statistical tools provided a basis for understanding why the system was unavailable.

Understanding why the system was unavailable was made possible by the combination of clear mathematical tools and qualitative analysis tools. The systems engineering methods such as system decomposition, in concert with the quality tools such as the Ishikawa Diagram provided a framework to understand the causes of the problem in the context of the statistical evidence. A clear advantage of the IPPEA methodology is the wide selection of tools that can be tailored to the specific problem

The brainstorming method of using a Morphological Matrix was useful to develop and organize alternatives to solve the problem. Most importantly, the probabilistic tools present in the methodology presented a powerful means to analyze the costs and benefits of those alternatives. A problem of this magnitude contains a large number of unknown quantities. Without the use of costly experimentation, an analyst needs a method of capturing uncertainty and incorporating it into the analysis. Modeling unknown factors with probability distributions and conducting Monte Carlo simulations to calculate results, was one of the cornerstones of this methodology. Additionally, the use of a simulation tool like Petri Nets provided a simple, effective way to model Stochastic processes.

The last goal of determining the best way of solving the problem met with mixed success. The methodology offers clear, effective methods to compare the merits of various alternatives. Linking the customer requirements to analytical requirements through the use of the QFD is the single most important part of the methodology. Furthermore, the use of an OEC to compare alternatives ensures that an analyst can recommend the best solution accounting for all of the attributes that affect the problem. The only limiting factor present in this problem was the lack of available data on the interactions between alternatives. Without even a limited study into some of the alternatives it was difficult to accurately predict the effects of combining alternatives into a coherent option. However, given the level of available information, the comparison between options presented is still an effective means of recommending a solution.

The only additional goal was to use Microsoft Office™ based tools to conduct the analysis. All of the statistical and numerical analysis was conducted in Microsoft Excel™ and JMP™, by SAS. JMP is fully compatible with Excel and is very intuitive to learn and use. All of the probabilistic studies and Monte Carlo simulations were performed in Crystal Ball™, an Excel add-in. Crystal Ball is a very simple, yet effective tool to incorporate uncertainty into any spreadsheet-style analysis. The only departure from the original goal was the use of Petri Nets to model phase inspections. Petri Nets are not fully mature in the current commercial software marketplace. Most of the applications tested for this research were freeware developed by college students, primarily in Europe. However, the promise of Petri Nets to model systems and their behavior could easily warrant the Army contracting a programmer to develop a specific software product.

In summary, the application of the IPPEA methodology, based on the generic Georgia Tech IPPD methodology, was successful in analyzing the Apache availability problem. With additional data and cooperation, this research could be refined and expanded to provide Army decision-makers with sufficient analysis to choose the best path to achieving the goal of 90% MC rates.

REFERENCES

AH-64 Apache Joint Aviation Technical Data Integration Homepage, www.apache.jatdi.mil.

"Apache Recapitalization Optimization Final Results," Report Submitted by Sandia National Laboratory to The Apache Program Executive Office, September 2002.

Daniel P. Schrage, "Georgia Tech's Systems Analysis Capabilities to Measure and Track 90% Mission Capability Efforts for Army Aviation Systems" Presentation to the Army Materiel Command, (2002).

David J. Smith, Reliability Maintainability and Risk, Practical Methods for Engineers, 6th ed. (Boston: Butterworth-Heinemann, 2002).

Department of the Army, *Cost Analysis Manual* (U.S. Army Cost Analysis Center, 2002).

Department of the Army, *Economic Analysis Manual* (U.S. Army Cost and Economic Analysis Center, 2001).

Department of Defense, *Integrated Product and Process Development* Handbook (Office of the Undersecretary of Defense, Acquisition and Technology, 1998).

"Feasability Analysis to Raise Readiness and Support Soldiers", Presentation by Aviation Project Manager to LTG Kern (2002).

Forrest W. Breyfogle III, Implementing Six Sigma, Smarter Solutions Using Statistical Methods, (New York: John Wiley & Sons, 1999).

George C. Dieter, Engineering Design, 3rd ed. (Boston: McGraw Hill, 2000).

John Moubray, Reliability Centered Maintenance, 2nd ed. (New York: Industrial Press, 1997).

John Neter, et. al., Applied Linear Statistical Models, 4th ed. (Boston: McGraw-Hill, 1996).

"Maintenance Officer Conference Briefs", Presented by U.S. Army Apache Unit Commanders to The Apache Program Executive Office, 2002.

Mohamed Ben-Daya, Salih O. Duffuaa, and Abdul Raouf, Maintenance Modeling and Optimization, (Boston: Kluwer, 2000).

Petri Nets World Online Homepage, www.daimi.au.dk/PetriNets.

Ralph Pallotta, Colonel, U.S. Army "AH-64 Apache," Presentation to the Army Science Board (2002).

"Sandia Support for Toward 90% Readiness," Presentation by Sandia National Laboratories to The Apache Program Executive Office, 15 October, 2001.

"Toward 90% Aviation Readiness, Evaluation of Inspection Interval / Duration," Presentation by Aviation and Missile Research, Development and Evaluation Center (2003).

"Toward 90% Aviation Readiness", Presentation Prepared by the Army Materiel Command, 14 June 2002.

"Toward 90% Readiness: Feasibility Analysis to Raise Readiness and Support Soldiers," Presentation by AMCOM Aviation Task Force, November, 2001.

U Dinesh Kumar, John Crocker, J. Knezevic, and M El-Haram, Reliability, Maintenance and Logistic Support, (Boston: Kluwer, 2000).

U.S. Army Force Management Support Activity Database.

U.S. Army Logistics Support Activity Readiness Integrated Database.

U.S. Army Military-Civilian Cost System (AMCOS) Database.

U.S. Army Operating and Support Management Information System (OSMIS) Relational Database.

U.S. Department of Defense Systems Management College, *Systems Engineering Fundamentals* (Fort Belvoir, Virginia: Defense Systems Management College Press, 1999).

Victor E. Sower, Michael J. Savoie, and Stephen Renick, An Introduction to Quality Management and Engineering, (Saddle River: Prentice Hall, 1999).

Wolfgang Reisig, A Primer in Petri Net Design, (Berlin: Springer-Verlag Press, 1992).